U·X·L
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weather and natural disasters

U•X•L Encyclopedia of Weather and Natural Disasters

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Anaxos, Inc., Editors

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Reader's Guide

Weather in all its manifestations—from peaceful blankets of mountain fog to ferocious hurricanes—fascinates most humans. Young children wonder why the sky is blue. Busy professionals wonder whether ice storms will cause flight delays. Backyard gardeners wonder whether their plants will survive a hot, dry summer. *The U•X•L Encyclopedia of Weather and Natural Disasters* presents a comprehensive, up-to-date survey of weather, weather-related topics, and natural disasters that gives readers the science behind the weather events that affect us all every day.

Scope and format

Each of the chapters in this five-volume series presents its topic in clear, nontechnical language. The topics are arranged in alphabetical order. The material is enlivened with eyewitness descriptions of recent weather phenomena, historical accounts of famous past weather events and disasters, biographies of famous figures in meteorology, practical information on handling extreme weather situations, relevant book and film recommendations, and hundreds of photographs, illustrations, and charts. Each chapter also presents step-by-step experiments, suitable for home or classroom, that allow students to have hands-on experiences with the foundations of weather and meteorology. Additionally, *The U•X•L Encyclopedia of Weather and Natural Disasters* provides a "Words to Know" section in each chapter, with key terms clearly defined. A cumulative index and a comprehensive "Where to Learn More" section at the back of each volume give readers easy access to material both within the series and in outside resources.

Volume 1 of this series serves as a general introduction to the topic of weather and natural disasters, and includes chapters on climate, clouds, and precipitation.

Volume 2 presents the first six of the alphabetically arranged chapters on weather and natural disaster topics: Avalanche, Blizzard, Drought, Dust Storm, Earthquake, and El Niño.

Volume 3 presents the following seven chapters: Flood, Fog, Hurricane, Landslide, La Niña, Local Winds, and Monsoon.

Volume 4 wraps up the alphabetically arranged chapters with six more chapters: Optical Effects, Thunderstorm, Tornado, Tsunami, Volcano, and Wildfire.

Volume 5 examines human involvement with weather and natural disasters, offering chapters on forecasting, climate change, and the influence of humans on weather.

Acknowledgements

The development of *The U•X•L Encyclopedia of Weather and Natural Disasters* was a collaborative effort by the staff of Anaxos, Inc., but several key members of the team require special acknowledgement and appreciation. Many thanks are owed to Dr. Elliot Richmond for his broad meteorological expertise and good humor. Special thanks also to Emily Baker-Falconer and Russ Falconer, for their organizational vigor and editorial acumen, and to Liza Banks, for her copyediting prowess.

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Timeline

c. 1650 B.C.E. The Mediterranean island of Thera is destroyed by a volcanic eruption. The event possibly gives rise to the legend of the lost civilization of Atlantis.

218 B.C.E. Carthaginian leader Hannibal's army is decimated by avalanches as he attempts to cross the Alps with tens of thousands of soldiers and a multitude of war elephants.

350 B.C.E Greek philosopher Aristotle writes *Meteorology*.

79 Eruption of Mount Vesuvius destroys Pompeii and Herculaneum in Italy.

1281 A Chinese fleet of around 4,000 warships is destroyed by a typhoon during an attempted invasion of Japan. The relieved Japanese called the typhoon *kamikaze,* or "divine wind," believing it came from the gods for their protection.

1375 An earthquake destroys the famous lighthouse of Alexandria, Egypt, one of two remaining wonders of the ancient world (the other being the great pyramids of Egypt).

1441 Invention of standardized rain gauge by King Sejong and Prince Munjong of Korea.

1450 Leone Battista Alberti invents first anemometer.

1606 Galileo invents the thermometer.

1643 Evangelista Torricelli invents the barometer.

1657 King Ferdinand II of Tuscany establishes the Accademia Del Cimento of Florence, which develops many early meteorological tools.

1686 English astronomer Edmund Halley publishes a ground-breaking study of trade winds and monsoons.

1707 Mount Fuji in Japan erupts for the last time.

1714 Gabriel Fahrenheit invents the first mercury thermometer.

1742 Swedish astronomer Anders Celsius outlines the centrigrade temperature scale. This would lead to what is now the Celsius scale.

1752 Benjamin Franklin performs his famous "kite" experiment, flying a kite that dangled a metal key during a thunderstorm to determine the relationship between lightning and electricity.

1783 Iceland's Mount Laki erupts, spewing massive clouds of ash into the atmosphere and killing up to one fifth of the population of Iceland.

1784 Benjamin Franklin theorizes that the abnormally cold European winter of 1783–1784 was due to the eruption of Mount Laki, becoming one of the first scientists to note the relationship between volcanic eruptions and climate cooling.

1786 Benjamin Franklin publishes an accurate map of the Gulf Stream.

1820 The U.S. Army begins making and recording formal weather observations.

1841 Elias Loomis creates the first synoptic weather map.

1842 James P. Espy is appointed first official U.S. government meteorologist.

1846 Irish astronomer and physicist John Thomas Romney Robinson invents the cup anemometer.

1849 The Smithsonian Institution establishes a national weather observation network using information relayed via telegraph from 150 observers across the country.

1860 As head of the newly established British Meteorological Office, Robert FitzRoy uses the new telegraph system to gather daily observations from across England to make "weather forecasts," a term he coined.

1863 Robert FitzRoy publishes *Weather Book*, an important meteorological text.

1870 President Ulysses S. Grant establishes a national weather warning service under the Secretary of War.

1873 International Meteorological Organization founded.

1875 Benito Vines, the director of the Meteorological Observatory at Belen in Havana, Cuba, issues an accurate hurricane warning two days before a hurricane hits Cuba. His warning saves many lives.

1876 A cyclone in Bangladesh kills more than 200,000.

1883 Eruption of Krakatau causes massive tsunamis that kill 36,000 in Java and Sumatra.

1887 The Yellow River in China floods, killing an estimated one million people.

1889 A dam bursts in Johnstown, Pennsylvania, causing a flood that kills 2,000 people.

1890 U.S. Weather Bureau is founded.

1892 Captain Camilo Carrilo tells the Geographical Society of Lima, Peru, of "El Niño," his term for a warm northerly current and associated climate noticeable around Christmas.

1897 Belgian Adrien de Gerlache sets off for the Antarctic (with a crew that included first-mate Roald Amundsen) to make geographical and meteorological observations of Antarctica. It is the first expedition to spend an entire winter in the Antarctic.

1898 U.S. Weather Bureau establishes a hurricane warning network at Kingston, Jamaica.

1900 A hurricane strikes Galveston, Texas, killing more than 6,000 people.

1902 Stratosphere is discovered. Two scientists, working independently, share credit for the discovery: Richard Assmann and Léon Teisserenc de Bort.

1906 Earthquake in San Francisco kills approximately 3,000.

1919 Introduction of the Norwegian Cyclone Model, a revolutionary method of weather map analysis and interpretation.

1921 Sakuhei Fujiwara publishes a paper on the "Fujiwara Effect," the rotation of two cyclones around each other.

1924 Sir Gilbert Walker coins the term "Southern Oscillation" to describe the current and climate shifts popularly known as El Niño.

1925 The so-called Tri-State Tornado ravages Missouri, Illinois, and Indiana, killing nearly 700 people.

1930 Russian scientist Pavel Mochanov successfully launches his radiosonde, a balloon-borne device that can take weather measurements and relay them by radio, into the stratosphere.

1934 The "Dust Bowl," a severe drought in southern plains states that lasted several years, begins.

1938 Guy Steward Callendar publishes "The Artificial Production of Carbon Dioxide and Its Influence on Temperature," considered the first description of global warming caused by carbon dioxide emissions.

1943 Pilot J. B. Duckworth intentionally flies into a hurricane off the coast of Texas for the purpose of weather reconnaissance.

1948 First correct tornado prediction made in Oklahoma.

1948 Pacific Tsunami Warning System is established in Honolulu, Hawaii.

1951 The World Meteorological Association, operating as a specialized agency of the United Nations, replaces the International Meteorological Association.

1954 The U.S. National Weather Service begins naming each season's hurricanes alphabetically using female names.

1956 F. K. Ball publishes his theory of the generation of Antarctic katabatic winds.

1959 World's first weather satellite, Vanguard 2, is launched.

1969 The Saffir-Simpson Hurricane Scale is created. The scale rates the strength of hurricanes on a scale of 1 to 5.

1969 Hurricane Camille hits the Gulf Coast of the U.S., killing several hundred people.

1970 The National Oceanic and Atmospheric Administration (NOAA) is established.

1971 Ted Fujita introduces the Fujita scales for rating tornadoes.

1978 Record-breaking blizzard hits northeastern U.S.

1980 Mount St. Helens in Washington State explodes.

1985 Discovery of the Antarctic ozone hole.

2004 Massive tsunami kills nearly 300,000 people in Thailand, India, and Indonesia.

2005 Hurricane Katrina pummels New Orleans and the Mississippi Gulf Coast, killing nearly 2,000 people and forcing millions of people from their homes.

2006 The U.S. experiences a record-breaking wildfire season, with nearly ten million acres burned.

2007 The Enhanced Fujita Scale replaces the Fujita scale as a system for rating tornadoes.

Words to Know

A

absolute humidity: the amount of water vapor in the air, expressed as a ratio of the amount of water per unit of air.

accretion: the process by which a hailstone grows larger, by gradually accumulating cloud droplets as it travels through a cloud.

acid precipitation: rain and snow that are made more acidic when carbon, sulfur, and/or nitrogen oxides in the air dissolve into water. Also known as acid rain.

acid rain: rain that is made more acidic when carbon, sulfur, and/or nitrogen oxides in the air dissolve into water. Also known as acid precipitation.

active solar collector: system for gathering and storing the Sun's heat that uses pumps and motors. Often used for heating water.

active volcano: a volcano that continues to erupt regularly.

adiabatic process: a process by which the temperature of a moving air parcel changes, even though no heat is exchanged between the air parcel and the surrounding air.

advection: the horizontal movement of a mass such as air or an ocean current.

aftershock: ground shaking that occurs after the main shock of an earthquake.

agricultural report: a specialized weather report tailored to the needs of farmers that includes current temperature, precipitation, and wind speed and direction, as well as frost warnings and predictions of temperature and precipitation for the days to come.

air mass: a large quantity of air throughout which temperature and moisture content is fairly constant.

air pollutant: any harmful substance that exists in the atmosphere at concentrations great enough to endanger the health of living organisms.

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

Air Quality Index (AQI): measurement of air quality, based on concentrations of surface ozone averaged over an eight-hour period for specific locations.

Alps: mountain system composed of more than fifteen principle mountain ranges that extends in an arc for almost 660 miles (1,060 kilometers) across south-central Europe.

anabatic wind: winds caused by warm air close to Earth's surface. The air is less dense than the surrounding air and travels upward along a slope.

Andes: mountain range extending more than 5,000 miles (8,045 kilometers) along the western coast of South America.

anemometer: an instrument that measures wind speed.

aneroid barometer: a type of barometer that consists of a vacuum-sealed metal capsule, within which a spring expands or contracts with changing air pressure.

anvil: the flattened formation at the top of a mature cumulonimbus cloud.

aquifer: an underground layer of spongy rock, gravel, or sand in which water collects.

arid: describes a climate in which almost no rain or snow falls.

ash: very small, fine fragments of lava or rock that are blasted into the air during volcanic explosions.

asthenosphere: region of the mantle below the lithosphere, composed of partially melted rock.

aurora: a bright, colorful display of light in the night sky, produced when charged particles from the Sun enter Earth's atmosphere.

avalanche: a large mass of snow, ice, rocks, soil, or a combination of these elements that moves suddenly and swiftly down a mountain slope, pulled by the force of gravity.

avalanche path: the course an avalanche takes down a slope, composed of a starting zone, a track, and a runout zone.

avalanche wind: a cloudlike mixture of snow particles and air pushed ahead of a slab avalanche as it races downward.

aviation report: a specialized weather report tailored to the needs of pilots that provides information on the height of the clouds, visibility, and storm systems.

B

backfire: a small fire set by firefighters in the path of an oncoming wildfire to burn up the fuel before the main fire arrives, thus blocking it.

backing wind: a wind that shifts direction, rotating counterclockwise higher in the atmosphere.

barchan dune: a sand dune that, when viewed from above, resembles a crescent moon, with the tips of the crescent pointing downwind. Also called barchane dune, barkhan dune, or crescentic dune.

barograph: an aneroid barometer that records changes in air pressure over time on a rotating drum.

barometer: an instrument used to measure air pressure.

basalt: a type of rock that forms from hardened lava.

blizzard: the most severe type of winter storm, characterized by winds of 35 miles (56 kilometers) per hour or greater, large quantities of falling or blowing snow, and low temperatures.

blocking system: a whirling air mass containing either a high-pressure system (a blocking high) or a low-pressure system (a blocking low), that gets cut off from the main flow of upper-air westerlies.

C

caldera: a large depression, usually circular or oval shaped, left behind when a volcano's summit collapses.

calvus: "bald"; describes when the upper part of a cloud is losing its rounded, cauliflower-like outline and becoming diffuse and fibrous.

capillatus: "having hair"; a cloud with a cirriform, streaky structure on its upper edges.

castellanus: "castlelike"; used to describe clouds with vertical extensions.

Cenozoic era: the historical period from sixty-five million years ago to the present.

chaos theory: the theory that the weather, by its very nature, is unpredictable. Every time one atmospheric variable (such as heat, air pressure, or water) changes, every other variable also changes—but in ways that are out of proportion with the first variable's change.

chinook: a dry, warm katabatic wind in North America that blows down the eastern side of the Rocky Mountains, from New Mexico to Canada in winter or early spring.

chinook wall cloud: a solid bank of wispy, white clouds that appears over the eastern edge of the Rocky Mountains in advance of a chinook wind.

chlorofluorocarbons (CFCs): compounds similar to hydrocarbons in which one or more of the hydrogen atoms are replaced by fluorine or chlorine.

cinder: a small piece of material thrown from a volcano during an eruption.

cinder cone: a volcanic cone made of lava fragments.

cirriform: a wispy, feathery fair-weather cloud formation that exists at high levels of the troposphere.

cirrostratus: a thin layer of high-altitude clouds that cover most of the sky, but are semitransparent.

cirrus: clouds at high levels of the troposphere, created by wind-blown ice crystals, that are so thin as to be nearly transparent.

Clean Air Act: set of environmental regulations limiting pollutants emitted by cars, factories, and other sources. First enacted by the U.S. Congress in 1970 and updated several times since then.

clear-cutting: the logging practice of harvesting all trees from vast forest tracts.

climate: the weather experienced by a given location, averaged over several decades.

coalescence: the process by which an ice crystal grows larger. The ice crystal collides and sticks together with water droplets as the ice crystal travels down through a cloud.

coastal flood: an overflow of water onto a coastal area caused by a storm surge, strong winds, or tsunami.

cold front: the leading edge of a moving mass of cold air.

cold-phase ENSO (El Niño/Southern Oscillation): another name for La Niña; colder-than-normal eastern Pacific waters.

composite volcano: a volcano with steep sides made of layers of lava and ash.

compressional warming: an adiabatic process by which an air parcel warms as it descends. The descending parcel is compressed by the increasing pressure of the surrounding air, which adds kinetic energy to the molecules. Also called compressional heating.

condensation: the process by which water changes from a gas to a liquid.

condensation nucleus: a tiny solid particle around which condensation of water vapor occurs.

conduction: the transfer of heat by collisions between moving molecules or atoms.

cone: the sloping outer sides of a volcano (not all volcanoes have cones).

conelet: a small cone on the side of a large volcano.

congestus: "congested"; describes clouds with upper parts that are piled up and sharply defined; resembles a head of cauliflower.

conservation tillage: the practice of leaving vegetation on fields during idle periods to protect the soil from erosion and trap moisture.

continental drift: geologic theory that all continents were part of a single, original landmass before they slowly separated and gradually drifted apart.

convection: the upward motion of an air mass or air parcel that has been heated.

convection current: circular movement of a gas or liquid between hot and cold areas.

convective cell: a unit within a thunderstorm cloud that contains updrafts and downdrafts.

convective zone: the region of warm tropical water over which thunderstorms form; the ocean under the Intertropical Convergence Zone.

conventional radar: instrument that detects the location, movement, and intensity of precipitation, and gives indications about the type of precipitation. It operates by emitting microwaves, which are reflected by precipitation. Also called radar.

convergence: the movement of air inward toward a central point, such as the trade winds blowing from the north and south near the equator.

Coriolis effect: the apparent curvature of large-scale winds, ocean currents, and anything else that moves freely across Earth, due to the rotation of Earth around its axis.

corona: a circle of light centered on the Moon or Sun that is usually bounded by a colorful ring or set of rings.

cosmic rays: invisible, high-energy particles that bombard Earth from space.

crater: the bowl-shaped area around the opening at the top of a volcano.

crepuscular rays: bright beams of light that radiate from the Sun and cross the sky.

crest: the highest point of a wave.

critical angle: the angle at which sunlight must strike the back of the raindrop in order to be reflected back to the front of the drop.

crown fire: a fire that spreads through the treetops, or crown, of a forest.

crust: the outermost layer of Earth, varying in thickness from 3.5 miles (5 kilometers) under the ocean to 50 miles (80 kilometers) thick under the continents.

cumuliform: a puffy, heaped-up cloud formation.

cumulonimbus: a tall, vertically developed cloud reaching to the top of the troposphere or above, and capable of producing heavy rain, high winds, and lightning.

cumulus: fluffy, white, mid-level clouds that look like white or light-gray cotton balls of various shapes.

cyclone: a weather system characterized by air that flows inward and circulates around a low-pressure area.

D

dart leaders: the series of dim lightning strokes that occur immediately after the original lightning stroke, that serve to discharge the remaining buildup of electrons near the base of the cloud.

debris avalanche: a downward slide of loose, earthen material (soil, mud, and small rocks) that begins suddenly and travels at great speeds;

similar to a snow avalanche. It builds into a fearsome mass of mud, trees, and rocks that can cause much damage.

debris slide: a slide of small rocks and shallow layers of loose soil that commonly follows volcanic eruptions.

deforestation: the removal of all or most of the trees from an area.

dendrochronology: the study of the annual growth of rings of trees.

deposition: the process by which water changes directly from a gas to a solid, without first going through the liquid phase.

derecho: a destructive, straight-line wind, which travels faster than 58 mph (93 kph) and has a path of damage at least 280 miles (450 kilometers) long. Also called plow wind.

desert climate: the world's driest climate type, with less than 10 inches (25 centimeters) of rainfall annually.

desert pavement: hard, flat, dry ground and gravel that remain after all sand and dust has been eroded from a surface.

desertification: the process by which semiarid lands turn to desert (also called land degradation). It is caused by prolonged drought, during which time the top layers of soil dry out and blow away.

dew point: the temperature at which a given parcel of air reaches its saturation point and can no longer hold water in the vapor state.

diffraction: the slight bending of sunlight or moonlight around water droplets or other tiny particles.

dispersion: the selective refraction of light that results in the separation of light into the spectrum of colors.

divergence: the movement of air outward, away from a central point.

Doppler radar: a sophisticated type of radar that relies on the Doppler effect, the change in frequency of waves emitted from a moving source, to determine wind speed and direction as well as the direction in which precipitation is moving.

dormant volcano: a volcano that has not erupted for many years.

downburst: an extremely strong, localized downdraft beneath a thunderstorm that spreads horizontally when it hits the ground, destroying objects in its path.

downdraft: a downward blast of air from a thunderstorm cloud, felt at the surface as a cool wind gust.

drizzle: precipitation formed by raindrops between 0.008 inches and 0.02 inches in diameter.

drought: an extended period when the amount of rain or snow that falls on an area is much lower than usual.

dry adiabatic lapse rate: the constant rate at which the temperature of an unsaturated air parcel changes as it ascends or descends through the atmosphere. Specifically, air cools by 5.5°F for every 1,000 feet (1.0°C for every 100 meters) it ascends and warms by 5.5°F for every 1,000 feet (1.0°C for every 100 meters) it descends.

Dust Bowl: the popular name for the approximately 150,000 square-mile-area (400,000-square-kilometer-area) in the southern portion of the Great Plains region of the United States. It is characterized by low annual rainfall, a shallow layer of topsoil, and high winds.

dust devil: a spinning vortex of sand and dust that is usually harmless but may grow quite large. Also called a whirlwind.

dust storm: a large cloud of dust blown by a strong wind.

E

earthflow: a landslide that consists of material that is moist and full of clay, yet drier than the material in mudflows.

earthquake: a sudden shifting of masses of rock beneath Earth's surface, which releases enormous amounts of energy and sends out shock waves that cause the ground to shake.

eccentricity: the alternating change in shape of Earth's orbit between a circle and an ellipse.

ecosystem: a community of plants and animals, including humans, and their physical surroundings.

effusive eruption: the type of eruption in which lava spills over the side of a crater.

El Niño: Spanish for "the Christ child;" an extraordinarily strong episode (occurring every two to seven years) of the annual warming of the Pacific waters off the coast of Peru and Ecuador.

El Niño/Southern Oscillation (ENSO): the simultaneous warming of the waters of the eastern Pacific and the accompanying shifts in air pressure over the eastern and western Pacific.

electromagnetic spectrum: the array of electromagnetic radiation, which includes radio waves, infrared radiation, visible light, ultraviolet radiation, x rays, and gamma rays.

ENSO: stands for El Niño/Southern Oscillation. It describes the simultaneous warming of the waters in the eastern Pacific Ocean and the shifting pattern of air pressure between the eastern and western edges of the Pacific.

entrainment: the process by which cool, unsaturated air next to a thunderstorm cloud gets pulled into the cloud during the mature stage of a thunderstorm.

Environmental Protection Agency (EPA): government agency charged with implementing the provisions of the Clean Air Act.

epicenter: the point on Earth's surface directly above the focus of an earthquake, where seismic waves first appear.

equinoxes: the days marking the start of spring and fall. Also the two days of the year in which day and night are most similar in length and the Sun appears to cross Earth's equator in its yearly motion.

erosion: the wearing away of a surface by the action of wind, water, or ice.

eruption: the release of pressure that sends lava, rocks, ash, and gases out of a volcano.

evaporation: the process by which water changes from a liquid to a gas.

evaporation fog: fog that is formed when water vapor evaporates into cool air and brings the air to its saturation point.

extinct volcano: a volcano that is never expected to erupt again.

extratropical cyclones: a storm system that forms outside of the tropics and involves contrasting warm and cold air masses.

eye: an area of clear sky and warm, dry, descending air at the center of a hurricane.

eye wall: a vertical area of thick clouds, intense rain, and strong winds marking the outer boundary of the eye.

F

fair-weather waterspout: relatively harmless waterspout that forms over water and arises either in conjunction with, or independently of, a severe thunderstorm. Also called nontornadic waterspout.

fall: the downward motion of rock or soil through the air or along the surface of a steep slope.

Fata Morgana: a special type of superior mirage that takes the form of spectacular castles, buildings, or cliffs rising above cold land or water.

fault: crack in Earth's surface where two plates or sections of the crust push and slide in opposite directions against one another.

fault creep: slow, continuous movement of plates along a fault, allowing pressure to be released.

fibratus: "fibrous"; describes clouds with hairlike strands with no hooks or curls at the end.

fire line: a strip of ground, cleared of all combustible material, that is dug by firefighters to stop the advance of a wildfire. Also called control line.

fire triangle: the combination of three elements required for any fire: fuel, oxygen, and heat.

firestorm: also called a blowup, it is the most explosive and violent type of wildfire.

fissure: a crack in Earth's surface through which volcanic materials can escape.

flash flood: a sudden, intense, localized flooding caused by persistent heavy rainfall or the failure of a levee or dam.

floccus: "flock of wool"; describes clouds with small tufts with ragged undersides.

flood: an overflow of water on land that is normally dry.

flood basalt: high temperature basaltic lava that flows from a fissure in Earth's crust and covers large areas of the landscape. Also known as plateau basalt.

focus: the underground starting place of an earthquake, also called the hypocenter.

fog: a cloud that forms near or on the ground.

food chain: the transfer of food energy from one organism to another. It begins with a plant species, which is eaten by an animal species; it continues with a second animal species, which eats the first, and so on.

foreshock: ground shaking that occurs before the main shock of an earthquake.

fossil fuels: coal, oil, and natural gas—materials composed of the remains of plants or animals that covered Earth millions of years ago and are today burned for fuel.

fractus: "fractured"; describes clouds with broken up, ragged edges.

freezing nuclei: a tiny particle of ice or other solid onto which supercooled water droplets can freeze.

front: the dividing line between two air masses of different temperatures.

frontal system: a weather pattern that accompanies an advancing front.

frostbite: the freezing of the skin.

fuel cell: device that generates electricity by combining hydrogen and oxygen; it emits water vapor as a by-product.

Fujita Intensity scale: scale that measures tornado intensity, based on wind speed and the damage created.

fumarole: a vent in Earth's surface that releases steam and other gases, but generally no lava.

funnel cloud: cone-shaped spinning column of air that hangs well below the base of a thunderstorm cloud.

G

gale-force wind: any wind whose sustained speed is between 39 and 54 mph (63 and 87 kph).

geologist: a scientist who studies the origin, history, and structure of Earth.

geostationary satellite: weather satellite that remains above a given point on Earth's equator, traveling at the same speed as Earth's rotation about 22,300 miles (35,900 kilometers) above the surface.

geyser: a regular spray of hot water and steam from underground into the air.

glacier: slowly flowing masses of ice created by years of snowfall and cold temperatures.

global warming: the theory that average temperatures around the world have begun to rise, and will continue to rise, due to an increase of certain gases, called greenhouse gases, in the atmosphere. Also called enhanced greenhouse effect and global climate change.

global water budget: the balance of the volume of water coming and going between the oceans, atmosphere, and continental landmasses.

glory: a set of colored rings that appears on the top surface of a cloud, directly beneath the observer. A glory is formed by the interaction of sunlight with tiny cloud droplets and is most often viewed from an airplane.

Great Depression: the worst economic collapse in the history of the modern world. It began with the stock market crash of 1929 and lasted through the late 1930s.

green flash: a very brief flash of green light that appears near the top edge of a rising or setting Sun.

greenhouse effect: the warming of Earth due to the presence of greenhouse gases, which trap upwardly radiating heat and return it to Earth's surface.

greenhouse gases: gases that trap heat in the atmosphere. The most abundant greenhouse gases are water vapor and carbon dioxide. Others include methane, nitrous oxide, and chlorofluorocarbons.

ground blizzard: the drifting and blowing of snow that occurs after a snowfall has ended.

ground fire: a fire that burns beneath the layer of dead plant material on the forest floor.

gust front: the dividing line between cold downdrafts and warm air at the surface, characterized by strong, cold, shifting winds.

H

haboob: a tumbling black wall of sand that has been stirred up by cold downdrafts along the leading edge of a thunderstorm or cold front. It occurs in north-central Africa and the southwestern United States.

hail: precipitation comprised of hailstones.

hailstone: frozen precipitation that is either round or has a jagged surface, is either totally or partially transparent and ranges in size from that of a pea to that of a softball.

hair hygrometer: an instrument that measures relative humidity. It uses hairs (human or horse) that grow longer and shorter in response to changing humidity.

halo: a thin ring of light that appears around the Sun or Moon, caused by the refraction of light by ice crystals.

harmattan: a mild, dry, and dusty wind that originates in the Sahara Desert.

haze: the uniform, milky-white appearance of the sky that results when humidity is high and there are a large number of particles in the air.

heat cramps: muscle cramps or spasms, usually afflicting the abdomen or legs, that may occur during exercise in hot weather.

heat exhaustion: a form of mild shock that results when fluid and salt are lost through heavy perspiration.

heat stroke: a life-threatening condition that sets in when heat exhaustion is left untreated and the body has spent all its efforts to cool itself. Also called sunstroke.

heat wave: an extended period of high heat and humidity.

heating-degree-days: the number of degrees difference between the day's mean (average) temperature and the temperature at which most people set their thermostats. The total number of heating-degree-days in a season is an indicator of how much heating fuel has been consumed.

heavy snow: snowfall that reduces visibility to 0.31 mile (0.5 kilometer) and yields, on average, 4 inches (10 centimeters) or more in a twelve-hour period or 6 inches (15 centimeters) or more in a twenty-four-hour period.

hollow column: a snowflake in the shape of a long, six-sided column.

Holocene: the most recent part of the Cenozoic era, from ten thousand years ago to the present.

horse latitudes: a high-pressure belt that exists at around 30° latitude, north and south, where air from the equatorial region descends and brings clear skies.

hot spot: an area beneath Earth's crust where magma currents rise.

hotshot: a specialized firefighter who ventures into hazardous areas and spends long hours battling blazes.

humilis: "humble" or "lowly"; describes clouds with a small, flattened appearance.

humiture index: an index that combines temperature and relative humidity to determine how hot it actually feels and, consequently, how stressful outdoor activity will be. Also called temperature-humidity index or heat index.

hurricane: the most intense form of tropical cyclone. A hurricane is a storm that forms in the northern Atlantic Ocean or in the eastern Pacific Ocean. It is made up of a series of tightly coiled bands of thunderstorm clouds, with a well-defined pattern of rotating winds and maximum sustained winds greater than 74 mph (119 kph).

hurricane warning: hurricane landfall is imminent.

hurricane watch: hurricane landfall is possible.

hurricane-force wind: sustained winds greater than 74 mph (119 kph).

hygrometer: an instrument used to measure relative humidity. It consists of a dry-bulb thermometer and a wet-bulb thermometer. Also called psychrometer.

hypothermia: a condition characterized by a drop in core body temperature from the normal 98.6°F (37°C) to 95°F (35°C) or lower.

I

ice age: a period during which significant portions of Earth's surface are covered with ice.

igneous rock: rock made of solidified molten material that made its way from the interior of the planet to the surface.

incus: "anvil" or "fan-shaped"; describes a cloud with a spreading, smooth or fibrous mass at the top.

induction: the process whereby excess electrical charges in one object cause the accumulation by displacement of electrical charges with the opposite charge in another nearby object.

inferior mirage: a mirage that appears as an inverted, lowered image of a distant object. It typically forms in hot weather.

insulator: a substance through which electricity does not readily flow.

intensity: description of the physical damage caused by an earthquake.

interglacial period: a relatively warm period that exists between two ice ages.

Intertropical Convergence Zone: a belt of warm, rising, unstable air formed from the inward-flowing trade winds from north and south of the equator.

intortis: "intertwined"; describes clouds with entangled, fibrous strands.

inversion, atmospheric: a stable reversal of the normal pattern of atmospheric temperature, formed when a warm air mass sits over a cold air mass near the surface.

ion: an atom that has lost or gained an electron, thereby acquiring a positive or negative electrical charge.

iridescence: an irregular patch of colored light on a cloud.

isobar: an imaginary line that connects areas of equal air pressure, after the air pressure measurements have been adjusted to sea level.

isotherm: an imaginary line connecting areas of similar temperature.

J

jet stream: the world's fastest upper-air winds. Jet streams travel in a west-to-east direction, at speeds of 80 to 190 miles (130 to 300 kilometers) per hour, around 30,000 feet (9,150 meters) above the ground. Jet streams occur where the largest differences in air temperature and air pressure exist. In North America, jet streams are typically found over southern Canada and the northern United States, as well as over the southern United States and Mexico. The northern jet stream is called the polar jet stream, and the southern jet stream is called the subtropical jet stream.

K

katabatic wind: a strong wind that travels down a mountain under the force of gravity, and is stronger than a valley breeze.

khamsin: a hot, dry, southerly wind that originates on the Sahara and produces large sand and dust storms.

kinetic energy: the energy of motion.

L

La Niña: Spanish for little girl, a period of cooler-than-normal water temperatures in the eastern Pacific near the coast of Peru and Ecuador. It often follows an El Niño.

lahar: a mudflow of volcanic ash and water that sometimes occurs after a volcanic eruption.

lake breeze: a wind similar to a sea breeze that can be felt at the edge of a large lake.

landfall: the point on a coast where the center of a hurricane first crosses.

landslide: the movement of large amounts of soil, rocks, mud, and other debris downward and outward along a slope.

latent heat: the heat that must be removed from a quantity of water vapor to cause it to turn into a liquid, or that must be added to a quantity of liquid water to cause it to turn into a vapor; called latent because the temperature of the quantity of water or water vapor does not change.

latitude: an imaginary line encircling Earth, parallel to the equator, that tells one's position north or south on the globe.

lava: molten rock that erupts from a fissure or a vent (*see* magma).

lava domes: volcanic formations built up from layers of viscous lava that does not flow far from its source.

lava tube: a tube formed when an outer layer of lava is cooled by the air and hardens and molten lava then flows out of the middle of the tube, leaving it hollow.

leeward: the opposite direction from which the wind is blowing. Also the slope of a mountain opposite to the direction of local or prevailing winds down which cold air descends, producing dry conditions.

lenticularis: "lens-shaped"; describes clouds that are elongated, or almond-shaped with well-defined outlines.

lightning: a short-lived, bright flash of light during a thunderstorm that is produced by a 100-million-volt electrical discharge in the atmosphere.

liquefaction: the transformation of water-saturated soil into a liquidlike mass, usually by the action of seismic waves.

lithosphere: the rigid outermost region of Earth, composed of the crust and the upper part of the mantle.

local winds: winds that blow across surface areas ranging from a few miles to about 100 miles (about 160 kilometers) in width. Also known as mesoscale winds or regional winds.

loose-snow avalanche: avalanche composed of loosely packed snow that begins at a single point and slides down a slope, fanning out in the shape of an inverted V.

M

magma: molten rock containing dissolved gas and crystals that originates deep within Earth. When it reaches the surface it is called lava.

magma chamber: a reservoir of magma beneath Earth's surface.

magnitude: the power of an earthquake, as recorded by a seismograph, or seismometer.

mammatus: round, pouchlike cloud formations that appear in clusters and hang from the underside of a larger cloud.

mantle: the thick, dense layer of rock that lies beneath Earth's crust. The mantle is about 1,800 miles (2,900 kilometers) thick and accounts for about 84 percent of Earth's volume.

marine forecast: a specialized weather forecast of interest to coastal residents and mariners, which gives projections of the times of high and low tide, wave height, wind speed and direction, and visibility.

Maunder minimum: a period of time from 1645 to 1715, during which sunspot activity was almost nonexistent.

mediocris: "mediocre"; describes clouds of moderate vertical development with lumpy tops.

mesocyclone: region of rotating updrafts created by wind shear within a supercell storm; it may be the beginnings of a tornado.

mesoscale winds: winds that blow across surface areas ranging from a few miles to about 100 miles (about 160 kilometers) in width. Also known as local winds or regional winds.

Mesozoic era: the historical period from 225 million years ago to 65 million years ago, best known as the age of the dinosaurs.

meteorologist: a scientist who studies weather and climate.

meteorology: the scientific study of the atmosphere and atmospheric processes, namely weather and climate.

middle latitudes: the regions of the world that lie between the latitudes of 30° and 60° north and south. Also called temperate regions.

Milankovitch theory: the theory stating that the three types of variation in Earth's orbit, taken together, can be linked with warm and cold periods throughout history. These variations include: the shape of Earth's orbit, the direction of tilt of its axis, and the degree of tilt of its axis.

mirage: an optical illusion in which an object appears in a position that differs from its true position, or a nonexistent object (such as a body of water) appears.

modified Mercalli scale: scale developed by Italian seismologist Giuseppe Mercalli to measure the intensity of an earthquake based on the amount of vibration felt by people and the extent of damage to buildings.

moist adiabatic lapse rate: the variable rate at which the temperature of a saturated air parcel changes as it ascends or descends through the atmosphere.

monsoon: a name for seasonal winds that result in a rainy season occurring in the summer on tropical continents, when the land becomes warmer than the sea beside it.

monsoon climate: a climate that is warm year-round with very rainy (flood-prone) summers and relatively dry winters. It encompasses much of southern and southeastern Asia, the Philippines, coastal regions of northern South America, and slices of central Africa.

mountain breeze: a gentle downhill wind that forms at night as cold, dense, surface air travels down a mountainside and sinks into the valley. Also called gravity wind or drainage wind.

mud slide: a landslide of mostly mud mixed with debris, often caused by heavy rains on steep land with sparse vegetation.

mudflow: a landslide consisting of soil mixed with water. It is wetter than the material in an earthflow.

multi-cell thunderstorm: a thunderstorm system that contains several convective cells.

multi-vortex tornado: tornado in which the vortex divides into several smaller vortices called suction vortices.

N

nebulosus: "nebulous"; describes clouds that are a thin, hazy veil.

NEXRAD: acronym for Next Generation Weather Radar, the network of high-powered Doppler radar units that cover the continental United States, Alaska, Hawaii, Guam, and South Korea.

nor'easter: a strong, northeasterly wind that brings cold air, often accompanied by heavy rain, snow, or sleet, to the coastal areas of New England and the mid-Atlantic states. Also called northeaster.

Northern Hemisphere: the half of the Earth that lies north of the equator.

numerical prediction model: a computer program that mathematically duplicates conditions in nature. It is often used to predict the weather.

O

obliquity: the angle of the tilt of Earth's axis in relation to the plane of its orbit.

occluded front: a front formed by the interaction of three air masses: one cold, one cool, and one warm. The result is a multi-tiered air system, with cold air wedged on the bottom, cool air resting partially on top of the cold air, and warm air on the very top.

ocean currents: the major routes through which ocean water is circulated around the globe.

oceanography: the study and exploration of the ocean.

Organized Convection Theory: a widely accepted model of hurricane formation.

orographic lifting: the upward motion of warm air that occurs when a warm air mass travels up the side of a mountain.

orographic thunderstorm: a type of air mass thunderstorm that's initiated by the flow of warm air up a mountainside. Also called mountain thunderstorm.

orographic uplift: the forcing of air upward, caused by the movement of air masses over mountains.

oxidation: a chemical reaction involving the combination of a material with oxygen.

ozone days: days on which the smog threshold is surpassed.

ozone hole: the region above Antarctica where the ozone concentration in the upper atmosphere gets very low at the end of each winter.

ozone layer: the layer of Earth's atmosphere, between 25 and 40 miles (40 and 65 kilometers) above ground, that filters out the Sun's harmful rays. It contains a higher concentration of ozone, which is a form of oxygen that has three atoms per molecule.

P

paleoclimatologist: a scientist who studies climates of the past.

Paleozoic era: the historical period from 570 million years ago to 225 million years ago.

particulates: small particles suspended in the air and responsible for most atmospheric haze. Particulates can irritate the lungs and cause lung disease with long exposure.

passive solar collector: system for collecting and storing the Sun's heat that has no moving parts and is generally used for home heating.

period: the time between two successive waves.

permafrost: a layer of subterranean soil that remains frozen year-round.

photochemical smog: a hazy layer containing ozone and other gases that sometimes appears brown. It is produced when pollutants that are released by car exhaust fumes react with strong sunlight.

photovoltaic cell: light-sensitive device containing semiconductor crystals (materials that conduct an electric current under certain conditions) that convert sunlight to electricity. Also called solar cells.

phytoplankton: tiny marine plants that occupy the lowest level of the food chain.

pileus: "felt cap"; small cap- or hood-shaped formation perched above or attached to the top of a cloud.

pipe: a narrow passageway that leads from a magma reservoir to a vent.

plate: a large section of Earth's crust.

plate tectonics: the geologic theory that Earth's crust is composed of rigid plates that are in constant motion with respect to each other, creating the major geologic features on the planet's surface.

Plinian eruption: a volcanic eruption that releases a deadly cloud of gas, dust, and ash.

polar easterlies: cold, global winds that travel across the polar regions, from the northeast to the southwest in the Northern Hemisphere and from the southeast to the northwest in the Southern Hemisphere.

polar front: the region or boundary separating air masses of polar origin from those of tropical or subtropical origin.

polar jet stream: a North American jet stream, typically found over southern Canada or the northern United States.

polar orbiting satellite: a weather satellite that travels in a north-south path, crossing over both poles just 500 to 625 miles (800 to 1,000 kilometers) above Earth's surface.

precession of the equinoxes: the reversal of the seasons every thirteen thousand years. This occurs because Earth spins about its axis like a top in slow motion and wobbles its way through one complete revolution every twenty-six thousand years.

precipitation: water particles that originate in the atmosphere (usually referring to water particles that form in clouds) and fall to the ground as rain, snow, ice pellets, or hail.

prescribed burn: a planned, controlled fire that clears flammable debris from the forest floor.

pressure gradient: the difference in air pressure between a high and low pressure area relative to the distance separating them.

psychrometer: an instrument used to measure relative humidity. It consists of a dry-bulb thermometer and a wet-bulb thermometer. Also called hygrometer.

Pulaski: a combination ax and hoe that is used by firefighters to clear brush and create a fire line. It was invented by forest ranger Edward Pulaski in 1903.

pumice: volcanic rock formed during the explosive eruption of magma; it has numerous gas bubbles and may float on water.

pyroclastic flow: a rapid flow of hot material consisting of ash, pumice, other rock fragments, and gas ejected by an explosive eruption.

R

radar: an instrument that detects the location, movement, and intensity of precipitation, and gives indications about the type of precipitation. It operates by emitting microwaves, which are reflected by precipitation. It is an abbreviation for **Ra**dio **D**etection **a**nd **R**anging. Radar may be called conventional radar to distinguish it from Doppler radar.

radiational cooling: the loss of heat from the ground upward into the atmosphere.

radioactive dating: a technique used to determine the age of rocks that contain radioactive elements, which works on the principle that radioactive nuclei emit high-energy particles over time.

radiosonde: an instrument package carried aloft on a small helium- or hydrogen-filled balloon. It measures temperature, air pressure, and relative humidity from the ground to a maximum height of 19 miles (30 kilometers).

rain band: a band of heavy thunderstorms forming a tightly coiled spiral around the center of a tropical storm.

rain gauge: a container that catches rain and measures the amount of rainfall.

rain shadow effect: the uneven distribution of precipitation across a mountain, with most of the precipitation falling on the windward side and very little falling on the leeward side.

rainbow: an arc of light, separated into its constituent colors, that stretches across the sky.

research buoy: a tethered or drifting buoy placed in the open ocean capable of recording atmospheric and ocean conditions and transmitting them to a satellite.

reflection: the process by which light both strikes a surface, and bounces off that surface, at the same angle.

refraction: the bending of light as it is transmitted between two transparent media of different densities.

regeneration: the process of making or starting anew.

relative humidity: a measure of humidity as a percentage of the total moisture a given volume of air, at a particular temperature, can hold.

Richter scale: the scale developed by American seismologist Charles Richter that describes the amount of energy released by an earthquake on a scale from 1 to 10. Each whole number increase in value on the scale indicates a ten-fold increase in the energy released. Earthquakes measuring 7 to 7.9 are major and those measuring 8 or above cause widespread destruction.

ridge: a northward crest in the wavelike flow of upper-air westerlies, within which exists a high pressure area.

Ring of Fire: the name given to the geologically active belt that surrounds the Pacific Ocean and is home to more than 75 percent of the world's volcanoes.

river flood: a flood caused when a river spills over its banks.

rock slide: a cascade of rocks (of any size) down a steep slope at high speeds.

roll cloud: a cloud that looks like a giant, elongated cylinder lying on its side, that is rolling forward. It follows in the wake of a gust front.

S

Saffir-Simpson Hurricane Damage Potential scale: a scale devised by Herbert Saffir and Robert Simpson intended to be used to predict a hurricane's destructive potential.

saltation: the wind-driven movement of particles along the ground and through the air.

saturated: air that contains all of the water vapor it can hold at a given temperature; 100 percent relative humidity.

saturation point: the point at which a given volume of air contains the maximum possible amount of water vapor.

scattering: multidirectional reflection of light by minute particles in the air.

sea breeze: the gentle wind that blows from over the sea to the shore during the day, due to differences in air pressure above each surface.

season: a period of the year characterized by certain weather conditions, such as temperature and precipitation, as well as the number of hours of sunlight each day.

sector plate: a star-shaped snowflake.

seismic waves: vibrations that move outward from the focus of an earthquake, causing the ground to shake.

seismograph: instrument used to detect and measure seismic waves. Also known as a seismometer.

semiarid: a climate in which very little rain or snow falls.

semipermanent highs and lows: the four large pressure areas (two high-pressure and two low-pressure), situated throughout the Northern Hemisphere, that undergo slight shifts in position, and major changes in strength, throughout the year.

severe blizzard: a blizzard in which wind speeds exceed 45 miles (72 kilometers) per hour, snowfall is heavy, and the temperature is 10°F (–12°C) or lower.

severe thunderstorm: a thunderstorm with wind gusts of at least 58 mph (93 kph); hailstones at least 3/4 inch (2 centimeters) in diameter; or tornadoes or funnel clouds.

shamal: a hot, dry, dusty wind that blows for one to five days at a time, producing great dust storms throughout the Persian Gulf.

shelf cloud: a fan-shaped cloud with a flat base that forms along the edge of a gust front.

shield volcano: a volcano with long, gentle slopes, built primarily by lava flows.

shower: a brief spell of localized rainfall, possibly heavy, that only occurs in warm weather.

simoom: a hot, dry, blustery, dust-laden wind that blows across the Sahara and the deserts of Israel, Syria, and the Arabian peninsula.

sinkhole: a natural, steep depression in a land surface caused by collapse of a cavern roof.

skin cancer: a disease of the skin caused primarily by exposure to the ultraviolet rays in sunlight.

slab avalanche: avalanche that begins when fracture lines develop in a snowpack and a large surface plate breaks away, then crumbles into blocks as it falls down a slope.

sling psychrometer: an instrument that measures relative humidity. It consists of a dry-bulb thermometer and a wet-bulb thermometer mounted side by side on a metal strip, which rotates on a handle at one end.

slump: the slow downhill movement of large portions (called blocks) of a slope. Each block rotates backward toward the slope in a series of curving movements.

smog: common name for photochemical smog—a layer of hazy, brown air pollution at Earth's surface comprised of ozone and other chemicals.

smog threshold: the level of smog allowed by law and set by the Environmental Protection Agency at 80 parts per billion (ppb) of surface ozone.

smokejumper: a specialized firefighter who parachutes to strategic locations from airplanes to battle wildfires.

snow fence: a device placed in fields and along highways that slows the wind and reduces the blowing and drifting of snow.

solifluction: the most rapid type of earthflow, occurring when snow or ice thaws or when earthquakes produce shocks that turn the soil into a fluid-like mass.

Southern Oscillation: shifting patterns of air pressure at sea level, between the eastern and western edges of the Pacific Ocean.

spissatus: "tightly packed"; describes icy formations at the top of a vertical cloud that are dense enough to block out the Sun.

spotting: the starting of new fires, called spot fires, by sparks and embers that drift ahead of an advancing wildfire.

squall line: a moving band of strong thunderstorms.

stable air layer: an atmospheric layer through which an air parcel cannot rise or descend.

stationary front: a boundary between two air masses at different temperatures which are not moving or are moving slowly.

steam eruption: a violent eruption that occurs when water comes in contact with magma, rapidly turns to steam, and causes the mixture to explode.

stepped leader: an invisible stream of electrons that initiates a lightning stroke. A stepped leader surges from the negatively charged region of a cloud, down through the base of the cloud, and travels in a stepwise fashion toward the ground.

storm surge: an abnormal rise of the sea over and above normal tides and due to strong winds and low pressure accompanying a storm or hurricane.

stratiformis: "covering" or "blanket"; describes clouds that form a thick layer.

stratosphere: the second-lowest layer of Earth's atmosphere, from about 9 to 40 miles (15 to 65 kilometers) above ground.

stratus: gloomy, gray, featureless sheets of clouds that cover the entire sky, at low levels of the atmosphere.

subduction zone: a region where two plates come together and the edge of one plate slides beneath the other.

subsidence: a gradual sinking of the land surface relative to its previous level.

subtropical jet stream: a North American jet stream, typically found over the southern United States or northern Mexico.

suction vortices: small vortices within a single tornado that continually form and dissipate as the tornado moves along, creating the tornado's strongest surface winds.

sunspot: an area of magnetic disturbance on the surface of the Sun, sometimes referred to as a sun storm.

supercell storm: the most destructive and long-lasting form of a severe thunderstorm, arising from a single, powerful convective cell. It is characterized by strong tornadoes, heavy rain, and hail the size of golf balls or larger.

supercooled water: water that remains in the liquid state below the freezing point.

superior mirage: a cold-weather mirage that appears as a taller and closer, and sometimes inverted, image of a distant object.

surface fire: a fire with a visible flame that consumes plant material and debris on the forest floor.

T

thermal: a pocket of rising, warm air that is produced by uneven heating of the ground.

thermograph: an instrument consisting of a thermometer and a needle that etches on a rotating drum, continually recording the temperature.

thermometer: an instrument used to measure temperature. It consists of a vacuum-sealed narrow glass tube with a bulb in the bottom containing mercury or red-dyed alcohol. Also called dry-bulb thermometer.

thunderstorm: a relatively small but intense storm system resulting from strong rising air currents; characterized by heavy rain or hail along with thunder, lightning, and sometimes tornadoes.

tidal station: a floating instrument center in the ocean that records water levels.

topography: the shape and height of Earth's surface features.

tornadic waterspout: tornado that forms over land and travels over water. Tornadic waterspouts are relatively rare and are the most intense form of waterspouts.

tornado: rapidly spinning column of air that extends from a thunderstorm cloud to the ground. Also called a twister.

tornado cyclone: spinning column of air that protrudes through the base of a thunderstorm cloud.

tornado family: a group of tornadoes that develop from a single thunderstorm.

tornado outbreak: emergence of a tornado family. Tornado outbreaks are responsible for the greatest amount of tornado-related damage.

trade winds: dominant surface winds near the equator, generally blowing from east to west and toward the equator.

translucidus: "translucent"; describes clouds that form a transparent layer covering a large part of the sky, through which the Sun or Moon shines.

transpiration: the process by which plants emit water through tiny pores in the underside of their leaves.

transverse dune: a series of connected barchan dunes, which appear as tall, elongated crescents of sand running perpendicular to the prevailing wind.

tropical cyclone: any rotating weather system that forms over tropical waters.

tropical depression: a storm with rotating bands of clouds and thunderstorms and maximum sustained winds of less than 38 miles (61 kilometers) per hour.

tropical disturbance: a cluster of thunderstorms that is beginning to demonstrate a cyclonic circulation pattern.

tropical storm: a tropical cyclone weaker than a hurricane, with organized bands of rotating thunderstorms and maximum sustained winds of 39 to 73 mph (63 to 117 kph).

tropical wave: an elongated area of low air pressure, oriented north to south, causing areas of cloudiness and thunderstorms.

tropics: the region of Earth between 23.5° north latitude and 23.5° south latitude.

tropopause: the boundary between the troposphere and the stratosphere, between 30,000 and 40,000 feet (9,000 and 12,000 meters) above ground.

troposphere: the lowest atmospheric layer, where clouds exist and virtually all weather occurs.

trough: a southward dip in the wavelike flow of upper-air westerlies, within which exists a low-pressure area. Also, the lowest point of a wave.

tsunami: a huge ocean wave that can travel at speeds up to 600 mph (965 kph) for hundreds of miles over open ocean before it hits land; caused by an earthquake, underwater volcanic eruption, or underwater landslide.

tsunami warning: an alert stating that a tsunami has been detected and is approaching the designated area. People are instructed to move to higher ground immediately.

tsunami watch: an alert stating that an earthquake has occurred with sufficient magnitude to trigger a tsunami. People are instructed to listen for further news.

typhoon: tropical cyclone that form in the China Sea or in the western North Pacific Ocean.

U

uncinus: "hook-shaped"; describes clouds with fibers creating the pattern called "mare's tail."

undulatus: "undulating"; describes clouds with wavelike formation within patches, layers, or sheets.

unhealthy air days: days on which surface ozone levels reach 80 parts per billion—a concentration considered unhealthy to children, people with respiratory problems, and adults who exercise or work vigorously outdoors.

unsaturated air: air that has less than 100 percent relative humidity.

updraft: a column of air blowing upward inside a vertical cloud.

upper-air westerlies: global-scale, upper-air winds that flow in waves heading west to east (but also shifting north and south) through the middle latitudes of the Northern Hemisphere.

upwelling: the rising up of cold waters from the depths of the ocean, replacing the warm surface water that has moved away horizontally.

V

valley breeze: an uphill wind that forms during the day as the valley air is heated and rises. Also called anabatic wind.

veering wind: a wind that shifts direction, turning clockwise as it moves higher.

vent: an opening in the surface of Earth through which molten rock, lava, ash, and gases escape.

ventifact: a rock, boulder, or canyon wall that has been sculpted by wind and wind-blown sand.

vertical cloud: a cloud that develops upward to great heights. Vertical clouds are the products of sudden, forceful uplifts of small pockets of warm air.

virga: rain that falls from clouds but evaporates in midair under conditions of very low humidity.

volcano: an opening in the surface of Earth (vent) through which molten rock, lava, ashes, and gases escape; it is also the name for the mountain or hill that is formed by the lava and other erupted material.

vortex: (plural: vortices) vertical axis of extremely low pressure around which winds rotate.

W

wall cloud: a roughly circular, rotating cloud that protrudes from the base of a thunderstorm cloud; it is often the beginning of a tornado.

warm front: the line behind which a warm air mass is advancing, and in front of which a cold air mass is retreating.

warm-phase ENSO (El Niño/Southern Oscillation): another name for El Niño; warmer-than-normal eastern Pacific waters.

warning: a severe weather advisory that means that a storm has been sighted and may strike a specific area.

watch: a severe weather advisory that means that while a storm does not yet exist, conditions are ripe for one to develop.

waterspout: rapidly rotating column of air that forms over a large body of water, extending from the base of a cloud to the surface of the water.

weather: the set of conditions of temperature, humidity, cloud cover, and wind speed at a given time.

weather aircraft: aircraft that carry weather instruments and collect data in the upper levels of the troposphere. They are primarily used to probe storm clouds, within which they measure temperature, air pressure, and wind speed and direction.

weather forecast: a prediction of what the weather will be like in the future, based on present and past conditions.

weather map: a map of a large geographic region, on which weather station entries are plotted. By looking at a weather map, a meteorologist can determine the locations of fronts, regions of high and low pressure, the dividing line between temperatures below freezing and above freezing, and the movement of storm systems. Also called surface analysis.

weather satellite: a satellite equipped with infrared and visible imaging equipment that provides views of storms and continuously monitors weather conditions around the planet.

westerlies: global-scale surface winds that travel from the southwest to the northeast in the Northern Hemisphere, and from the northwest to the southeast in the Southern Hemisphere, between about 30° and 60° latitude.

whiteout: a condition in which falling, drifting, and blowing snow reduces visibility to almost zero.

wildfire: a large, uncontrolled fire in grass, brush, or trees.

wind farm: a large group of interconnected wind turbines.

wind power: power, in the form of electricity, derived from the wind.

wind shear: a condition in which a vertical layer of air is sandwiched between two other vertical layers, each of which is traveling at a different speed and/or direction, causing the sandwiched air layer to roll.

wind sock: a cone-shaped cloth bag open on both ends, through which wind flows that is used to determine the direction and estimate the speed of the wind.

wind speed: the rate at which air is moving relative to the ground.

wind turbine: a windmill designed to convert the kinetic energy of wind into electrical energy.

wind wave: a wave caused by the action of wind on the water surface.

windbreak: row of trees or shrubs placed in a farm field to slow the wind and keep it from blowing away the soil.

windchill equivalent temperature: the temperature at which the body would lose an equivalent amount of heat, if there were no wind. Also called windchill index.

windchill factor: the cooling effect on the body due to a combination of wind and temperature.

windward: the direction from which the wind is blowing. Also the slope of a mountain on the side of local or prevailing winds, up which the air cools as it ascends producing moist, cloudy, or rainy conditions.

Weather: An Introduction

Weather plays an important role in our lives. It influences how people dress, what they can do outdoors, and even their moods. When people talk about weather, they usually mean things like wind, rain, snow, thunderstorms, and sunshine. But what causes the weather? Where does it all come from?

All forms of weather are produced by complex, constantly changing conditions in Earth's atmosphere. However, the driving force behind the weather is the Sun.

It starts with the Sun

The Sun continually generates energy, which escapes from its surface and flows through space. Solar energy travels 93 million miles (149 million kilometers) to reach Earth. It warms all of Earth's atmosphere, some parts more than others. The area of Earth that receives the Sun's rays most directly, the equatorial region, is heated the most. The poles, conversely, never receive sunlight directly. Sunlight strikes the poles only at a steep angle. Hence, they are warmed the least.

Another factor that determines how much solar energy strikes any particular part of Earth at any time is the season, a period of year characterized by certain weather conditions. Most places in the world have four seasons: winter, summer, spring, and fall. In winter, the Sun shines for the fewest hours per day and never gets very high in the sky. In summer, day is longer than night, and the Sun shines high in the sky. In spring and fall, the Sun rises to an intermediate height, and there are roughly the same number of hours of daylight as darkness.

The change in seasons is caused by a combination of Earth's tilt and its yearly journey around the Sun. Earth's axis of rotation is tilted 23.4° away from the perpendicular. At different points along Earth's orbit around the Sun, the Northern Hemisphere, the half of the earth which

Try this: How the seasons change

Place a lamp (minus the lampshade) on the desk in front of you. Now take a tennis ball or a ping-pong ball and draw a horizontal line around its middle. This line represents Earth's equator. Mark an "N" on the top half of the ball (for the Northern Hemisphere) and an "S" on the bottom half (for the Southern Hemisphere).

First hold the ball with the "N" pointing straight up and the "S" pointing down. Now tilt the ball so the "N" is tilted slightly away from the perpendicular. This arrangement represents the 23.4 degree tilt of Earth's axis away from the perpendicular. Hold the ball this way in front of the light and move it in a circle around the light in this order: to the right of the light, behind the light, to the left, and finally to the front again.

You'll notice that when the ball is to the right of the light (similar to Earth on the first day of winter), light from the lamp strikes the "S" half of the ball more directly than it does the "N" half. When the ball is directly behind or in front of the light (representing the start of spring and fall, respectively), light strikes both "N" and "S" halves at the same angle. When the ball is to the left of the light, light strikes the "N" half more directly. This position marks the start of summer in the Northern Hemisphere.

lies north of the equator (which includes the United States) is tilted either toward or away from the Sun. For instance, on or about June 21, the first day of summer, the Northern Hemisphere receives more sunlight than on any other day. On or about December 21, the first day of winter, the Southern Hemisphere, the half of the earth that lies south of the equator, receives its greatest amount of sunlight.

For two days each year the hemispheres receive approximately equal amounts of sunlight. These days are on or about March 21, the vernal equinox, and on or about September 23, the autumnal equinox. These two days mark the beginnings of spring and fall, respectively.

The uneven heating of the atmosphere sets the atmosphere in motion. Air moves through the atmosphere in such a way as to even out the distribution of heat around the planet, with warm air moving from the equator to cold areas at the poles and cold air back toward the equator. The movement of air between the equator and the poles is influenced by other factors as well, such as differences in composition of air over land and sea, and Earth's rotation. The result is a complex web of air currents whirling around the globe—the ingredients of weather.

When solar energy strikes Earth Energy that comes from the Sun is often referred to as "sunlight." Yet, it is really a combination of many types of electromagnetic radiation. Electromagnetic radiation is energy in the form of waves of electricity and magnetism. Solar energy that reaches Earth's surface is made up almost entirely of visible light (which can be seen), and infrared radiation.

Infrared radiation is a form of electromagnetic radiation that takes the form of heat and has a wavelength longer than that of visible light. Small amounts of x rays, ultraviolet rays, and radio waves from the Sun also penetrate Earth's atmosphere.

Only two forms of solar energy reach and heat up the lower levels of atmosphere and Earth's surface. These are visible light and infrared radiation. They are the only two forms of solar energy that affect Earth's weather. When radiation is absorbed by gas molecules in the atmosphere, by clouds, or by the ground, it is converted into heat.

Most x rays and ultraviolet rays are absorbed high in Earth's atmosphere and never reach the surface. This is fortunate for humans, since a large dose of either type of radiation would be deadly. Radio waves also penetrate the atmosphere, but in such tiny amounts that they have no warming effect on Earth.

Only about two-thirds of the total solar energy reaching Earth's outer atmosphere is absorbed by Earth. One half of that radiation is absorbed by the atmosphere and the other half by Earth's surface. Ultraviolet radiation is selectively absorbed by the ozone layer, an atmospheric layer that exists between 25 and 40 miles (40 and 64 kilometers) above Earth's surface. Infrared radiation is absorbed by clouds and gases in the lowest atmospheric levels, and then reradiated in all directions.

Most of the solar radiation that reaches Earth's surface is in the form of visible light. About two-thirds of that light is absorbed by living and nonliving materials and transformed into heat. This heat causes snow and ice to melt and water to evaporate.

About one-third of solar radiation striking Earth is reflected back into space. A number of factors are responsible for this effect. One of the most important is clouds. When solar energy strikes a thick cloud, as much as 95 percent of the energy is reflected. Thinner clouds turn away up to 50 percent of the radiation that strikes them.

On the ground, the greatest reflectors of sunlight are snow and ice. Snow and ice reflect up to 95 percent of the solar energy that strikes them. Thus, air is colder when there's snow on the ground. Water, on the other hand, is a good absorber of energy. Water reflects only 10 percent of the solar energy that strikes it. Sand reflects more radiation than water (about 15 to 40 percent), but much less than snow.

The Earth also radiates heat Solar energy that reaches Earth's surface in the form of visible light is reradiated in the form of infrared radiation (heat). Heat leaves Earth's surface and is absorbed by clouds and water vapor in the air. Clouds absorb large amounts of infrared radiation, which is why cloudy nights tend to be warmer than clear nights, all other things being equal. Clouds radiate infrared energy in all directions, throughout the atmosphere, back toward Earth, and out into space.

All parts of Earth's surface are constantly absorbing and emitting heat. For the temperature to remain constant at any one location, the surface must absorb and emit energy at the same rate. When absorption outpaces emission, the surface warms. One can experience this effect when walking on an asphalt parking lot in bare feet. When emission outpaces absorption, the surface cools. This effect occurs at night when there is no incoming sunlight to offset the heat radiating from the ground.

Earth maintains a long-term balancing act with regard to heat. Over a period of years, the quantity of heat absorbed is almost identical to the quantity released back into space. Many scientists, however, believe that a warming trend has begun in recent decades. This effect may be caused by increased amounts of certain gases in the air, primarily carbon dioxide. Carbon dioxide and other gases formed during industrial processes trap heat.

The mechanics of heat transfer The primary way that heat is transferred in the atmosphere is by convection. Convection is the movement of masses of air caused by differences in temperature. It can be explained by two key concepts. First, heat causes air molecules to move more quickly. Second, warm air rises.

When air is heated, the molecules within it move rapidly and spread out. As a result, warm air loses density and becomes thinner and lighter. The surrounding cool air, which is denser, slides beneath the warm air, pushing it upwards. As the warm air rises, it cools. When it is no longer warmer than the air around it, it stops rising.

Convection is a critical element in the formation of weather patterns. It is the process that carries warm air up from the ground, to be replaced by cold air. The cold air is then warmed and cycles upward again.

Heat can also be transferred by a second method called conduction. This method depends upon collisions between individual molecules, in which heat is transferred from a fast-moving, warm molecule to a slow-moving, cold molecule. As the cold molecule is heated, it also moves more quickly, and a chain reaction of molecular heat transfer follows. Conduction is a very slow process because, even in the densest layer of the atmosphere, collisions between molecules are relatively rare.

Heat and temperature

Most people consider heat and temperature to be the same. After all, one can feel the heat increase at the oven door when one raises the temperature in the oven. However, while heat and temperature are closely related, they are not exactly the same.

What's the difference between heat and temperature? The key to this difference is kinetic energy, the energy of motion. All substances are made of tiny particles (molecules or atoms) that are in constant motion. Motion ceases only at absolute zero, –459°F (–273°C). Heat is defined as the *total* kinetic energy of the particles of a substance, whereas temperature is the *average* kinetic energy of a substance.

The crux of this distinction is that heat takes into account the total volume of a substance. That is, given two volumes of the same liquid at the same temperature, the larger one contains more heat because it contains more matter. The larger volume contains a greater number of moving molecules and, hence, more total kinetic energy.

To illustrate this concept, imagine a cup of coffee at 140°F (60°C) and a bathtub of water at 85°F (29°C). If you let them both cool, the coffee would reach room temperature much more quickly than the water. This is because the water in the bathtub possesses a larger quantity of kinetic energy, which it must lose in order to cool down. The coffee cup, which contains relatively little kinetic energy, cools quickly. Although the coffee had a higher starting temperature (*average* kinetic energy) than the bathwater, the bathwater possessed more heat (*total* kinetic energy).

Specific heat The specific heat of a substance is the amount of heat required to raise the temperature of 0.0353 ounce (1 gram) of the substance by 1.8°F (1°C). The amount of heat (measured in units called calories) necessary to raise the temperature differs from substance to substance.

The specific heat of a substance is measured relative to that of water: It takes 1 calorie to raise 1 gram of liquid water 1°C. Water, therefore, has a specific heat of 1.0. This is one of the largest specific heats of any naturally occurring substance.

By way of comparison, the specific heat of ice at 32°F (0°C) is 0.478; wood is 0.420; sand is 0.188; dry air is 0.171; and silver is 0.056. Thus, it can be seen that it takes much less heat to raise the temperature of sand than it does to raise the temperature of water. This explains why on a sunny day at the beach, the sand heats much quicker and feels much hotter than the water.

Who's who: Joseph Black

As a graduate student, Scottish chemist Joseph Black (1728–99) discovered the existence of carbon dioxide, which he called "fixed air." Black also was the first person to explain the concept of specific heat: that each substance requires a particular amount of heat to raise its temperature 1°C.

Black is most famous for solving the mystery of latent heat. He was first drawn to the question by German physicist Gabriel Daniel Fahrenheit's finding that water can remain in the liquid state even below its freezing point. This state is called supercooled water. On striking a surface, supercooled raindrops freeze. The freezing of water is a process that occurs when heat is lost. While heat loss can usually be measured with a thermometer, in this case the water froze with no accompanying drop in temperature. This discovery led Black to the conclusion that water possesses hidden or "latent" energy that comes and goes as water changes phases.

FURTHER READING ON LATENT HEAT AND JOSEPH BLACK: **WILLIAMS, RICHARD. "THE MYSTERY OF DISAPPEARING HEAT."** ***WEATHERWISE.*** **AUG./SEPT. 1996: 28–29.**

Latent heat A large amount of heat is needed to raise the temperature of water even slightly. This effect is magnified when water undergoes a phase change between any two of the three phases: liquid, solid, or gas. During a phase change, water or ice absorbs, or emits, very large amounts of heat energy without any corresponding change in temperature. The energy associated with a phase change of water is called latent heat.

This heat is "latent" because it does not perform a warming function but instead is "stored" or "hidden" as it produces a phase change. A tremendous amount of energy is absorbed in the process of melting ice or of evaporating or boiling water. Conversely, when water freezes or when water vapor condenses, that heat energy is released back into the environment. If a cup of water and a cup of ice—both at 32°F (0°C)—were placed side by side, the ice would take much longer to reach room temperature than the water. The reason for this is that ice must first absorb enough heat to transform it to water.

Latent heat is also responsible for keeping a cold drink *with* ice colder than a cold drink *without* ice. It works like this: as heat is added to the beverage, it breaks down the crystal structure of the molecules of ice. The added heat changes ice from a solid to a liquid without changing the temperature of the surrounding liquid. If heat were added to a drink without ice, that heat would warm the liquid instead.

Latent heat has important implications on a global scale. More than half of the solar energy that strikes Earth is stored in the form of latent heat. Since ice is able to store large amounts of solar energy in the form of latent heat, it is slow to melt. Imagine if the Arctic or Antarctic ice caps were to melt just because of the heat they absorbed on one mild day. This would create unfathomable floods. Similarly, latent heat of vaporization is why the oceans do not evaporate.

WORDS TO KNOW

air mass: a large quantity of air throughout which temperature and moisture content is fairly constant.

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

convection: the upward motion of an air mass or air parcel that has been heated.

Coriolis effect: the apparent curvature of large-scale winds, ocean currents, and anything else that moves freely across Earth, due to the rotation of Earth about its axis.

cyclone: a weather system in which winds spiral counterclockwise, into a low-pressure area. Also called storm.

front: the dividing line between two air masses.

kinetic energy: the energy of motion.

latent heat: the energy that is either absorbed by or released by a substance as it undergoes a phase change.

latitude: an imaginary line encircling Earth, parallel to the equator, that tell one's position North or South on the globe.

precipitation: water particles that originate in the atmosphere (usually referring to water particles that form in clouds) and fall to the ground.

supercooled water: water that remains in the liquid state below the freezing point.

troposphere: the lowest atmospheric layer, where clouds exist and virtually all weather occurs.

Windchill On blustery winter days, weather forecasts usually include the windchill factor, the cooling effect on the body determined by temperature and wind, as well as the temperature. Wind magnifies the effects of low temperature because moving air removes heat from the body quicker than still air does. The body is ordinarily surrounded by a very thin layer of still air, called the boundary layer. Heat is constantly lost through the boundary layer by conduction, but this process is very slow. However, increased wind reduces the boundary layer in thickness and heat loss accelerates.

Due to the danger of frostbite, the freezing of the skin, in cold, windy conditions, forecasters added an index called the windchill equivalent temperature (WET), also called the "windchill index." This value represents the temperature at which the body would lose an equivalent amount of heat if there were no wind. For instance, if it was 32°F (0°C) with winds blowing at 15 miles per hour (mph), or 24 kilometers per hour (kph), the WET would be 15°F (–9°C). If it was 0°F (–18°C) and the wind was blowing at 10 mph (16 kph), the WET would be –20°F (–29°C).

The atmosphere: Where weather occurs

The air called atmosphere extends more than 600 miles (977 kilometers) above Earth's surface. Yet relative to the diameter of Earth, it is no thicker than a coat of paint. The atmosphere, where all weather occurs, is what sustains life on Earth.

The atmosphere contains the air we breathe and the water vapor that drives weather patterns. It shields us from most of the lethal components of the Sun's rays while allowing through the harmless components. It regulates the temperature of the planet, keeping us from getting burned up by the Sun's heat during the day or frozen to death during the dark night. In addition, the atmosphere protects us from most potentially devastating debris from space.

The atmosphere consists of 78 percent nitrogen, 21 percent oxygen, and 1 percent argon, with minute quantities of water vapor, carbon dioxide, and other gases. It is held to Earth by the force of gravity, which acts most strongly close to the surface. For this reason, the pressure and density of gases in the atmosphere decreases with altitude (height). In fact, half of the mass of our atmosphere is contained within 4 miles (6 kilometers) of the planet's surface. While 99 percent of the atmosphere is calm, the air in the lowest 6 miles (10 kilometers) is constantly on the move.

Layers of the atmosphere Beginning with a series of hot-air balloon experiments in the late 1800s, scientists have determined that the atmosphere is made up of five distinct layers. The bottom layer, where clouds exist and virtually all weather occurs, is called the troposphere. As one rises through the troposphere, the temperature drops rapidly. About 9 miles (14 kilometers) above ground is the stratosphere. Jet planes cruise in the stratosphere to take advantage of strong winds found there and to reduce friction experienced with air in the troposphere. The temperature rises gradually from a low of about –75°F (–60°C) at the lowest level of the stratosphere to a high of about 32°F (0°C) at its upper boundary. The rate of temperature increase in the stratosphere rises sharply in the region between about 20 and 30 miles (32 and 48 kilometers). The reason for this change is the presence of a band of ozone in that portion of the stratosphere. Ozone is a form of oxygen that has three atoms per molecule instead of the usual two. It absorbs ultraviolet rays, which have a warming effect.

The ozone layer, which protects earth from the Sun's harmful rays, may be the atmosphere's most famous layer. The reason is that the ozone layer has been damaged by chemical pollutants. The loss of ozone from the stratosphere is a concern because ozone protects life on Earth from serious harm. For example, some forms of skin cancer are caused by exposure to certain kinds of ultraviolet radiation that are absorbed by ozone. Fortunately, governments around the world have now banned most of these dangerous substances, giving the protective shield an opportunity to regenerate.

The region of the atmosphere above the stratosphere is the mesosphere. This belt extends upwards from about 30 to 55 miles (48 to 88 kilometers) above Earth's surface. Within the mesosphere, the temperature falls from about 32°F (0°C) at its lower boundary to nearly –150°F (–100°C) at its upper boundary.

In the next higher zone, called the thermosphere, temperatures rise to about 1,800°F (1,200°C). The thermosphere extends from a height of about 55 miles (88 kilometers) to about 300 miles (483 kilometers) above Earth's surface. The extreme heat in this layer burns up debris, such as meteors and non-operational satellites, falling toward Earth. Many of the molecules in both the upper mesosphere and lower thermosphere become ionized (electrically charged) by x rays and ultraviolet rays in solar radiation. For this reason, that region is also called the ionosphere.

The highest atmospheric layer is the exosphere. Molecules of gas in the exosphere break down into atoms. In addition, because gravitational attraction is so low, many molecules escape into space.

Who's who: Antoine Lavoisier

French chemist Antoine-Laurent Lavoisier (1743–94) is widely considered the father of modern chemistry. Originally trained to be a lawyer, Lavoisier soon discovered his passion in science. In the 1780s, Lavoisier identified the life-giving element present in air as "oxygen." Lavoisier is equally famous for describing what occurs when things burn, for formulating the system of naming chemical compounds, and for improving the accuracy of scientific methods.

Through his experiments, Lavoisier learned that many substances give off carbon dioxide when they burn. He also learned that oxygen has to be present in order for burning to occur. Also, Lavoisier isolated a second element present in large quantities in the air. To that element, originally discovered by the Scottish chemist Daniel Rutherford, he gave the name "azote." Today that element is known as nitrogen.

Air pressure and weather

Air pressure (also known as "barometric pressure" or "atmospheric pressure") is an all-important concept in the world of weather. Air pressure is the pressure exerted by the weight of air over a given amount of Earth's surface. Changes in air pressure produce winds, cause the development of clouds, and clear the way for sunny skies. The air pressure

Who's who: John Dalton

English chemist and Quaker John Dalton (1766–1844) chose to explore the simplest unit of matter: the atom. In the early 1800s, Dalton postulated that all forms of matter, in all three phases (solid, liquid, and gas) are composed of tiny particles called atoms and that these atoms can combine to form "compound atoms," which are now known as "molecules."

It was Dalton's interest in the weather that led to the development of his atomic theory. For fifty-seven years he kept daily records of temperature, barometric pressure, dew point, rainfall, and other conditions. He contemplated the nature of air and concluded that it, like every solid, liquid, or gas, is made up of tiny particles.

Using his weather observations in combination with his atomic theory of air, Dalton learned how condensation occurs. First, he demonstrated that water vapor is a gas and can mix with other gases in the air. Then he proved that the amount of water that air can hold (the saturation point) depends upon the temperature of the air. From there he extrapolated that at every temperature, there is a corresponding saturation point. By dividing the amount of water in the air by the amount of water at which air at that temperature would be saturated, he came up with an explanation of relative humidity.

at any given time provides weather forecasters with important clues about what the weather holds for the next several hours or days.

Much of what is known about temperature and wind conditions in the troposphere was collected by hot-air balloonists beginning in the late 1700s. Two of the most famous of these upper-air explorers were Englishmen James Glaisher and Robert Coxwell, who made twenty-eight flights over England between 1862 and 1866.

The highest and riskiest ascent made by Glaisher and Coxwell was in September 1862. At an altitude of 29,500 feet (9,000 meters, or more than 5.5 miles), Glaisher lost consciousness due to the lack of oxygen. The balloon continued to rise, and at 37,500 feet (11,400 meters, or more than 7 miles) Coxwell was on the verge of passing out, too. At the last moment Coxwell managed to guide the balloon into a descent.

Unpiloted hot-air balloons were invented shortly thereafter. These balloons carried instruments to greater heights than humans could ever withstand. Using these balloons, French meteorologist Teisserenc de Bort learned that at about 9 miles (14 kilometers) above ground the air temperature no longer decreases but begins to increase. De Bort had discovered the second atmospheric layer, the stratosphere.

What is air pressure? Simply put, air pressure is the pressure exerted by the weight of air over an area of Earth's surface. It is a function of the number of molecules of air in a given volume, the speed with which they are moving, and the frequency with which they collide. Although they are too small to see, air molecules are always in motion at tremendous speeds. In fact, at ground level, there are 400 sextillion (400 plus twenty-one zeroes) air molecules per cubic inch. They are moving at an average speed of 1,090 mph (1,753 kph).

The rapid movement of air molecules means that they frequently collide with one another and any objects they encounter. These collisions are responsible for air pressure. If air is heated, molecules move more quickly, collide more often, and cause an increase in pressure. If air is cooled, molecules move less rapidly, and air pressure decreases.

Air pressure can be altered by adding air to, or removing it from, a closed container, such as a bicycle tire. Each time one drives down the plunger on a bicycle pump, more air molecules are squeezed into the same volume of space. With each movement of the plunger, air pushes out against the inside of the tire, and the tire feels hard. If one were to continue pumping long enough, the air pressure would increase to the point where the tire would explode.

Air pressure changes with altitude Measurements of air pressure may be given in a variety of units. The unit most commonly used by meteorologists is the millibar (mb). The unit of air pressure in the English system is pounds per square inch (psi). At sea level, air pressure is equal to about 1,000 mb (14.7 psi). Atmospheric pressure decreases with higher altitudes. At about 1,000 feet (300 meters) above sea level, air pressure is about 900 mb (14.1 psi). At 4 miles (6 kilometers) above the ground, the point at which half of the atmosphere's mass is above and half is below, the air pressure is about 500 mb (7.3 psi).

A key reference to: Laws of air pressure

Boyle's Law was first published in 1660 by British chemist Robert Boyle (1627–91). The law states that at a constant temperature, the volume occupied by a gas is inversely proportional to the pressure applied to the gas. For example, when the pressure applied to a given volume of air is doubled, the air shrinks to half its volume. In other words, air under pressure becomes compressed. Boyle is also noted for his invention of two of the earliest types of barometer: the water barometer and the siphon barometer.

The companion to Boyle's Law is Charles's Law (also called Gay-Lussac's Law). This 1802 finding by French physicist Jacques Alexandre César Charles (1746–1823) and French chemist Joseph-Louis Gay-Lussac (1778–1850) states that at a constant pressure, the volume of a gas is proportional to the temperature of the gas. This means that as heat is applied to a sample of air, the air expands, and as heat is taken away, the air contracts. Gay-Lussac, incidentally, set a record for height in a hot-air balloon flight in 1804, of over 4 miles (6 kilometers) above ground. His record remained unbroken for the next fifty years.

Air molecules are constantly bombarding us from all directions, exerting a constant pressure of about 1,000 mb (14.7 psi) at sea level. People don't feel anything hitting them because the air pressure inside the body balances that outside it. The only way people notice air pressure is if it changes rapidly, such as when they ascend or descend in an airplane, or drive on a steep mountain road. In those cases, the air pressure around them changes more quickly than does the air pressure in their ears and sinuses.

Who's who: Blaise Pascal

French mathematician and philosopher Blaise Pascal was the first person to explain the connection between air pressure and altitude. He hypothesized that the weight of the atmosphere above Earth's surface is responsible for air pressure at the surface and, by extension, that air pressure decreases as elevation increases.

To test his hypothesis, Pascal conducted an experiment using the newly invented barometer. He took barometer readings at the base and the peak of a mountain. He found that he was correct. The air pressure measured 935 mb at ground level and only 828 mb at the mountaintop.

Anyone who has flown on an airplane has experienced the "popping" of his or her ears during take-off and landing. This "popping" is the body's attempt to equalize the pressure imbalance by releasing air from the eustachian tube (the passage connecting the eardrum and the throat).

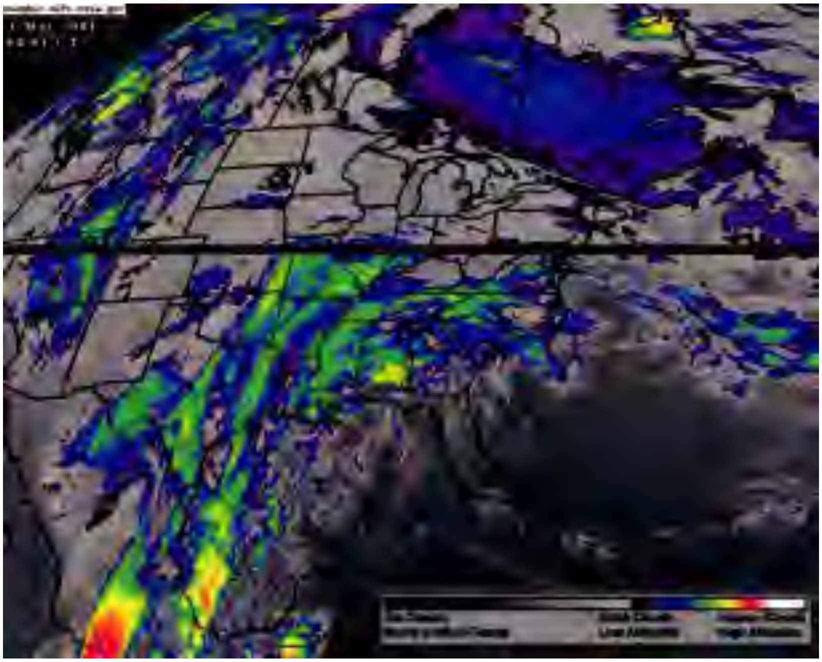
High-pressure and low-pressure systems Altitude is not the only factor associated with differences in air pressure. Air pressure also differs from location to location on the ground and even from one hour to the next at a single location. It is these changes at ground level that are connected with weather patterns. Even a very small difference in air pressure between two points can signal profound changes in the weather.

Television weather forecasters regularly refer to systems of high pressure and low pressure. There is no set definition of a "high" or "low" pressure system: they are only defined relative to one another. For example, if one area has an air pressure of 1,000 mb (14.5 psi) and a second area has an air pressure of 975 mb (14.3 psi), the former is considered a "high-pressure" area and the latter, a "low-pressure" area.

High- and low-pressure systems are the result of multiple air masses (which are large quantities of air consistent throughout in temperature and moisture) of different temperature and moisture content entering and leaving an area. In the middle latitudes, between 30° and 60°, which includes the United States, this parade of air masses is nearly constant. As one air mass is replaced by another, the air pressure rises or falls, and the weather changes.

High-pressure systems are usually associated with clear skies and low-pressure systems with clouds and precipitation, or water droplets that originate in the atmosphere and fall to the ground. These are only generalities and, due to the interaction of other factors in the atmosphere, do not always hold true. To understand how pressure systems affect the weather, it is necessary to combine the concepts of convection and air pressure.

As air is heated, it rises. It leaves in its wake an area of low pressure. One consequence of rising air (and hence a low-pressure area) is that it causes water vapor in the air to condense and form clouds.



An infrared satellite image showing a low pressure system moving up from the Gulf of Mexico and a cold area moving down from Canada that could combine in the Carolinas to create a severe snowstorm, 2001. © REUTERS/CORBIS.

Clouds form over low-pressure areas because cool air can hold less water than warm air. The warm air carries water vapor upward until it reaches the dew point. This is the temperature at which air can no longer hold water in the vapor state, and the water begins to condense into clouds.

In a region of high pressure, colder, drier air from above sinks toward the surface. The cold air becomes warmer as it falls. This causes water and ice in the clouds to dissolve and the clouds themselves to thin or evaporate entirely, leaving only clear, sunny skies.

Wind: Air in motion

Wind is the natural movement of air. Winds are produced and acted upon by numerous forces. Among these are air pressure differences, Earth's rotation, and friction. Essentially, air attempts to flow from areas of high pressure to areas of low pressure but is prevented from traveling along such a path directly because of Earth's rotation. Wind speed, although largely a function of pressure differences, is also influenced by Earth's surface features.

Pressure changes produce winds The flow of air across a pressure differential is a crucial factor to understanding wind. A pressure differential or pressure gradient is the difference in atmospheric pressure at any two given locations. The movement of air from a high-pressure to a low-pressure area is the atmosphere's attempt to equalize differences in pressure. When the pressure between the two areas is equalized, the wind stops blowing.

Two main factors determine how fast the wind moves: the difference in air pressure and the distance between two areas. Either a greater pressure differential or a smaller distance between the areas makes for a stronger wind. Conversely, either a smaller pressure differential or a greater distance between the two areas makes for a weaker wind.

These two factors taken together are called the pressure gradient force (PGF). To illustrate, in the case of a pressure gradient of 10 mb between two locations set 1,000 kilometers apart, the pressure gradient force is 10mb/1,000km, or 0.01mb/km. On the other hand, a pressure difference of 40 mb at the same distance apart would produce a pressure gradient of 40mb/1,000km = 0.04mb/km. A pressure gradient four times as large would produce a wind speed four times as great in the same time.

Friction slows the winds Topography (the physical features of land) doesn't produce winds, but it does affect wind speed. As wind blows across a pressure differential, it encounters hills, trees, tall buildings, sand dunes, and other objects that create friction and slow it down. Relatively flat surfaces—such as water, prairies, and deserts—exert little friction on the wind. Over flat terrain, winds reach greater speeds than they do over hilly terrain. Farmers know that planting a row of trees on otherwise flat land goes a long way toward preventing soil erosion caused by strong winds.

Earth's rotation curves the winds Imagine a wind blowing from north to south because of a pressure differential between two areas. If the space between the two areas were perfectly flat, one might expect the wind to blow in a perfectly north-south direction. But such is not the case. Instead, the wind is diverted slightly because of an effect known as the Coriolis effect. The effect is named for the French scientist Gustave-Gaspard de Coriolis. De Coriolis used mathematical formulas to explain that the path of any object set in motion above a rotating surface will curve in relation to any object on that surface.

To an observer beyond one of Earth's poles, say on a space shuttle, the wind would not appear to curve—it would blow in a straight line while Earth spun beneath it. But relative to observers on Earth—that is to say, all of us—the wind does appear to curve. One way to understand the

Coriolis effect is to think of a person riding on a carousel who throws a ball straight up into the air. When the ball comes down, it lands behind the person who threw it. To the person on the carousel, it seems that the ball's path has curved backwards. However, to a person standing next to the carousel the ball appears to have traveled in a straight vertical path while the carousel rotated beneath it. To relate this example to Earth, then humans are all on the carousel, and the wind appears to curve as it travels.

The Coriolis effect influences the direction of winds as follows: In the Northern Hemisphere it curves them to the right. In the Southern Hemisphere it curves them to the left. The Coriolis effect is felt most strongly at the poles. It does not exist at all at the equator, where opposing forces (the turn to the right and the turn to the left) are canceled out.

Putting it all together The forces of pressure gradient and the Coriolis effect create complex global wind patterns. In the Northern Hemisphere, winds spiral clockwise around high-pressure systems (where air is falling) and counter-clockwise around low-pressure systems (where air is rising). In the Southern Hemisphere, the opposite is true. What causes the wind to move like this?

The spiral pattern represents the path of equilibrium between opposing forces. Imagine a hot-air balloon that's being carried along by the wind. [Note that this example applies only to the Northern Hemisphere. The Coriolis effect works in reverse in the Southern Hemisphere.] At the start of its journey, the balloon is pushed away from a high-pressure system. It moves into a low-pressure system, which is characterized by rising, warm air. Yet, rather than following a straight line into the center of the system, the balloon is pushed to the right by the Coriolis effect.

It is now caught in a tug-of-war between forces pushing it toward the low-pressure system and those pushing it to the right. The balloon finds and settles into a pattern where these two forces are in balance. As it moves from point A to point B to point C and so on, it's simultaneously driven in toward the low-pressure system and to the right. Connecting the points of equilibrium between these forces is a circular path, running counterclockwise around the low pressure area.

Now consider the opposite case, where the balloon is swept into the descending, cold air of a high-pressure system. This time, the balloon is simultaneously being pushed away by the high-pressure system and being tugged to the right by the Coriolis effect. The balloon travels to the point where these two forces are in balance. The path of equilibrium around a high-pressure system runs clockwise.

One more factor is necessary to complete the description of how the wind travels: friction. Friction causes wind near the ground to behave differently than wind at higher altitudes. The reason is that winds near the ground are slowed down, lessening the Coriolis effect. In fact, for wind blowing toward a low-pressure system just above the ground, the Coriolis effect is so weak that the wind blows right into the low-pressure area. Wind blowing toward that same system in the upper air, due to the Coriolis effect (unimpeded by friction), would circle around the system, as described above.

Global wind patterns The Sun heats Earth unevenly and the atmosphere strives to even out heat distribution. (Winds are responsible for about two-thirds of the world's heat distribution and ocean currents, the major routes through which ocean waters move, for about one-third of the burden.) In general, winds move between the equator and the poles, bringing warm air to cold areas and cold air to warm areas. Global wind patterns are made more complex by a number of factors, such as Earth's rotation and the location of land and sea. The result is a complex pattern of swirling winds encircling the globe. These wind patterns are what create the variety of weather conditions at specific regions north and south of the equator.

The global motion of the winds begins with the flow of warm air from the equator to the poles. The air doesn't travel all the way to the poles in one interrupted journey, however. It travels through a series of loops in which warm air rises and cold air falls at different latitudes. It is also important to note that, due to the Coriolis effect, these winds do not travel due north or south, but between points southwest and northeast in the Northern Hemisphere and between points northwest and southeast in the Southern Hemisphere. Remember that the Coriolis effect acts differently in the Northern and Southern hemispheres. In the following discussion, examples are given only for the Northern Hemisphere. It can be assumed that the opposite is true in each example for the Southern Hemisphere.

Hadley cells The first of these loops, which extend from the equator to 30° north and south latitudes, are called Hadley cells. They are named for George Hadley, an English scientist who first explained this air flow pattern in 1753. The air that flows through the Hadley cells begins at the equatorial region (from about 10° south latitude to 10° north latitude), also known as the tropics. This area is the warmest region on Earth, because sunlight hits the surface most directly. The air is warmed and rises by the process of convection. The upward movement of air creates a low-pressure zone, which produces the clouds and rains for which the tropics are famous.

Warm air continues rising to the top of the troposphere, cooling as it goes. Then it begins to spread out toward the poles. At approximately 30° north and south latitudes the air sinks to the surface, warming as it descends. The latitudes at which air rises and falls, marking the boundaries of the cells, are only approximations and shift throughout the year.

High-pressure systems are created in these regions, meaning that skies are generally clear and little precipitation occurs. It stands to reason that 30° north and south are the latitudes at which most of the world's deserts are located.

Air descending at these latitudes displaces air at the surface. Most of the displaced air moves back toward the low-pressure belt at the equatorial zone, forming the trade winds. Northern- and Southern-hemisphere trade winds meet at the heat equator, the warmest part of the equatorial zone. The location of the heat equator is generally north of the geographic equator, due to the greater mass of land in the Northern Hemisphere, and it shifts north to south with the changing seasons.

Where the trade winds meet, they form a broad band of light, variable east-west winds. This area, which is generally cloudy and rainy, is called the doldrums. Another name for this region is the intertropical convergence zone.

Ferrel cells Ferrel cells encompass the next wind cycle, in which equatorial air moves one step closer to the poles. These cells are named for American meteorologist William Ferrel, who first described them in 1856. The Ferrel cells cover the region of the globe from about 30° to 60° north and south latitude, in other words, the temperate regions.

The Ferrel cells begin where the Hadley cells leave off, with the air that falls at 30° latitude. Some of this air, rather than returning to the equator, continues in the direction of the poles. The winds traveling to the poles

A key reference to: How the horse latitudes and doldrums got their names

"Horse latitudes" and "doldrums" are colorful terms used to describe two regions of Earth at which the winds are nearly still. The horse latitudes are a high-pressure belt that exists at around 30° north and south latitudes of the equator. It is in this region that air from the upper troposphere descends to Earth's surface, bringing clear skies.

While sunshine does not create a problem for sailors, the lack of wind does. Over time many ships stalled in the horse latitudes. When food ran low, the first to forego feedings were the horses on board. They often were slaughtered to feed the crew or simply thrown overboard. The preponderance of horse corpses floating in the waters throughout this region led to the name "horse latitudes."

The term *doldrums,* an old English word for "dull," is another name for the intertropical convergence zone. This is the zone near the equator where the trade winds coming from north and south meet and nearly cancel each other out. The warm tropical air, rather than traveling horizontally (and creating wind) rises straight up. So-named by sailors stranded in this part of the world, the doldrums are known for their warm, rainy, and still conditions.

generally come from the southwest and are curved to the northeast (in the Northern Hemisphere) by the Coriolis effect. For this reason, they are called westerlies. At around 60° north and south latitude the westerlies encounter cold polar air. The points where this occurs are called the polar fronts.

The contrast in temperature between these air masses causes the warmer air to rise. This results in a low-pressure system, bringing clouds and precipitation to regions such as southern Alaska and central Canada. The air that rises forms a circulation pattern called the upper-air westerlies. These winds, which flow from west to east, are responsible for driving most of the weather systems of the middle latitudes. These winds travel in waves that carry warm air toward the poles and cold air toward the equator.

Polar cells The final leg of the trek bringing warm air from the equator to the poles takes place within the polar cells. These cells extend from the poles, to 60° north and south latitude.

Some of the warmer air (relative to the cold polar air) rising at the sixtieth parallels heads to the poles. It cools drastically along the way. Once this air reaches a pole, it descends, forming a high pressure area. The displaced air at the surface then heads south. These cold winds, which head from the northeast to the southwest across the polar regions, are known as the polar easterlies.

At around the sixtieth parallel the polar easterlies, which have warmed slightly, meet the westerlies (warmer air coming from the thirtieth parallel). The warm air rises and heads back to the pole, completing the polar cell.

Some heat is lost through every cell between the equator to the poles. This means that the atmosphere's attempt to distribute heat across the planet is only partially successful—the poles remain forever colder than the equator.

Global pressure patterns Air rises and falls at certain latitudes as it makes its way from the equator to the poles and back. On Earth's surface, rising air creates low-pressure areas and falling air creates high-pressure areas. These major pressure areas exist along the boundaries between wind cells. The highs are located around 30° north and south latitude and at the poles, where cold air descends, and the lows are around the equator and 60° north and south, where warm air rises.

It's important to distinguish between the major pressure areas encircling the globe and the minor ones responsible for our day to day weather. The major high- and low-pressure areas, caused by global wind circulation, cover thousands of square miles each and can persist for months or longer. Small, localized high- and low-pressure areas form and die out in a matter of hours or days.

The world's major high- and low-pressure areas undergo significant shifts north and south with the seasons. They move to the north when it's summer in the Northern Hemisphere and to the south when it's winter in the Northern Hemisphere. However, four large pressure areas—two high and two low—maintain their basic position throughout the year. These systems are called semipermanent highs and lows. They are called "semipermanent" because they undergo changes in strength, as well as slight shifts in position, throughout the year.

The semipermanent systems are all located in the Northern Hemisphere. The Southern Hemisphere has far less land mass than the Northern Hemisphere overall, and has virtually no land between 50° latitude and Antarctica. It is the contrast in temperature of land and sea that results in changes in air pressure. Thus, the Southern Hemisphere has a fairly continuous low-pressure belt running across the globe at around 60° latitude. In contrast, the Northern Hemisphere, due to the positions of land masses, has areas of great temperature contrast at this latitude. In the subtropical region, at around 30° south latitude, the Southern Hemisphere has a series of well-defined but shifting high-pressure areas.

The semipermanent highs and lows are called the Pacific High, the Azores-Bermuda High, the Aleutian Low, and the Icelandic Low. In general, the lows produce storms, and the highs influence the direction in which the storms travel.

The Azores-Bermuda High strongly affects North American weather, especially the states bordering the Gulf of Mexico and the Atlantic coast. It occupies a huge area in the east Atlantic Ocean, between the eastern coast of North America and the western coast of Europe. It changes in size throughout the year. When the pressure system is large, it strongly repels all storms that come its way. Even the strongest hurricanes, generated in the band of warm waters running from the south of Florida eastward to northern Africa, are bent around this system. As a hurricane heads north, it encounters the large high-pressure system and is forced westward through the Caribbean and toward the eastern seaboard of the United States.

Upper-air winds The winds that blow in the middle and upper levels of the troposphere, also known as winds aloft take on a different pattern than the three main types of surface winds that blow between the equator to the poles—trade winds, westerlies, and polar easterlies—and the major pressure systems that generate and steer surface winds.

In general, the winds aloft run in the opposite direction from surface winds. For example, the surface trade winds blow toward the equator from the northeast to the southwest (in the Northern Hemisphere) and the upper-air trade winds blow back to the subtropics (30° latitude) from southwest to northeast.

Upper-air westerlies In the middle latitudes, however, the winds circulate in a different pattern: they move in wavelike patterns from west to east. Where these waves crest to the north they form ridges, and when they dip to the south they form troughs. It is essential to understand the flow of upper-air westerlies since they have a very significant impact on the weather of the United States and Canada.

These waves, through a series of ridges and troughs, cycle warm air masses northward and cold air masses southward. From the base of a trough, the southerly winds blow warm air masses northward. From the top of a ridge, northerly winds blow cold air masses southward. The net result is that upper-air westerlies transfer heat toward the poles and cold air toward the equator. In addition to cycling warm and cold air, upper-air westerlies transport high- and low-pressure systems from west to east. These pressure systems exist within the ridges and troughs.

Large-scale waves in the atmosphere are easy to observe as large-scale meanders of the jet stream, which is discussed in the next section. When these loops become very pronounced, they may detach as masses of cold or warm air and become cyclones or anticyclones. These air masses are primarily responsible for day-to-day weather patterns at mid-latitudes.

Jet streams The world's fastest upper-air winds are embedded within westerlies as well as within subtropical winds aloft. They are called jet streams. Jet streams are narrow bands of wind that blow through the top of the troposphere in a west to east direction at an average speed of about 60 mph (97 kph). The fastest moving jet streams greatly exceed that value, however, and have been clocked at more than 280 mph (450 kph).

Jet streams occur in regions with the largest differences in air temperature and pressure at high altitudes. In the middle latitudes of each hemisphere, this region occurs over the polar front, where the mild westerlies meet the cold polar easterlies. In the subtropical latitudes of each hemisphere, this region occurs around 30° north and south, where the warm trade winds meet the westerlies.

In either hemisphere, jet streams tend to move faster during winter than during summer. The reason for this pattern is that a larger temperature differential exists in winter. For example, in winter it may be 32°F (0°C) in Michigan and 80°F (27°C) in Florida, a difference of almost 50°F (10°C). On a typical day in summer in contrast, it can be about 80°F (27°C) in Michigan and 100°F (38°C) in Florida, a difference of only 20°F (11°C).

In addition, the latitudes at which jet streams travel shift throughout the year. In winter they are closer to the equator and in summer, closer to the poles. The reason for this pattern is that during the Northern Hemisphere's winter, cold polar air is swept further south. In the process, the cold air/warm air boundary also moves farther south. Conversely, in the summer, mild air is swept farther north and the cold air/warm air boundary moves northward. Note that these northward and southward shifts in cold air/warm air boundaries occur simultaneously in the Southern Hemisphere.

Jet streams are not the only phenomenon to inhabit the boundary between warm air and cold air. Storms also occur in this region. For this reason, weather forecasters consider the path of the jet stream a useful tool in predicting where storms will occur. Jet streams are also reliable indicators of temperature changes. When a jet stream dips southward, it brings cold air with it. When a jet stream shifts to the north, it brings warmer air in its wake.

Convergence and divergence Within a jet stream, winds regularly shift in direction and speed. They alternate between north and south as they pass through the stream's ridges and troughs. They speed up or slow down as they pass in and out of the jet maximum, the fastest region within the jet stream. Any change in wind speed or direction causes air to either pile up or spread out. In the former case, when air moves inward toward a central point, it is called convergence. In the latter case, when air moves outward from a central point, it is called divergence.

Convergence and divergence are perhaps easier to understand in this example involving traffic patterns. Convergence is when a stream of cars enters an already crowded freeway, causing a slowdown. Divergence is what occurs when a two-lane highway expands to a four-lane highway. Cars spread out between all four lanes and traffic speeds up.

When winds converge at high altitudes, they diverge at the surface. When winds diverge at high altitudes, they converge at the surface. This is because convergence and divergence affect air pressure over a vertical gradient. Specifically, convergence raises air pressure and divergence lowers air pressure. Thus, when winds diverge aloft, lowering the pressure, surface winds converge to the point beneath the divergence. The surface winds then rush upward to the low-pressure area. The surface winds stop rising when the pressure between points above and below has been equalized.

To speak of the factors that produce large-scale weather patterns in the middle latitudes, the story starts with convergence and divergence aloft. With the upper-air winds (westerlies and the jet stream), areas of convergence and divergence coincide with ridges and troughs. Winds tend to strengthen as they curve clockwise in ridges and weaken as they curve counterclockwise in troughs. Thus, as winds approach a trough they decrease in speed, converging to the west of a trough. As winds pass through the trough and head into a ridge, they curve clockwise and pick up speed. This situation results in divergence just before the winds enter to the west of a ridge.

Let's look at the case of convergence aloft. In the upper air, winds blow toward a central point and pressure builds. The air can't keep on piling up indefinitely, so it looks for an escape. If the air is already at the top of the troposphere it can rise no farther. Thus, it is forced to travel downward to an area where pressure is lower.

This downward travel of the air creates an area of high pressure on the surface, from which winds flow out in a clockwise direction. In other words, an anticyclone is created. The air from above will continue to descend, strengthening the anticyclone, until the pressure at the surface equals the pressure aloft. The air from above warms as it descends, causing the water vapor within it to evaporate. Thus, an anticyclone is associated with clear, settled weather conditions.

Now take the opposite case, where winds aloft are diverging. The air below travels upward toward this area of low pressure, leaving a surface area of low pressure in its wake. A convergence forms on the surface, where air rushes counterclockwise into the center of this surface low and rises. As the rising air cools, it forms clouds and precipitation.

This system is called a cyclone, also known as a storm. As long as the divergence aloft is stronger than the surface convergence, air will be pulled upward and the cyclone strengthened. Once these two forces come into balance, the storm dies out.

Air masses

An air mass is one of the few stable elements in the ever-changing world of weather. An air mass is a large quantity of air where temperature and moisture content is fairly consistent throughout. Air masses commonly cover thousands of square miles, the size of several states. Air masses are produced by the heating or cooling effect of the land or water beneath them.

Air masses form primarily over polar and tropical regions. Since the air does not stay still for long over temperate latitudes (including the United States), air masses generally do not form over those regions.

When a single air mass remains over a region for an extended period, it produces conditions called air mass weather, a period of unchanging weather conditions. This pattern occurs in various parts of the United States depending on the time of year. For example, the Southeast can count on hot weather and daily afternoon thunderstorms in the summer, and the Pacific Northwest is treated to cold, rainy weather for long periods in the winter.

Each air mass is given a two letter classification. The first letter refers to the air mass's point of origin, and the second tells whether it has traveled over land or sea. The second factor is crucial to determining the mass's moisture content. The first letter of the designation may be "c" for continental, meaning that it has traveled over land and is dry or "m" for maritime, meaning that it has traveled over oceans and seas, and is moist. The second letter of an air mass's identifier tag may be "P" (polar), "A" (arctic) or "T" (tropical). Some meteorologists do not use a separate designation for arctic air, since arctic air that travels southward becomes warmer and is virtually indistinguishable from polar air.

The combination of the two letters of a designation describes the temperature and moisture content of an air mass. For instance, the label mT refers to a warm, moist air mass that formed in the tropics and traveled over water.

Continental arctic air mass (cA) This frigid air originating near the North Pole greatly affects the weather of Canada and, to a far lesser degree, the weather of the northern United States. It forms above Greenland, Siberia, northern Alaska, northern Canada, and islands in the Arctic Ocean. The temperature of this dry air can dip as low as –45°F (–43°C) in the winter. For the most part it produces cold, dry conditions. Occasionally it picks up moisture while crossing a body of water and brings snowy weather.

Maritime arctic air mass (mA) This air mass is largely responsible for the cold weather experienced by western Europe. It brings low temperatures in the summer and very low temperatures in the winter. It forms over the ice-covered Arctic region and travels over large bodies of water (such as the northern Atlantic Ocean and Greenland Sea), which warm it somewhat and cause it to absorb more moisture before reaching Europe. This air mass brings rain in the summer and snow in the winter.

Continental polar air mass (cP) This type of air mass forms over land in Alaska, northwestern Canada, northern Europe, and Siberia. A cP air mass begins as very cold, dry, stable air and picks up heat and a small amount of moisture (mostly from the Great Lakes) as it travels south over warmer ground. A cP air mass that starts out with a temperature between –40 and –34°F (–40 and –37°C) over Alaska, may warm up to between 20 and 23°F (–7 and –5°C) by the time it reaches Florida.

A cP air mass exhibits greatly different qualities in summer than in winter. In the winter it consists of very cold, dry air, almost as cold as arctic air. It brings low temperatures and clear skies to the north and central United States, and even dips into the southern states on occasion. Its southernmost penetration occurs when much of the United States is covered by snow. Snow reflects incoming sunlight and keeps the ground and air above it colder. In the summer, a cP air mass starts out cool and warms considerably as it travels south.

Maritime polar air mass (mP) Siberia and the northern Pacific and Atlantic oceans are the points of origin of mP air masses. These air masses start out cold, but not as cold as their continental counterparts. Usually their temperatures hover just above freezing. As they travel south over warmer waters, they become warmer and wetter.

The regions affected most by these air masses are western Europe, southern Australia, New Zealand, and the east and west coasts of North America. Maritime polar air masses bring snow and rain in winter and fog and drizzle in summer. The mP air mass that travels over the Atlantic Ocean brings about the days of dreary weather the East Coast experiences in spring and early summer.

Continental tropical air mass (cT) These air masses build up over desert regions and are the world's hottest. A mass of continental tropical air tends to hover where it forms but sometimes moves away. If it hovers over another region for any length of time, it can bring about a drought. As an example, a cT mass may form over the deserts of the southwest United States and then travel to the plains states, where it remains for weeks. A cT air mass picks up moisture as it crosses over lakes and rivers, making it cooler and more humid.

Maritime tropical air mass (mT) An mT air mass consists of warm, moist air and forms over tropical and subtropical waters. The mT air masses that invade the eastern United States begin over the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean. Those that affect the western United States form over the Pacific Ocean, from Mexico to Hawaii.

In the summer, mT air masses bring very warm, humid air and rain. Along the Gulf Coast they bring daily thunderstorms. In the winter, mT air is usually prevented by a wall of cold polar air from reaching all but the extreme south of the United States. On the rare occasion when mT air is drawn northward, it brings unseasonably mild weather and clouds. It also brings the rains that wash away the snow, disappointing skiers.

Fronts: Where the action is

Air masses are transported around the globe by winds. As one air mass blows into a region, it encounters an air mass that is already there. What occurs next is often described as a battle, since in order to advance, one air mass must push the other out of the way.

The line where two air masses meet is called a front. A front is so named because of its similarity to the line where two armies meet in battle. Fronts can be moving or stationary. When they are moving, it means that one air mass is gaining ground, while another is losing ground. In contrast, a stationary front marks a region of stability between the air masses.

As a front passes through an area, it produces weather conditions ranging from gentle winds and light rains to violent storms. When a mass of cold air displaces a mass of warm air, it is said that a cold front has come through. Conversely, when a cold air mass is displaced by a warm air mass, a warm front has come through.

The interaction of warm and cold air masses is most common in the middle latitudes, in other words, the temperate regions. Included among these regions are the continental United States and southern Canada in the Northern Hemisphere and southern Australia in the Southern Hemisphere. The mixing of air with great differences in temperature and pressure produces storms. It is the temperate regions, therefore, that experience some of the world's most violent weather.

Warm fronts A warm front is the leading edge of a mass of warm air that overtakes a mass of colder air. The warm air, being less dense, slips over the cold air, which hovers close to the ground. The warm air cools as it rises and the water vapor within it condenses. This results in the formation of wispy clouds at high altitudes.

A warm front has a very gradual slope. In fact, when the leading edge of the air mass is 3,000 feet (914 meters) above a particular point, the base can still be more than 100 miles (161 kilometers) away. As the middle level and base of the warm front come in contact with the colder air mass, the warmer air cools and water vapor condenses. This forms layers of clouds at middle and lower altitudes.

As a warm front approaches an area, the air pressure decreases and precipitation begins, sometimes lasting for several days. Fairly strong winds may accompany this precipitation for a day or so when the base of the front sweeps past an area. Once the front passes through, skies generally clear up and temperatures rise.

Cold fronts Cold fronts are more closely associated with violent weather than are warm fronts. When a cold front moves into an area, the cold air (being denser than the existing warm air) wedges underneath the warm air and forces it sharply upward. This occurs because a cold front is very steep. At a distance of only about 30 miles (48 kilometers) behind the leading edge of the air mass, the cold air may reach 3,000 feet (914 meters) above ground. The precise steepness of cold front depends on the speed at which it's moving.

The warm air that is forced upward by the cold air mass produces tall clouds, and sometimes cumulonimbus (thunderstorm) clouds. These clouds, in turn, bring rain and possibly thunderstorms. The storms are accompanied by strong winds, produced by a drop in pressure created by the rising warm air. Where a cold front advances rapidly, fierce thunderstorms develop in a band called a squall line.

Cold fronts tend to pass through an area very quickly, so their effects are harsh but short-lived. The drop in temperature cold fronts bring is variable. Temperatures may drop just a few degrees to more than 35°F (10°C). In the summer, a cold front may simply bring drier air into a region, lowering the humidity considerably while barely affecting the temperature. The cold front leaves in its wake a band of clouds that produce rains, though of lesser intensity than the initial storms.

Stationary fronts A stationary front represents a standoff between two air masses. It occurs when one air mass pushes against a second air mass, and neither side budges.

If both air masses are relatively dry, then clear to partly cloudy conditions prevail at the front. However, if the warmer air is moist, then some of this air rises above the cold air and forms clouds and, possibly, precipitation.

When one air mass begins to move over or under the other air mass, the front ceases to be stationary. It becomes either a cold front or a warm front, depending on which air mass is advancing and which is retreating.

Occluded fronts The final possible outcome of a meeting between air masses is called an occluded front (or "occlusion"). An occluded front is formed by the interaction of three air masses: one cold, one cool, and one warm. The result is a multitiered air system, with cold air wedged on the bottom, cool air resting partially on top of the cold air, and warm air pushed up above both colder air masses.

There are two types of occluded front: cold and warm. Cold occlusions, which are much more common than warm ones, occur when a fast-moving cold front overtakes a slower-moving warm front. The cold front thrusts the warm air upward and continues to advance until it encounters cool air. The leading edge of the cold front then noses under the cool air, forcing it upward also.

When a cold occluded front is approaching (but before it reaches an area), the weather is similar to that when a warm front passes through. Clouds form in the upper, middle, and lower layers of the troposphere and there is precipitation. As the front passes overhead, however, it is accompanied by stormy weather and a sharp drop in temperature, similar to that associated with a cold front.

A warm occlusion forms under similar conditions as a cold occlusion, except that the cool air mass is the one advancing on the warm air. It pushes the warm air up and runs into cold air. The advancing cool front is then pushed upward, above the cold front. As a warm occluded front passes through an area, it produces weather conditions similar to those produced by an advancing warm front.

What is a storm?

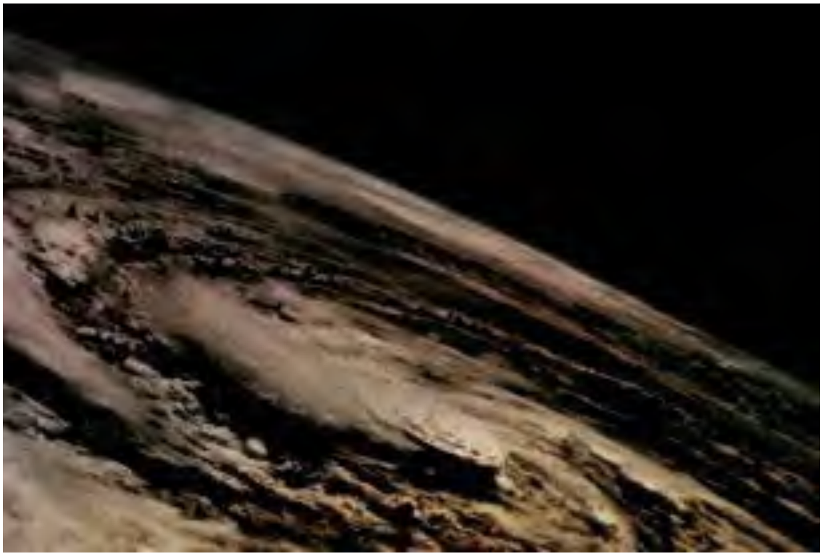
The word "storm" has come to represent many different types of weather phenomena. It is most often associated with unsettled weather conditions, such as heavy rain, thunderstorms, and snowstorms. Storms thus defined can be severe, causing floods, damaging homes, and even causing injury or death; or they can be mild, bringing rain or snow but causing little or no damage.

Storms are large-scale weather systems centered around an area of low atmospheric pressure, drawing in contrasting warm and cold fronts. They produce wind, clouds, precipitation, and the types of unsettled weather listed above, and cover hundreds to thousands of square kilometers. In a global sense, storms are a major mechanism of air circulation, pushing cold air southward and warm air northward.

Another word for a large-scale storm is a cyclone. A cyclone is a weather system in which winds spiral counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere, around a low-pressure area. The technical name for the kind of storm system that sweeps through the middle latitudes is an extratropical cyclone (or "midlatitude cyclone"). This term literally means a cyclone that is formed outside of the tropics. It differs from a tropical cyclone, one formed in the tropics, in that tropical cyclones are storms that don't involve fronts. While tornadoes are sometimes called cyclones, it should be noted that a tornado is one particular kind of cyclone.

Conditions ripe for storms The formation and sustenance of an extratropical cyclone requires vast amounts of energy. This energy is generated by the contrast between cold air and warm air. Temperature contrasts are particularly strong along fronts, and that is where cyclones are generally found. Occasionally, extratropical cyclones are formed in the absence of fronts. In such cases, contrasts in air temperature within a single air mass are produced as the air mass travels across warm and cold surfaces and is heated unevenly.

The birth of an extratropical cyclone also depends on conditions in the upper atmosphere. Specifically, an area of horizontal divergence is required. The divergence of winds aloft reduces the pressure at the top of a vertical column of air. Air from below ascends to this low-pressure area aloft, creating a surface area of low pressure. This, in turn, results in the convergence of both cold air and warm air at the center of the surface low. The contrasting air temperatures enhance the pressure gradient, causing the winds to blow faster. The process of cyclogenesis has begun.



A hurricane photographed from space. FMA, INC.

Cyclogenesis: The birth of a cyclone As air converges upon the center of the surface low-pressure area, warm air rises over cold air. The warm air cools as it rises, and the vapor within it begins to condense and form clouds. With the transformation of water vapor into liquid water comes a release of latent heat, the energy that is either absorbed or released by a substance as it undergoes a phase change, which also provides energy to the storm system.

The heavy, cold air then slides beneath the rising warm air and noses farther into the warm front. As a result, it pushes more warm air upward. The winds spiral in a counterclockwise fashion (in the Northern Hemisphere) and the fronts rotate. The greater the contrast between temperatures of the fronts, the greater the pressure differential. The greater the pressure differential between the center of the storm and the surrounding air, the faster the winds blow.

Another force that affects the cyclone's wind speed is the conservation of angular momentum. This scientific law states that as the radius of a spinning object decreases, its speed increases, and as its radius increases, its speed decreases. For example, think of a figure skater spinning on the ice. When she places her arms straight over her head, she spins faster. When she stretches her arms out to her sides, she spins more slowly.

Similarly, the speed at which a cyclone turns is related to how tightly the winds are wrapped about its center. As winds blow into the center of the low-pressure system, they spiral more and more tightly. However, if the storm center is forced to expand, the winds spin more slowly and the storm loses intensity.

Tracing the path of a storm The paths that storms follow shift throughout the year, as the boundaries between cold air and warm air shift. As warm air covers more of the Northern Hemisphere in summer, this boundary shifts to the north, through Canada and the northern United States. As cold air makes its way southward in winter, the boundary shifts accordingly, running through the central and southern states. Storms tend to follow these boundaries, since they feed on contrasting warm and cold air.

Weather conditions along a storm's path A storm generally involves three air masses: one cold, one warm, and one cool. This is the pattern one finds in the formation of an occluded front, a cold air mass that overtakes a warm air mass. As air masses move from west to east, the cold front is to the west and nudges along the warm air, which, in turn, butts up against the cool air to the east. The air masses cover huge north-south areas, often running from the northern edge to the southern edge of the United States. Thus, the same storm system can affect the weather across the entire country.

Weather conditions look quite different on either side of the storm. Locations ahead of (to the east of) the storm experience a high layer of thin clouds that grow thicker as the warm front approaches. For locations to the west, where the cold front has already passed through and the storm is over, clear skies and chilly air remain.

Now let's look at conditions for locations where the storm is overhead. As the steep cold front advances, it forces the warm air up sharply. This powerful convection produces tall clouds that often give rise to thunderstorms and possibly even tornadoes, all along the cold front. At the same time, 625 miles (1,006 kilometers) to the east, the warm front passes through. The gentle slope of the warm front noses upward, over the cool air. This produces clouds and light rain. Between the cold and the warm front is a pocket of warm air. That area experiences warm temperatures and hazy or clear skies.

As the whole system moves eastward over the next few days, the cold front outpaces the warm front. As a result, the pocket of warm air between the cold and cool air grows smaller and smaller. When the cold air finally meets the cool air, the warm air is forced completely off the surface. An occluded front is thus formed, and the storm begins to die out. Rain and clouds at the occluded front can persist for days.

Anticyclones An anticyclone, or high-pressure area, typically follows on the trail of a cyclone. The anticyclone strengthens the cyclone by providing a contrast in pressure with the cyclone's low. It is also brings about the calm, clear weather seen once a storm passes.

Anticyclones are the opposite of cyclones in every respect. They are centers of high pressure from which winds flow outward in a clockwise (in the Northern Hemisphere) pattern. Anticyclones form when there is a convergence of air above. That air descends, forming a high-pressure area on the surface, from which winds diverge.

Because clouds and water droplets in the air evaporate, or change from liquid to gas, as the descending air warms, anticyclones usually bring about clear skies. While cyclones are associated with competing fronts, anticyclones favor the formation and sustenance of a single, uniform air mass.

Water in the air

Water plays an important role in the creation of all weather conditions. Some concentration of water always exists in the air, even on sunny days. When that concentration is so great that the air can hold no more water vapor, the water begins to condense (enter the liquid phase). Condensation, the process of becoming liquid, may take the form of clouds, fog, dew, or frost. When water (or ice) in the clouds aggregates into units that are large enough, it falls to the ground as rain or snow.

How water becomes a gas Water molecules are always in motion. The speed with which they move is a function of temperature. That is, a function of their average kinetic energy. When they possess very little heat, water molecules are nearly still. The molecules are drawn together by their opposing electrical charges into the hexagonal (six-sided) crystalline configuration of ice. Except for slight vibrations, frozen molecules cease to move.

As heat is added to the ice, the molecules begin to move more rapidly. With the addition of enough heat, the molecules move fast enough to break the bonds of the ice structure. The result is that ice melts and becomes liquid water.

The molecules in liquid water are still connected to one another, although not in the rigid configuration of ice. They remain linked because there is an electrical attraction between oxygen atoms and hydrogen atoms in different molecules.

With the addition of more heat, the molecules in liquid water move even faster. The molecules at the surface eventually move fast enough to

A key reference to: Why you feel cooler after a shower

Have you ever wondered why your skin feels cool after showering or taking a swim? Before you dry off you may find your skin covered with goose bumps, even when it's hot outside. The goose bumps are caused by the evaporation of water from your skin.

The process of evaporation requires energy called latent heat. This type of heat does not raise the water's temperature but makes possible the conversion of water from one phase to another. When water evaporates from your body, it takes away latent heat, which makes your skin feel cooler.

overcome the electrical attractions connecting them to other molecules. Those molecules break free, leaving the liquid water and entering the air as a gas.

The process by which water changes from a liquid to a gas is called evaporation. Evaporation occurs naturally from any body of water. For example, water evaporates from a lake when the lake is heated by the Sun. When water molecules enter the gaseous phase, they retain the heat they absorbed in the liquid, which is the heat they require to break free. Thus, evaporation takes heat away from water and adds it to the air.

Absolute humidity Absolute humidity is a measure of the amount of water vapor in the air. It is expressed as the mass of water per unit volume of air. For instance, the absolute humidity on a given day may be 0.5 cubic inches of water per cubic yard of air. There is a limit as to how much water vapor can exist within a given volume of air at any given temperature. That limit is called the saturation point. For example, if you fill a cup of water halfway and seal the top with plastic wrap, the air in the top half of the cup will soon reach the saturation point. After that, water molecules will evaporate from the water's surface and condense back into it, at the same rate.

The saturation point is a function of air temperature. The warmer the air, the more water it can hold, and the higher the saturation point. For example, at about 50°F (10°C), a cubic yard of air can hold about 0.5 cubic inches of water vapor. At about 75°F (about 23°C), the same parcel of air can hold an entire cubic inch (17 grams) of water. At 100°F (37°C), a cubic yard of air can hold 2 cubic inches (50 grams) of water.

Another factor affecting saturation is air flow. On a still day, air remains in place and becomes saturated relatively quickly. However, on a windy day, air reaches the saturation point more slowly. When there is wind, the humid air is blown away, and the water vapor goes with it. As drier air moves in, more water molecules can evaporate into it. For this reason, puddles of water, as well as clothes on a line, dry more quickly when it's windy (and warm) than when it's still (or cold).

Relative humidity The absolute humidity of an air parcel (a small volume of air that has a consistent temperature) is merely a measure of how much water vapor is in the air. But this tells us little without the proper context. A much more meaningful description of the moisture content of the air is the relative humidity. This tells us *how* saturated the air is. In other words, it expresses humidity as a percentage of the total moisture the air can hold. To find the relative humidity of a parcel of air, divide the amount of water vapor present in the air by the maximum amount of water the air at that temperature can hold. Then multiply by 100 to find the percentage.

As an example, consider two different parcels of air. The first air parcel has a volume of 1 cubic yard and a temperature of 50°F (10°C). It contains 0.4 cubic inches of water vapor. At that temperature, a cubic yard of air is capable of holding 0.44 cubic inches of water. Thus, the relative humidity is 0.4 divided by 0.44 times 100, which equals 91 percent. The second cubic yard of air has a temperature of about 75°F (23°C) and contains 0.7 cubic inches of water vapor. At that temperature, the air can hold 1.07 cubic inches of water. The relative humidity of the second parcel is 65 percent. Thus, while the second air parcel has a higher absolute humidity, the first parcel has a higher relative humidity.

You can extrapolate from the above example to understand why the relative humidity is higher at night than during the day. Consider a day in which the absolute humidity is 0.5 cubic inches of water per cubic yard of air. Say the temperature peaks in the afternoon at about 85°F (29°C). At that temperature, a cubic yard of air can hold 1.42 cubic inches of water. Thus the relative humidity is 35 percent. In the evening, the temperature drops to about 60°F (15°C), at which point a cubic yard of air can hold only 0.6 cubic inches of water. If the absolute humidity remains the same, the relative humidity rises to 83 percent.

A key reference to: Why people use humidifiers and dehumidifiers

Have you ever wondered why the air in your home feels so dry in the winter? Or why your basement gets damp in the summer? Both of these phenomena are due to changes in relative humidity, changes that are brought about by the heating or cooling of air in our homes with no corresponding change in absolute humidity.

First let's examine the case of dryness in winter. Remember that at low temperatures, air can hold very little water. When the cold outside air enters your house and is heated, its absolute humidity stays the same but its *relative* humidity greatly decreases. Humidifiers, which put water vapor back into the air, raise the relative humidity inside the house back to a comfortable level.

Now take the opposite case, which occurs in the summer. Recall that warm air can hold more water than cold air. When warm air from outside enters your basement, which is generally cooler than the rest of the house, the absolute humidity stays the same but the *relative* humidity increases. This results in dampness, a condition that favors the growth of mildew. To counter this effect some people use dehumidifiers, which take water out of the air.

Dew point Another measure of humidity is called the dew point. The dew point is the temperature at which a given parcel of air becomes saturated (reaches 100 percent relative humidity) and water vapor begins to condense (return to the liquid phase). The dew point is so-named because it is the temperature at which dew forms on the ground.

Consider the following example in which a cubic yard of air contains 0.6 cubic inches of water vapor. During the day, when the temperature reaches 75°F (23°C), the air is capable of holding 1.07 cubic inches of water vapor. At that point the air has a relative humidity of 56 percent. As the temperature falls (and the absolute humidity remains the same), the relative humidity increases. When the temperature reaches about 60°F (15°C), the relative humidity is 100 percent, the air is saturated, and dew begins to form. Thus, 60°F is the air's dew point. Where the absolute humidity is higher, the dew point is higher; and where absolute humidity is lower, the dew point is lower.

Condensation

At the dew point, water vapor condenses to the liquid state. The form this liquid water takes depends on two factors: the distance above Earth's surface at which condensation occurs and the temperature of that medium. When water condenses on Earth's surface itself, it forms either dew or frost. When water condenses in the air just above the ground it forms fog. At higher levels, it condenses to form clouds.

Dew The wetness felt on the grass, particularly in the spring or fall, is dew, the condensation of water vapor on a cold surface. It occurs whenever the ground is cold enough to reduce the temperature of the air directly above it to the dew point. This assumes that the dew point is above freezing. If the dew point is below freezing, frost will form.

Dew forms only on surfaces that lose heat quickly and become colder than the dew point of the air, such as the surface of grass and plants. Dew doesn't form on the pavement or a baseball diamond, because hard surfaces retain more heat than the air. Thus, the air above hard surfaces seldom reaches its dew point.

Dew is more likely to form on clear nights than on cloudy nights. The reason for this tendency is that Earth's surface radiates heat upward at night, when there is no incoming solar heat to warm the surface back up. Clouds trap some of that heat and reradiate toward the ground.

In the absence of clouds, that heat is lost into space. Thus, on clear nights surface temperatures drop more dramatically than they do on cloudy nights.

Dew formation plays an important role in the regulation of air temperature. When water changes from a gas to a liquid, it releases latent heat, the same energy it absorbed during the evaporation process. When dew forms, it warms the air around it, thus slowing the rate at which the temperature drops throughout the night. It does this so efficiently that nighttime temperatures generally don't drop below the dew point. An exception to this rule occurs when a cold air mass enters a region during the night, causing a sharp decline in temperature.

Weather forecasts often give both the temperature and the dew point. The temperature may tell the current condition, but the dew point tells what to expect at night. Remember, at the dew point, relative humidity is close to 100 percent. On a day when temperatures are high, the dew point will also be high, say around 70°F (21°C). It is expected that the night air will be in the 70s with nearly 100 percent humidity.

Weather report: Supercooled water

Often when it rains in the winter, cold rain falls and forms icicles on houses and trees, as well as sheets of nearly impassable ice on the ground. Why is the water liquid in the air but becomes ice when it strikes a surface? The answer lies in the mechanics of supercooled water.

Supercooled water is water that exists in a liquid state below 32°F (0°C). It has not frozen because it takes more than cold temperatures to freeze water. It also takes a freezing nucleus, a particle of ice or other solid on which water vapor can condense. In the absence of a freezing nucleus, a water droplet will not turn to ice until it cools to about –40°F (–40°C). Most freezing rain contains some ice crystals. Once those ice crystals hit the ground, they provide the freezing nuclei around which supercooled raindrops can form ice.

Frost Frost formation is very similar to dew formation, except that it occurs at temperatures below freezing. In contrast to dew, frost will form on any surface, even dirt and concrete. During winter, these surfaces become sufficiently cold for moisture to gather. Dirt and concrete don't absorb enough heat during a winter day for them to remain warmer than the frost point (at which an air parcel can hold no more air when the temperature is below freezing) of the night air.

Central to an explanation of frost formation is a concept of supercooled water. Supercooled water is water that exists in a liquid form below 32°F (0°C), the freezing point of water. When the dew point is below 32°F (0°C), water vapor first condenses on a surface as "supercooled dew" and then freezes. This initial layer of frost grows as water vapor from the air freezes directly onto it.

The process of water changing directly from gas to solid ice without first passing through the liquid phase is called deposition. The reverse of deposition, when ice passes directly from the solid state to water vapor without first melting, is called sublimation. During the process of deposition, latent heat is released to the environment. During sublimation, it is absorbed.

Frost that is formed by the process of deposition is called "true frost" or hoar frost. Hoar frost has the intricate structure that can be seen on a windshield on a cold winter day. Hoar frost also forms on the inside of the windows—or between the panes of double-pane glass—in the home. Water vapor freezes onto a window when the air just inside the window is cooled to the dew point, provided the dew point is below 32°F (0°C).

Another type of frost is produced by the freezing of dew that has already formed on a surface. This occurs when the dew point is above freezing, and the temperature later falls below 32°F (0°C). This type of frost does not form crystal structures like hoar frost, but droplets of ice.

Fog Fog is condensation that occurs in lower levels of air. It is essentially a cloud that has formed close to Earth's surface. Fog in temperate regions is composed of water droplets; in polar and arctic regions it may also be composed of ice crystals. Condensation in the air is generally defined as "fog" when it restricts visibility to 1 kilometer. If visibility is greater than 1 kilometer, the condition is defined as "mist." In this discussion, all condensation in the lower levels of air will be referred to as "fog."

The process of condensation in the air begins with condensation nuclei. Similar to dew and frost, which won't form in the absence of a surface, the water droplets that constitute fog and clouds need something to cling to. Condensation nuclei are tiny solid particles suspended in the air. Even in relatively clean air, there are about two thousand of these particles in every cubic inch. Examples of condensation nuclei include pollen, sea salt, sand, volcanic dust, factory smoke, and other industrial pollutants.

As has been shown in experiments using purified air, individual water vapor molecules do not readily stick together. Even when they do collide and form tiny droplets, those droplets will likely disintegrate. It has been theorized that in the absence of condensation nuclei, water would not condense into raindrops. Rather, the air would grow increasingly saturated with water vapor until it was unable to hold another molecule. Then water would fall to the ground in massive, destructive sheets.

A thin layer of advection fog forms over a cold Lake Erie surface as warm, moist air blows offshore. FMA, INC.

There are several types of fog, which differ according to the conditions under which that fog was formed. Fog is produced in one of two ways: either when air is cooled to its dew point by contact with a cold surface; or when air is brought to its saturation point by evaporation from a wet surface. What follows is a brief outline of three major categories of fog.

The first type of fog, with which most people not in the coastal areas of the United States are familiar, is radiation fog (sometimes called ground fog). This type of fog forms on clear summer nights when winds are nearly still. After sunset, heat radiates away from the ground, cooling the ground and the air above it. Once this air is cooled to the dew point, water vapor condenses and forms a fog. When the Sun rises the next morning and warms the air, the fog quickly dissipates.

The second type of fog is called advection fog. This is the thickest and most persistent type of fog and may form at any time of day or night. Advection fog is formed by advection, the horizontal movement of air. Specifically, it forms when a warm, moist layer of air crosses over a cold surface. The air loses heat to the cold surface. Once the air cools to the dew point, fog is formed.

A third class of fog is called evaporation fog. Like advection fog, it involves the interaction of cold air and warm air. But unlike advection fog—where warm, humid air travels over the cold air—the cold air in this case travels over a warmer body of water. Evaporation fog usually forms over inland lakes and rivers in the fall, when the air is cool but the water still retains heat. Water evaporates from the lake or river, saturates the cold air, and condenses. This fog often appears as "steam" that rises from a body of water.

Cloud formation

The subject of cloud formation has already been touched upon several times in this volume. As air rises, it cools. Once the air reaches the dew point, water vapor within it begins to condense into clouds. When a cold front advances into a warm front, the warm air is thrust upward in a powerful convection, which produces tall clouds. When water condenses on the ground it forms dew or frost, and when it condenses in the air it forms fog or clouds.

Why rising air cools and falling air warms Both the cooling of air as it rises and the warming of air as it falls are adiabatic [add-ee-uh-BAT-ick] processes. In an adiabatic process no heat is exchanged between a moving air parcel and the ambient (surrounding) air, even as the temperature of the air parcel changes. "Air parcel," refers to a volume of air that has a consistent temperature throughout and experiences minimal mixing with the surrounding air. The mechanism by which ascending air cools is called expansional cooling. Conversely, the mechanism by which descending air warms is called compressional warming.

Expansional cooling is the most significant process in the formation of clouds. It works like this: as a parcel of air rises, the pressure of the air around and above it decreases. This decrease occurs because the density of air decreases with altitude. With fewer molecules, air exerts less pressure. In order to equalize its pressure with that of the ambient air, molecules within the parcel push outward, enlarging the parcel. However, the number of molecules within the parcel does not change. The result is that the same number of molecules is spread over a greater area. In other words the density of the air parcel decreases.

The expansion of air requires energy. That energy comes in the form of molecular kinetic energy (energy of motion), which is the same as heat. Before expanding, the molecules store that kinetic energy, meaning they are warmer. Once the molecules spend kinetic energy moving away from one another, they slow down and collide less frequently. They have a decreased kinetic energy, which is to say they have become cooler.

Conversely, as an air parcel falls, it is compressed by the increasing pressure of the surrounding air. The parcel is squeezed into a smaller volume, thereby increasing the density of the air within it. This leads to a greater number of collisions between molecules, hence greater kinetic energy. The increase in kinetic energy within the air parcel translates into an increase in temperature.

Temperature changes in unsaturated air The change in temperature of a rising or falling air parcel is a measurable quantity. For air that is not yet at the saturation point (having less than 100 percent relative humidity), the rate of change is called the dry adiabatic lapse rate. This rate of change is constant. Air cools by about 5°F (–15°C) for every 1,000 feet (304 meters) it ascends and warms by 5°F for every 1,000 feet it descends.

Temperature changes in saturated air Once air becomes saturated, the rate at which temperature changes with altitude occurs more slowly and is no longer a constant. The scale that applies to saturated air is called the moist adiabatic lapse rate.

The reason that saturated air cools more slowly than unsaturated air as it rises is that water vapor condenses within saturated air (and forms a cloud), releasing latent heat. Whereas latent energy is absorbed in the process of evaporation, it is liberated in the process of condensation.

Thus as water vapor condenses out of saturated air, it releases latent heat and raises the temperature of the air parcel. This increase in temperature, however, is not enough to offset the decrease in temperature due to expansional cooling. It merely slows the rate at which the cooling occurs.

The amount by which the release of latent heat slows the cooling of an ascending air parcel depends upon that parcel's temperature. In the warmest saturated air, cooling proceeds at a rate of about 2°F (–17°C) for every 1,000 feet (304 meters) ascended. In the coldest saturated air, cooling proceeds at a rate of about 5°F (–15°C) for every 1,000 feet ascended. The average moist adiabatic lapse rate, about 3°F (–16°C) per 1,000 feet, is often used as a constant, for convenience in weather forecasting.

The reason that the moist adiabatic lapse rate depends upon temperature is that when the air parcel first becomes saturated (and is at its warmest), condensation within it releases the most latent heat. In this case, it offsets the declining temperature by the greatest amount. As the saturated air continues to rise, it cools. At the same time, the air parcel can hold a smaller amount of water vapor. The rate of condensation decreases, and the release of latent heat declines. As a parcel of saturated air decreases in temperature, it provides less of a buffer to the expansional cooling.

By the same token, as saturated air descends, it warms at the moist adiabatic lapse rate. As air sinks and its temperature rises, water droplets (and clouds) evaporate into it. The process of evaporation absorbs latent heat and impedes the rate at which the temperature of the air rises. In other words, evaporation partially offsets compressional warming. Once the falling air is no longer saturated and the water droplets within it have all evaporated, it begins warming at the dry adiabatic lapse rate.

Using the dry adiabatic lapse rate, it is possible to determine the temperature of an unsaturated air parcel at various heights within the atmosphere, provided we know its temperature at the surface. If we know the air parcel's dew point, it is possible to determine at what height clouds will form. Knowledge of air temperature at all levels of the troposphere is a critical element in creating weather forecasts.

Air stability and vertical motion The vertical movement—or lack thereof—of an air parcel is dictated by differences in temperature and density between the air parcel and the ambient air. Those differences and the resultant degree of vertical movement of air are referred to as air stability (also called "atmospheric stability"). Air stability is the key to both the size and shape of the clouds and the intensity of the precipitation that results when a rising parcel of air reaches the dew point.

The rules of air stability state that as long as an air parcel has a higher temperature and lower density than the surrounding air, it will rise. When this parcel is no longer warmer than the air around it—when its pressure and density have become equal to those of its surroundings—the air parcel stops rising. On the other hand, as long as an air parcel has a lower temperature and higher density than the air around it, it will continue to fall.

A stable air layer, through which a parcel of air cannot rise or descend, marks the end point of an air parcel's vertical journey. A layer of air is stable at the height where an air parcel reaches the temperature of the ambient air and ceases to move. An unstable air layer is one through which an air parcel moves upward or downward. In other words, a layer of air is unstable at heights where an ascending parcel is warmer than the ambient air or a descending parcel is colder than the ambient air. If we know the surface temperature of a rising air parcel and the temperature of the troposphere at various heights, we can determine the height of a stable air layer.

In order for clouds to form, unstable conditions must exist at least long enough for a rising parcel of air to reach its dew point. For cloudy skies to turn clear—caused by a descending parcel of air—unstable conditions must also exist. In stable atmospheric conditions, where the relative humidity is high enough, fog may form and, prevented from rising, will persist.

What causes air stability and instability Unstable conditions exist within the troposphere when relatively cold air layers are situated above relatively warm surface air. This is what most commonly occurs, as air generally cools off with increasing altitude. Sometimes, however, a layer of warm air exists above colder air. This produces stable conditions. The warm air layer acts as a ceiling, or an upper limit, beyond which warm air parcels will rise no farther. There are various factors that lead to the development of both stable and unstable conditions.

Air becomes stable when either an upper layer of air warms or the surface air cools. The former may be caused by a warm air mass blowing in above, while the layer of air below experiences no change in temperature. The other route to stability—the cooling of the surface air—may occur when the ground loses heat at night or a cold air mass arrives.

An absolutely stable atmosphere is produced by an inversion. An inversion is a condition in which air temperature increases with height. An inversion can occur when a thick layer of unsaturated air sinks, covering a large area. Since the upper levels of the air layer cover a greater vertical distance than the lower levels, the air within them has farther to fall—and more time to undergo compressional warming. The top of the layer therefore becomes warmer than the air below it. The relatively warm air layer acts a lid on any rising air parcel, preventing it from rising further. The presence of low-lying fog, haze, and smog (a hazy layer of pollution at Earth's surface) are all indicators that an inversion has occurred near the surface.

Air instability is caused by the opposite conditions that produce stability, either the warming of the surface air or the cooling of an upper layer of air. The warming of the surface air may be caused by the absorption of solar heat by the ground during the day or the influx of a warm air mass. Or a mass of cold air might be brought in by the winds aloft, while the layer of air below experiences no change in temperature.

The stability of air over land changes significantly throughout the day, from the most unstable at the warmest time of day to the most stable at the coldest time of night. At night the ground loses heat and the air just above it cools. At sunrise this stability can be witnessed (in clear, calm weather) as fog rests on the ground. As the day progresses, the surface layer of air is heated by the Sun. When it becomes warmer than the air above, unstable conditions prevail. As the lower air continues to warm and the difference between lower and upper layers increases, instability increases. Thus, instability is greatest at the hottest time of day. As day passes into night, the surface air cools and the cycle begins again.

Air stability and cloud shapes When the air is unstable, parcels of air rise throughout the day. If they rise high enough to cool to the dew point, clouds will form. In some cases, the unstable air layer is shallow, meaning that at a relatively low altitude the ambient air becomes warmer than the rising air parcel. In such cases, the clouds that form are puffy and small. If, however, the layer of unstable air is deep, tall clouds such as those that bring thunderstorms may form.

When the air is stable, one won't find individual pockets of rising air, hence no puffy clouds. Clouds form in stable conditions only when an

Cirrus clouds above and cumulus clouds below. FMA, INC.

entire layer of air rises. This occurs when air flows into the center of a low-pressure area and rises or when a warm front advances and slides over a cold air mass. In those cases, the lifting of warm air produces a nearly continuous, flat sheet of clouds.

On a typical day, one may see both types of clouds at the same time. The reason for this pattern is that layers of stable and unstable air may be stacked on top of one another over a single location on the ground. As a result, small puffy clouds and sheets of clouds form at different altitudes.

The lifting of air Air does not just rise spontaneously: it needs a push. That push comes in three different forms: convection, frontal uplift, and orographic lifting.

Convection is the lifting of air that has been heated. When heat is applied, air molecules move more quickly. The molecules spread out, the air loses density, and the air becomes thinner. As long as it is warmer and lighter than the surrounding air, it continues to rise.

Convection occurs when the ground is heated by the Sun. That heat is then radiated upward from the ground, warming the air above it. This causes air parcels, often referred to as "bubbles," to rise and form individual puffy clouds upon reaching the dew point.

Frontal uplift and orographic lifting each cause an entire mass of warm air to rise. Frontal uplift occurs when a warm air mass and a cold air mass come together at a front. The cold air mass occupies the space closest to the surface while the warm air mass rises over the cold air. As the warm air mass reaches the dew point, it forms a sheet of clouds. Orographic lifting occurs when a warm air mass encounters a mountain and rides upward along the surface. This process results in a variety of unusual cloud types, including those shaped like banners and those shaped like flying saucers.

Clouds and precipitation

Although they cover, on average, 60 percent of the sky, clouds hold just one one-thousandth of 1 percent (0.001 percent) of the world's water. Nonetheless, they are critical elements in the cycling of water from the ground into the air and back. Without clouds to regulate the intensity of solar heat, all water would evaporate, and Earth would experience an interminable drought, or extended period of time with abnormal dryness. Clouds also trap heat that is reradiated up from the ground, preventing the surface from growing too cold.

Anatomy of a cloud A cloud is a collection of many billions of water droplets, condensed from air that has cooled to its dew point. Those water droplets may take one of two forms: liquid water or ice crystals. Whether they form as a liquid or as ice depends on the temperature of the air. When condensation occurs within air that is warmer than 32°F (0°C), it takes the form of liquid droplets. When the temperature of the air is 32°F or below, condensation usually takes the form of ice.

Clouds of liquid water droplets include another vital set of ingredients: condensation nuclei. A condensation nucleus is any solid particle in the air. As explained in the section on fog, sea salt, dust, pollen, sand, and industrial pollutants all act as nuclei around which molecules of water condense.

There are various ways in which ice crystals form within clouds, depending on atmospheric conditions. Ice crystals may either be produced by the freezing of liquid water droplets or the deposition (the process by which water changes directly from a gas to a solid) of water vapor.

First, let's consider the freezing of water droplets. At temperatures below –40°F (–40°C), water freezes directly into ice, in a process called spontaneous nucleation. However, at higher temperatures the process becomes more complicated. Except for the largest droplets, water will not assume the crystalline structure of ice in the absence of freezing nuclei. Freezing nuclei are solid particles, such as clay, vegetable debris, or ice crystals themselves, suspended in the air, upon which water droplets

A supercell thunderstorm in Kansas. ©JIM REED/CORBIS.

freeze. Freezing nuclei serve a function in the formation of ice crystals similar to that of condensation nuclei in the formation of water droplets.

Freezing nuclei exist in the atmosphere in relatively small numbers and are sometimes in short supply within clouds where temperatures are below 32°F (0°C). This accounts for the presence of supercooled water, water that exists in a liquid state below the freezing point, within some clouds.

The second method of forming ice crystals, the deposition of water vapor, happens much less frequently than does the freezing of water droplets. Deposition only occurs at temperatures below –4°F (–20°C) and in the presence of special freezing nuclei called deposition nuclei. Deposition nuclei, examples of which include ash, diatoms, and spores, are relatively rare in the atmosphere.

Since air temperature generally declines with increasing altitude, ice-crystal clouds are most often found at the highest levels of the troposphere;

liquid-water clouds at lower levels; and clouds containing both liquid and ice at middle levels.

Who's who: Alfred Wegener

Alfred Wegener (1880–1930) was a German meteorologist and geophysicist who solved the mystery of raindrops. He reasoned that supercooled raindrops often coexist with ice crystals in clouds. Ice crystals, which have a lower vapor pressure than liquid water, attract water molecules to them.

Although this discovery was remarkable, Wegener is more famous for developing the theory of continental drift in 1912. This theory states that 200 to 250 million years ago all land on Earth was joined together in one huge continent. Over the years forces deep within the Earth caused the land to break apart and the chunks to move away from one another, eventually reaching their current configuration.

FURTHER READING ON ALFRED WEGENER: WITZE, ALEXANDRA. "ALFRED WEGENER." *NOTABLE TWENTIETH-CENTURY SCIENTISTS.* VOL. 4. ED. EMILY J. MCMURRAY. DETROIT: GALE RESEARCH INC., 1995.

What makes rain and snow fall In order for water to fall to the ground as rain, water droplets in clouds have to become large enough—and obtain a terminal velocity great enough—to reach the ground. It takes from one million to fifteen million water droplets to form an average raindrop, which is about 0.08 inches (2 millimeters) in diameter. Whereas the terminal velocity of a water droplet is about 0.02 mph (0.03 kph), the terminal velocity of a raindrop is about 15 mph (24 kph).

Just how do cloud droplets grow to the size of a raindrop? The most obvious answer is condensation. That is, more and more water vapor molecules condense into a liquid until the drops of water become large enough to fall to the ground. This process alone, however, is quite slow and cannot possibly account for the amount and rate of rainfall experienced in the middle latitudes. Rain often starts falling just thirty minutes after a cloud begins forming. During that time condensation alone can not produce drops of water large enough to fall.

Early in this century, scientists discovered the answer: ice. Ice crystals often exist together with supercooled water droplets in clouds. Such clouds are called cold clouds.

Ice crystals grow more quickly than, and at the expense of, water droplets in cold clouds. The reason for this has to do with vapor pressure, the pressure exerted by a vapor when it is in equilibrium with its liquid or solid. Equilibrium is defined as the saturation point, the point at which the same number of molecules are entering and leaving the gaseous state.

Within cold clouds, vapor pressure is greater over the surface of a water droplet than it is over the surface of an ice crystal. This pressure differential creates a force that directs water vapor molecules away from the water droplets and toward the ice crystals. In the process, it lowers the pressure over the water droplets. To maintain equilibrium, more molecules then evaporate from the surface of water droplets, which, in turn, are directed toward the ice crystals. Each time the cycle repeats, the ice crystals grow larger and the water droplets grow smaller.

When an ice crystal becomes large enough, it begins to fall, attracting water molecules as it goes. Usually, during its descent, it takes on the form of a snowflake. If the air warms above the freezing point during an ice crystal's descent, the ice melts and hits the ground as rain. If the air remains below freezing, snow occurs.

Ice crystals within clouds, however, can't account for all precipitation. In the tropics there are warm clouds, clouds that are too warm to contain ice. Yet these clouds still produce plenty of rain. Scientists have concluded that in warm clouds, water droplets must collide to form bigger drops. While meteorologists are still seeking to answer the question of just how this happens, one current theory is that large droplets form around giant sea-salt condensation nuclei and that these large droplets become even larger by colliding with smaller droplets.

The water cycle Precipitation represents one portion of the water cycle (or "hydrologic cycle"), the continuous exchange of water between the atmosphere, and the oceans and landmasses on Earth's surface. The other side of this equation is evaporation, the process by which liquid water at Earth's surface is converted to a gas and is returned to the atmosphere. Some of that water vapor then forms clouds, which return the water to Earth as rain or snow.

Most of Earth's water—about 97.2 percent—exists in the oceans. The rest, save the 0.001 of one percent that exists as water vapor in the atmosphere, is contained in the polar ice caps. All three phases of water—solid, liquid and gas—continually coexist on Earth. The water cycle is driven by the continuous conversion of water molecules among these three phases.

Between 85 and 90 percent of the moisture that enters the atmosphere comes from the oceans. The rest evaporates from the soil, vegetation, lakes, and rivers that exist on the continental landmasses. Even plants emit water through tiny pores on the underside of their leaves in a process called transpiration.

Some of the moist air above oceans is carried overland by the wind. Clouds form and swell, and drop rain and snow on the ground. When precipitation hits the ground, it either sinks into the surface or runs off, depending on the surface composition. For example, rainwater will sink into soil and sand. The excess water will form puddles on the surface or seep down into underground streams or reservoirs. Water found under Earth's surface is known as groundwater. If the water strikes a hard surface, like rock or pavement, it will either run off and flow into rivers and lakes or drip through cracks and make its way to the groundwater.

The oceans experience a net loss of water in this portion of the cycle. More water evaporates from them than returns as precipitation. This deficit is corrected when water in rivers and streams flows back into the oceans. Thus the global water budget—the volume of water coming and going from the oceans, atmosphere, and continental landmasses—is kept in balance.

Land and weather

The different properties of land and sea result in the formation of different weather patterns over each. The two major differences between land and sea can be loosely categorized as heat retention and surface features. These characteristics affect temperature highs and lows, cloud formation, and storm systems. Also, certain types of topography (physical features of land) create their own small-scale weather patterns.

Heat retention Land heats up and cools down relatively quickly, whereas water is slower to absorb heat and slower to release it. Water absorbs and stores heat in a form called latent heat. Latent heat does not affect the temperature of water; it is the energy used to drive changes in phase from solid to liquid or liquid to gas.

The fact that land rapidly absorbs solar heat during the day, and rapidly loses heat at night, results in greater temperature extremes on land than at sea. These differences in heat retention can be experienced if one goes swimming both in the afternoon and in the evening on a summer day. When one swims in the heat of the day, the water feels cooler than the air. Yet once the Sun goes down and the air temperature drops, the water becomes the warmer medium.

Sea and land breezes Two manifestations of the temperature differential (and corresponding pressure gradient) created between land and water throughout the day are sea breezes and land breezes. These are the breezes that one feels at the beach. The sea breeze blows toward shore during the day, when the sand is warmer than the water, and the land breeze blows toward the water during the night, when the water is warmer than the sand.

During the day, when the sand warms quickly, a low-pressure area is created over the sand. In comparison, a high-pressure area forms over the water. A gentle wind flows from the high-pressure to the low-pressure (from the water to the sand). This wind is known as a sea breeze.

At night, the sand loses heat more quickly than does the water, so the process is reversed. The breeze flows from the high-pressure area over the sand, out to the low-pressure area over the water. This wind is known as a land breeze.

Mountain weather The peaks and valleys of a mountain range alter the behavior of a large-scale weather system as it travels across the mountains. These surface features also produce small-scale weather patterns unique to that topography. For instance, a storm slows as it crosses a mountain range and re-intensifies on the other side. When the storm travels over the mountain, the storm center is flattened between the mountaintop and the top of the troposphere. The spinning winds at the storm center are therefore forced to expand horizontally, which slows the spinning. When the storm emerges on the other side of the mountain, it has more room to stretch out vertically and spins faster again.

Mountains also produce distinct, small-scale weather patterns that are limited to the mountainous area. For instance, some clouds have unique shapes that resemble banners or disks. These clouds form at the tops of mountains and are the products of orographic lifting. Orographic lifting is the process in which a warm air mass rides upward along the surface of a mountain. As the air rises, it cools. Once it reaches the dew point, condensation occurs and clouds form.

The rain that comes from these clouds generally falls on the peak and the westward, or windward, side of the mountain, the side on which the warm air ascended. On the other side of the mountain—the eastward or leeward side—conditions are much drier. As air descends across the leeward side, it warms, causing water droplets and clouds to evaporate. The uneven distribution of precipitation across a mountain is known as the rain-shadow effect.

A rain shadow may occupy the base of a single large mountain or the entire region east of a mountain range. An example of the former is Mount Wai'-'ale'ale, on the island of Kauai in Hawaii. The windward side of this mountain is considered the rainiest place on Earth. Near the peak of the mountain, the windward side receives on average 40 feet (12 meters) of rainfall a year. The leeward side of the mountain, in contrast, is

Downslope winds off Table Mountain near Cape Town, South Africa, show both a chinook-type wall cloud and a smoke layer from brush fires burning on the flat mountain top. FMA, INC.

extremely dry. It receives only 20 inches (50 centimeters) of rainfall, on average, each year.

A larger-scale rain-shadow effect occurs east of the Rocky Mountains, in the high plains of the central United States. This region receives relatively little rainfall especially compared to the windward side of the Rockies. In South America, a similar situation exists in the arid region east of the Andes Mountains. Many of the world's deserts lie in the rain shadow of mountain ranges.

Oceans and weather

The oceans cover more than 70 percent of Earth's surface. They have a tremendously important role in global heat distribution. What is more, they are involved (in conjunction with the winds) in generating global weather patterns and influencing climate, the weather experienced by a given location, averaged over several deacdes. The Sun heats Earth unevenly, and the atmosphere strives to even out heat distribution. While winds are responsible for about two thirds of the world's heat distribution, ocean currents are responsible for the remaining one third.

Oceans retain heat over long periods of time, even as the amount of energy they receive from the Sun varies. While this enables ocean currents to carry heat from the equator to the poles, it also means that the temperature of the oceans is often different from that of land at similar latitudes. On the coasts, the exchange of cold air and warm air can generate wind, rain, and storms.

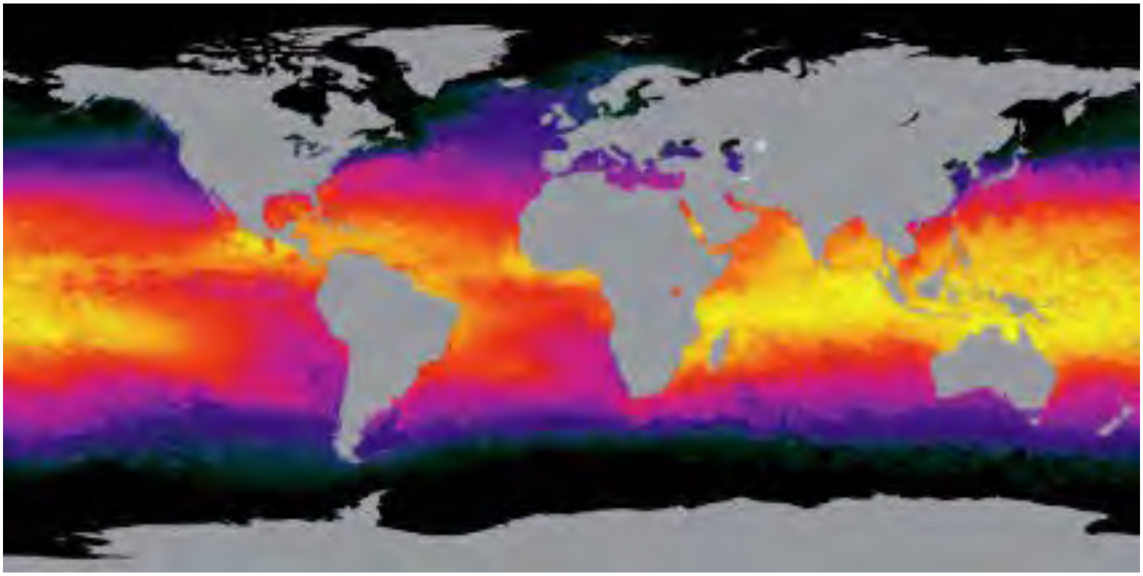
There are also seasonal differences between land and sea. While the temperature changes that accompany a new season take effect immediately on land, they lag behind by several weeks in the oceans. It isn't until several weeks after the first day of winter that oceans reach their lowest temperature of the year, and until several weeks after the first day of summer that they reach their highest temperature of the year. As a result, still-warm ocean air warms up some coastal regions as winter sets in. Still-cold ocean air slows the warming of some coastal areas in the spring.

Ocean currents Ocean currents are permanent or semipermanent large-scale circulations of water, at or below the ocean surface. Ocean currents are closely tied to the global circulation of winds. As the wind blows, it causes the surface layer of water to move with it. As the surface water flows, it gradually piles up and creates differences in pressure in the levels of water beneath it. The result is that deeper water moves as well. Due to the relatively high friction that exists between layers of water, ocean currents move much more slowly than the wind.

Ocean currents, like air currents, are influenced by the Coriolis effect, the rotational force of Earth. The Coriolis effect deflects the motion of both ocean currents and air currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This causes surface waters to blow in a direction, on average, 45 degrees different than that of the wind. That's because once the wind starts the surface waters in motion, the Coriolis effect alters the direction of the water flow.

Similar to the winds, ocean currents travel in a circular fashion around major high-pressure systems in the atmosphere above them. The large circular patterns of ocean currents are called gyres [JEE urs]. Ocean currents—like winds—travel clockwise around atmospheric high-pressure systems in the Northern Hemisphere and counterclockwise around atmospheric high-pressure areas in the Southern Hemisphere.

Upwelling Water travels in a series of loops from the equator to the poles and back. The net effect of ocean currents is to cycle heat from the warm equatorial region to the poles. While one would expect surface water to become consistently colder as it travels north and warmer as it travels south (in the Northern Hemisphere), this is not always the case. Sometimes this trend is interrupted, due to a phenomenon called upwelling.



Computer model of global sea temperatures in 2001. Temperatures range from 35° C (yellow) in the tropics to –2° C (black) in the polar regions. NASA/PHOTO RESEARCHERS, INC.

Upwelling is the rising of cold waters from the depths of the ocean. Upwelling occurs when surface water along a coast flows out to sea, and deep water flows in and rises to replace it. This directional flow of water is set in motion when the wind blows parallel to the coastline. An example of where this occurs is Cape Mendocino, in northern California. Due to upwelling, the waters off the coast of Cape Mendocino are cooler in the summer than are the waters off the coast of Washington State, which is farther north.

The process that is responsible for Cape Mendocino's cold waters begins with the winds in that region, which blow from north to south along the California coast, in a clockwise fashion around the Pacific High. The surface water is pushed southward by the wind and curved to the right by the Coriolis effect. Where the wind blows parallel to the coast at Cape Mendocino, the surface water flows out to sea.

Why then does deeper water flow inward toward the coast and upward to replace the surface water? Because at great enough depths of the water, something very curious happens: the water flows in a direction that's opposite that of the surface water. That is to say, where the surface water flows out to sea, the water 100 yards (110 meters) or so below flows in toward the surface.

This changing pattern of water flow along a vertical gradient is called the Ekman Spiral. It works like this: First, imagine ocean water as being made up of a series of vertical layers. Each layer exerts a frictional drag on the layer beneath it, meaning that water travels more slowly the deeper one goes. In addition, the Coriolis effect rotates each successively deeper layer of water farther to the right than the layer above it. Thus, at great enough depths, the water flow reverses direction. In the case of Cape Mendocino, as the surface water flows out to sea, deep, cold water flows toward land. It continues upward, along the ocean floor until it meets the coast.

El Niño/Southern Oscillation The most striking example of how ocean currents can influence global weather patterns is a phenomenon known as the El Niño/Southern Oscillation (ENSO). This phenomenon begins as the annual warming of the waters off the coast of Peru. In years when this phenomenon is stronger and more persistent than usual, it can bring drought, storms, and floods to far-flung locations around the globe.

El Niño and the Southern Oscillation are actually two different but interrelated and simultaneous events. El Niño, Spanish for "child," was given its name by the residents of the Peruvian coastal area. The name refers to the Christ child, since El Niño usually occurs around Christmas.

The waters off the coast of Peru are typically quite cold and rich in nutrients, the ideal habitat for fish. The area is known particularly for its anchovy populations. Once a year, however, warm waters move in from the equatorial region. These waters are nutrient-poor and unable to sustain fish. Most years, this warming persists for only a month or so before the cold waters return. Occasionally—usually once every three to seven years—the warm waters do not leave. When they remain for a year or two, the period is called a major El Niño event.

The most immediate consequence of a major El Niño event is felt by the coastal Peruvians, whose fishing-based economy is disrupted. Since the warm water is inhospitable to marine life, dead fish, gulls, and marine plants litter the beaches. Their decomposing carcasses and resultant increase of bacteria in the water produce a foul odor. A major El Niño event even affects the poultry industry in the United States, since fish meal produced in Peru is fed to chickens here. Meteorologists did not begin to learn about the larger impact of a major El Niño event and its connection with the Southern Oscillation until the 1950s.

One sign that El Niño has arrived is the dwindling of fish populations, especially anchovies.

The Southern Oscillation is the name given to the shifting pattern of air pressure that occurs between opposite ends of the Pacific Ocean in the Southern Hemisphere. Generally, pressure is higher over the eastern Pacific, near South America, and lower over the western Pacific, near Australia. This pressure gradient drives the trade winds westward, and toward the equator. Every few years, however, this pressure differential reverses. Since surface water circulations and sea level are also driven by trade winds, the Southern Oscillation has long-range effects. Weather patterns are disrupted not only throughout the Pacific region of the Southern Hemisphere but into the Northern Hemisphere as far north as Alaska and northern Canada.

That major El Niño events and the Southern Oscillation occur in the same years (these are commonly referred to as "ENSO years") is no coincidence. The warming of the waters off the coast of Peru results in a decrease of air pressure in the eastern Pacific. As a result, the air pressure in the western Pacific rises.

At present, ENSO is being widely studied by meteorologists. Even as meteorologists learn to predict more easily when El Niño years will occur, they still find it difficult to predict how ENSO will influence the weather at different locations. Unlocking the mystery of ENSO will surely be of great value in making long-range predictions of future weather (forecasts) and climatic change.

[*See Also* **Clouds; Fog; Forecasting; Human Influences on Weather and Climate; Hurricane; Local Winds**]

For More Information

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Climate

Climate is the weather experienced by a given location, averaged over several decades. A region's climate tells how hot or cold, wet or dry, windy or still, and cloudy or sunny it generally is. It also tells whether these conditions prevail year-round or if they change with the seasons.

Throughout history, climate has been an important factor in determining where groups of people choose to settle. While humans are resourceful enough to survive almost anywhere on the planet, most population centers are in areas where temperature and rainfall are adequate to sustain some form of agriculture. There are fewer settlements in regions of extreme dryness or cold, such as deserts or the arctic. Climate also influences how people live. It largely defines choices of architecture, clothes, food, occupation, and recreation.

Climate is determined not only by average weather conditions but also by seasonal changes in those conditions and weather extremes. Thus, for example, a climate can be described as hot and wet year-round, frigid and dry year-round, or warm and rainy in the summer and cold and dry in the winter. Certain parts of Asia and Africa have monsoon climates, meaning they are warm year-round and relatively dry for half the year yet experience heavy rainfalls over the other six months. In other regions of the world severe blizzards or hurricanes are irregular, yet not uncommon, occurrences.

The climates of the world are differentiated by many factors, including latitude (distance north or south of the equator), temperature (the degree of hotness or coldness of an environment), topography (the shape and height of land features), and distribution of land and sea. Climate is also defined by the plants that exist in a region. What's more, climate is not a fixed property of a region. The climate has changed considerably

WORDS TO KNOW

acid precipitation: rain and snow that are made more acidic by sulfuric and/or nitric acid in the air.

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

continental drift: the theory that over the last 200 to 250 million years, forces deep within Earth's core have caused the single huge continent to break apart and continents to drift around the globe.

cosmic rays: invisible, high-energy particles that bombard Earth from space.

dendrochronology: the study of the annual growth of rings of trees.

dew point: the temperature at which a given parcel of air reaches its saturation point and can no longer hold water in the vapor state.

eccentricity: the alternating change in shape of Earth's orbit between a circle and an ellipse.

equinoxes: the days marking the start of spring and fall and the two days of the year in which day and night are most similar in length.

evaporation: fog that is formed when water vapor evaporates into cool air and brings the air to its saturation point.

extratropical cyclones: a storm system that forms outside of the tropics and involves contrasting warm and cold air masses.

front: the dividing line between two air masses.

global warming: the theory that average temperatures around the world have begun to rise, and will continue to rise, due to an increase of certain gases, called greenhouse gases, in the atmosphere. Also called enhanced greenhouse effect.

haze: the uniform, milky-white appearance of the sky that results when humidity is high and there are a large number of particles in the air.

horse latitudes: a high-pressure belt that exists at around 30° latitude, north and south, where air from the equatorial region descends and brings clear skies.

over the 4.6 billion years since Earth was formed. It continues to change today, as it will in the future.

Elements of climate The two criteria that are most significant in defining climate type are temperature and precipitation (water that originates in the atmosphere and falls to the ground). These criteria, in turn, are influenced by a number of atmospheric, oceanographic, and topographic factors, such as: uneven heating of Earth by the Sun; distribution of land and water; ocean currents; wind circulation patterns; the locations of high- and low-pressure systems; mountain ranges; and altitude. Elements of secondary importance to defining climate are winds, humidity, air pressure, and sunshine versus cloud cover.

Temperature There are two temperature statistics that are relevant to climate: annual mean (average) temperature and annual temperature range. To calculate the annual mean temperature, you need a year's worth of daily mean temperatures. A daily mean is the average of a day's maximum and minimum temperatures. For instance, if a day's high temperature is 60°F (15°C) and the low is 30°F (–1°C), the average is 45°F (7°C). Then add up the average temperature for every day throughout a year and divide by 365 to get the annual mean. A given location's annual mean temperature can be compared to the world's average, 59°F (15°F), to determine the relative warmness or coldness of that location's climate.

The annual temperature range is found by subtracting the year's lowest mean monthly temperature from the year's highest mean monthly temperature. Thus, if a city averaged 80°F (27°C) in July, its hottest month, and 40°F (4°C) in January, its coldest month, it would have an annual temperature range of 40 degrees. Some places in the United States, such as San Francisco, California, have a temperature range as small as 10 degrees. The annual temperature range reveals whether or not a location experiences different seasons, which is just as important as the annual mean temperature in identifying climate type.

Standardized global temperature information has been corrected for the influences of topography by a process known as "adjustment to sea level." Temperature drops at a rate of 3.6°F for every 1,000 feet (300 meters) you ascend above sea level. Thus, when taking the temperature on a mountain at a height of 4,000 feet (1,200 meters), you would add 14.4 degrees from the reading on the thermometer to find the temperature adjusted to sea level.

If you plot out mean annual sea level temperatures throughout the world, you find bands (called isotherms) that roughly correspond to latitude. Isotherms are imaginary lines connecting areas of similar temperature. That is, temperatures are highest at the equator, decline with increasing latitudes, and are lowest at the poles. This is due to the uneven heating of Earth by the Sun. The Sun strikes Earth most directly near the equator and most indirectly (at the steepest angle) at the poles. The atmosphere, through the movement of global winds, strives to even out the distribution of heat but does not totally erase these differences.

The isotherms veer from their paths where landmasses meet the sea. This is due to the different heating and cooling behaviors of land and water (water takes longer to heat up and retains heat longer than land does). The bending of isotherms along the coasts is also caused by ocean currents, which carry warm water toward the poles and cold water toward the equator. A third cause of this temperature differential at the coasts is upwelling, the rising up of cold waters from the depths of the ocean.

Precipitation Two measures of precipitation are relevant to determining climate: total annual precipitation and a month-by-month breakdown of when precipitation occurs. The former statistic is an indicator of the overall wetness or dryness of a region, while the latter indicates whether or not a region experiences distinct rainy and dry seasons.

Tropical rain forests, the world's wettest places, receive 60 inches (150 centimeters) or more of rain annually, while deserts and polar regions, the world's driest places, typically receive less than 10 inches (25 centimeters).

The amount of rainfall determines the type of plant and animal life a region can support. However, the distribution of precipitation throughout the year is also an important factor—particularly in relatively dry regions. For instance, if an area receives little total annual rainfall, but most comes during the summer months, that region may be suitable for agriculture. However, if the limited precipitation of a relatively dry region is spread more or less evenly throughout the year, it may not be able to sustain crops.

Wet and dry regions are scattered across the globe. There are some general trends, however, that correspond to global air circulation patterns. For instance, around the equator, where the trade winds (dominant surface winds that blow from east to west) converge and air rises, precipitation is relatively high. Precipitation is also high, about 60°, in the middle latitudes (the regions of Earth that lie between 30° and 60° latitude), where the westerlies meet the polar easterlies and air rises. Westerlies are global-scale surface winds that travel in the middle latitudes from southwest to northeast in the Northern Hemisphere (the half of Earth that lies north of the equator) and from northwest to southeast in the Southern Hemisphere (the half of Earth that lies south of the equator). Polar easterlies are cold global winds that travel across the polar regions, from the northeast to the southwest in the Northern Hemisphere and from the southeast to the northwest in the Southern Hemisphere.

In the subtropical regions around 30° latitude, where the trade winds meet the westerlies and air sinks, conditions are much drier. Most of the world's deserts are located there. The polar regions, where the polar easterlies converge and air falls, are also characterized by dryness. It should be noted that these latitudes are not fixed. As Earth makes its yearly revolution around the Sun, the amount of sunlight received at each

WORDS TO KNOW

isotherm: an imaginary line connecting areas of similar temperature.

leeward: the eastward side of the mountain, on which cold air descends, producing dry conditions.

middle latitudes: the regions of the world that lie between the latitudes of 30° and 60°, north and south. Also called temperate regions.

monsoon: rainy season that occurs during the summer on tropical continents, during which the land becomes warmer than the sea beside it.

obliquity: the angle of the tilt of Earth's axis in relation to the plane of its orbit.

ocean currents: the major routes through which ocean water is circulated around the globe.

orographic lifting: the upward motion of warm air that occurs when a warm air mass travels up the side of a mountain.

ozone layer: the layer of Earth's atmosphere, between 25 and 40 miles (40 and 65 kilometers) above ground, that filters out the Sun's harmful rays. It consists of ozone, which is a form of oxygen that has three atoms per molecule.

paleoclimatologist: a scientist who studies climates of the past.

permafrost: a layer of subterranean soil that remains frozen year-round.

polar easterlies: cold, global winds that travel across the polar regions, from the northeast to the southwest in the Northern Hemisphere and from the southeast to the northwest in the Southern Hemisphere.

radioactive dating: a technique used to determine the age of rocks that contain radioactive elements, which works on the principle that radioactive nuclei emit high-energy particles over time.

rain shadow effect: the uneven distribution of precipitation across a mountain, with most of the precipitation falling on the windward side and very little falling on the leeward side.

semipermanent highs and lows: the four large pressure areas (two high-pressure and two low-pressure), situated throughout the Northern Hemisphere, that undergo slight shifts in position, and major changes in strength, throughout the year.

smog: common name for photochemical smog, a layer of hazy, brown air pollution at Earth's surface comprised of surface ozone.

sunspots: areas of magnetic disturbance on the surface of the Sun, sometimes referred to as "storms."

topography: the shape and height of Earth's surface features.

trade winds: dominant surface winds near the equator, generally blowing from east to west and toward the equator.

transpiration: the process by which plants emit water through tiny pores in the underside of their leaves.

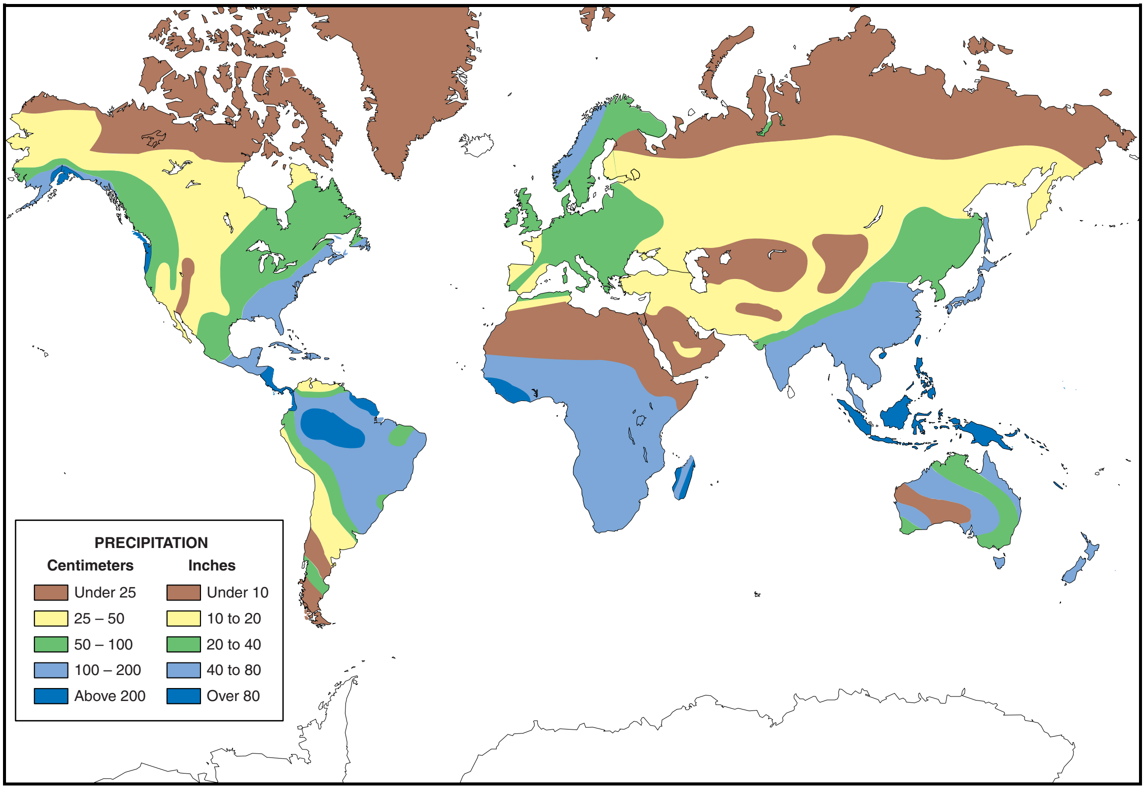
tropical storm: a tropical cyclone weaker than a hurricane, with organized bands of rotating thunderstorms and maximum sustained winds of 39 to 73 mph (63 to 117 kph).

upwelling: the rising up of cold waters from the depths of the ocean, replacing the warm surface water that has moved away horizontally.

virga: rain that falls from clouds but evaporates in mid-air under conditions of very low humidity.

westerlies: global-scale surface winds that travel from the southwest to the northeast in the Northern Hemisphere, and from the northwest to the southeast in the Southern Hemisphere, between about 30° and 60° latitude.

windward: the westward side of a mountain, on which warm air ascends, forms clouds, and yields precipitation.



Global precipitation map.

latitude changes, causing northward and southward shifts in wet and dry latitudes.

Precipitation is also connected with temperature in that warm air can hold more moisture than cold air. In the polar regions, the air holds so little moisture that precipitation is a rare event. This situation stands in contrast to the tropics, where warm air holds an abundance of water and rain is plentiful.

Another factor influencing precipitation is topography. As air travels over a mountain, orographic lifting, the upward lifting of warm air that occurs when a warm air mass travels up the side of a mountain, results in cloud formation and precipitation. Thus, the west (windward) side of a mountain range receives ample rainfall while the east (leeward) side stays relatively dry.

The positions of large-scale high and low pressure systems around the globe are a final factor influencing precipitation. These storm-producing and storm-directing zones are influential in determining the westerly and easterly (horizontal) patterns of precipitation.

Climates of the world Although most people are familiar with certain climate types, such as tropical rain forest, desert, and tundra, no universally accepted, official system of climate designation exists. The first system to be used widely among scientific circles was the Köppen system, developed in 1918 by German meteorologist Wladimir Köppen (1846–1940). Köppen divided the world into five climate types, based primarily on precipitation and secondarily on temperature. They are humid tropical; arid (dry); humid subtropical; humid temperate; humid cold; and polar. Köppen then broke each of these climatic regions down into subclimates.

In the early 1930s, American climatologist C. Warren Thornthwaite (1899–1963) proposed another system, the Thornthwaite classification. He later revised the system in 1948 and again in 1955. Thornthwaite's system is based largely on precipitation levels but also takes into account the rate at which moisture returns to the atmosphere by evaporation (the process of water changing from a liquid to a gas) and transpiration (water lost through plant leaves and stems). He developed an index using the ratio of precipitation to evaporation and added a factor called potential evapotranspiration, the total amount of water that would be produced by a combination of evaporation and transpiration, given sufficient precipitation. He translated this formula into five different climate types named for their characteristic vegetation: rain forest, forest, grasslands, steppe, and desert.

Most of the classification schemes found in textbooks today, including the one presented here, are some combination of Köppen's and Thornthwaite's systems. In this chapter, the climates of the world will be described in the following general categories, some with subdivisions: humid tropical; dry; subtropical; temperate; subpolar; polar; and mountain.

Note: It would be helpful to have a world atlas beside you while reading this section to better understand the locations of the regions described.

Humid tropical climates Humid tropical climates, as the name implies, are warm and wet. The mean temperature for any month seldom falls below 64°F (18°C), so there is no winter. But there is plenty of rainfall in these climates. They receive on average about 60 inches (150 centimeters) of rain per year, which may be concentrated over a few months or spread throughout the entire year.

A key reference to: Climate types (hot/wet to cold/dry)

Rain forest: warm and rainy all year long. Covers portions of South America, eastern Central America, Caribbean Islands, central Africa, East Indies, eastern Madagascar, and Myanmar.

Monsoon: warm year-round with very rainy (flood-prone) summers and relatively dry winters. Covers much of southern and southeastern Asia, the Philippines, coastal regions of northern South America, and slices of central Africa.

Savanna: warm year-round with rainy summers and drought-prone dry winters; receives less rainfall than monsoon climates. Covers much of south-central and eastern Africa, portions of India, western Central America, Brazil, southern Florida, southeast Asia, and northern Australia.

Desert: world's driest regions, with less than 10 inches (25.4 centimeters) of rainfall annually; warm and cold varieties. Examples of warm deserts include: the Sahara (Africa), the Great Sandy (Australia), and the Mojave and Sonoran (southwestern United States). Examples of cold deserts include: the Atacama (Chile), the Great Basin (Nevada), and the Gobi (Asia).

Steppe: semidry grasslands (receive less than 20 inches [50.8 centimeters] of rainfall annually) that occur in the rain shadow of a mountain range or on the edge of a desert. Covers portions of central Mexico, southern South America, northwestern Africa, west-central Asia, and the western United States.

Humid subtropical: hot, muggy summers and mild, wet winters. Covers the southeastern United States, eastern China, southern Japan, southeastern South America, and the southeastern coasts of Africa and Australia.

Marine: long, cool summers and mild winters; coastal climate characterized by low clouds, fog, and drizzle for much of the year. Covers the coastal areas of the northwestern United States, the British Isles, New Zealand, western France, and southeastern South Africa.

Mediterranean: relatively dry climate with dry summers and rainy, mild winters. Covers the following coastal lands: those surrounding the Mediterranean Sea, central and southern California, southwestern Africa, southeastern and southwestern Australia, and central-western Chile.

Temperate: four distinct seasons with warm, humid summers and cold, snowy winters. Covers the northeastern United States and southern Canada, and parts of central Europe, central Asia, southeastern Chile, southern Australia, and New Zealand.

Subpolar: cold northern climate with long, harsh winters and short, cool summers. Covers Alaska and most of central and northern Canada, northern Europe, and northern Asia.

Tundra: bitterly cold winters and cool summers; for at least one month of the year the average temperature is above freezing. Covers the northern portions (except for the northernmost extremes) of North America, Europe, Asia, Iceland; and the coasts of Greenland and Antarctica.

Arctic: barren lands of snow and ice that never thaw. Covers Ellesmere Island and the northern section of Baffin Island (Canada), and the interiors of Greenland and Antarctica.

Humid tropical climates are located in belts that are 20- to 40-degrees wide on either side of the equator. They cover the largest portion of Earth of any climate zone. They account for nearly 20 percent of the land and 43 percent of the oceans, totaling 36 percent of Earth's surface. This category is subdivided into three specific climate types: rain forest, monsoon, and savanna.

Rain forest Rain forests are warm regions in which the rainy season usually lasts all year. Average rainfall for each month is over 2 inches (5 centimeters), and annual total rainfall usually exceeds 60 inches (150 centimeters). In some areas it may exceed 160 inches (400 centimeters) annually. On most days, heavy showers fall in the afternoon and skies clear by the evening.

Tropical rain forests exist at low elevations in regions very close to the equator. They cover the Amazon lowland of South America, portions of eastern Central America and the Caribbean Islands, the Congo River basin of Africa, the coastal area of western Africa, the East Indies from Sumatra to New Guinea, and a slice of Myanmar in southeastern Asia. Tropical rain forests also exist in isolated areas, such as the Atlantic coast of Brazil, the Pacific coast of Colombia, the Guiana highlands in northern South America, and eastern Madagascar.

Tropical rain forest in Ecuador. ©WOLFGANG KAEHLER/ CORBIS.

Because of their proximity to the equator, rain forests experience about the same number of daylight hours year-round. Therefore, the annual temperature range is small, generally less than 6°F (3.3°C). The biggest change in temperature comes between day and night. The average daytime temperature is around 90°F (32°C), while the average nighttime temperature is about 72°F (22°C). The high humidity and cloud cover prevent the temperature of the rain forest from rising as high as it does on summer days in the subtropics and even in some parts of the temperate latitudes.

Tropical rain forests are also called tropical wet climates. They are noted for their abundant and varied plant and animal life. Whereas rain forests cover only 7 percent of the world's land, they contain 50 percent of all species of plants and animals. This total includes over 1.5 million species of plants and animals, the greatest biodiversity in the world.

Plants grow at all different heights throughout the rain forest, from the canopy (the uppermost spreading branchy layer of a forest) to the floor. The largest plants are the towering, broadleaf evergreens, such as mahogany and kapok trees. These trees block out most of the sunlight. Near the forest edge and in clearings where sunlight penetrates, vines and shrubs predominate. The undergrowth there is so thick that it's often impossible to walk through.

The great variety of plants provides sustenance for an equally impressive array of animals. In a rain forest, you will find animals occupying every possible niche: monkeys in the treetops; colorful birds such as toucans and parrots flying overhead; lizards scaling tree trunks; frogs, snakes, and insects on the ground; and termites tunneling underground. During the day, iguanas can be seen basking in the Sun while armadillos stay in their burrows to keep cool. Several species, such as fruit bats, moths, and caimans (cousins of the crocodile), become active at night.

Monsoon In this type of tropical climate, the year is divided into dry and rainy seasons. While monsoon regions generally receive as much total annual rainfall as do rain forests, the precipitation is concentrated in the summer months. Typically, about 120 inches (300 centimeters) of rain falls during the rainy season, causing destructive flooding. Rainfall in the spring and fall is moderate while the months of December, January, and February are dry. The official designation of a monsoon climate is one in which monthly precipitation drops below about 2 inches (6 centimeters) for one or two months of the year.

The name *monsoon* comes from the Arabic word “mausim” for “season.” A monsoon is actually a seasonal reversal of wind patterns. During winter, when the monsoon area is tilted away from the Sun, the winds that sweep across the region are primarily trade winds, blowing out toward the sea. These winds bring warm, dry air to the region. When spring arrives, the winds shift and carry moisture from the Indian Ocean over the land. At this time of year, the monsoon area is almost directly beneath the Sun. The land is heated intensely, which causes the surface air to rise. This air is replaced by the moist winds, which produce heavy rains that last throughout the summer months.

While monsoon climate is limited mostly to southeast Asia, a full 50 percent of the world’s population lives in that area. The monsoon region encompasses most of India; the Indus Valley of Pakistan; portions of Nepal, Bhutan, Bangladesh, Myanmar, Malaysia, Vietnam, Thailand, Laos, and the Philippines; and the southeast tip of China. Some Atlantic coastal regions of northern South America also experience monsoon climate, as do parts of central Africa.

The total annual rainfall in monsoon regions is generally sufficient to sustain forests, even through the dry period. In some areas, these forests resemble rain forests, while in other areas the forests are less dense and

Monsoon lightning storm over the California desert. ©GENE BLEVINS/LA DAILY NEWS/ CORBIS.

merge into scrublands. These lands are cultivated primarily with rice, a crop that thrives on flooding.

Animals that have evolved to survive in both wet and dry seasons live in monsoon regions. One example is the collared anteater, which eats ants in the wet season and termites in the dry season. Another example is the iguana, a reptile that can regulate temperature by changing its skin color and water loss by concentrating its urine.

Savanna A savanna (sometimes spelled "savannah") is a relatively flat land covered with coarse grasses that are several feet tall, and scattered, stunted deciduous trees such as baobabs and acacias. Like a monsoon climate, this climate is tropical, with wet and dry seasons. Yet the dry periods in savanna regions last longer than in monsoon regions, and annual precipitation is much lower.

Savannas are located farther from the equator than are rain forests and monsoon climates. While savannas are most common in south-central and eastern Africa, they also exist in the following locations: central and eastern India, western Central America, areas of Brazil north and south of the Amazon basin, southern Florida, parts of southeast Asia, and northern Australia.

Savannas usually receive between about 30 and 60 inches (75 and 150 centimeters) of rainfall annually, much less than rain forests and monsoon regions receive. In general, the farther a savanna is from the equator, the lower its annual rainfall. The amount of rainfall in savannas is not at all predictable, either from month to month or from year to year. In a single year, a devastating flood may be followed by a severe drought. A relatively wet year may be followed by one that is quite dry.

For at least five months out of each year, the savanna rainfall typically totals less than 2 inches (6 centimeters) per month. The dry season occurs during the winter months (December, January, and February), when high pressure systems are prominent in the region. In the summer, low-pressure systems predominate, and rainfall is abundant.

In addition to wet and dry seasons, a savanna has seasonal shifts in temperature. While the mean temperature stays above about 70°F (21°C) even in the coolest months, it hovers closer to 80°F (27°C) in the warmest months (March, April, and May). In the warm months, afternoon temperatures often range between 90 and 100°F (32 and 38°C).

African savannas are teeming with wildlife. Those grasslands are regions where lions, leopards, wild dogs, and other carnivores relentlessly

A herd of zebra graze on the savanna grasslands in Kenya. JLM VISUALS.

pursue speedy and well-camouflaged herbivores like antelopes, gazelles, and zebras.

Dry climates There are two types of climate considered to be dry or arid: deserts and steppes. While deserts are the drier of the two, in neither climate does annual rainfall keep pace with the rate at which water is lost due to evaporation and transpiration. Dry climates are generally found in the region between 15° and 30° latitude (although sometimes at higher latitudes) and are sometimes bordered by mountain ranges. They cover about a quarter of the world's landmass. That total is greater than for any other climate type.

A climate's designation as dry depends on both its annual rainfall and its temperature. The mean temperature must be high enough to result in the evaporation of what little rainfall there is. To illustrate this point, consider the annual rainfall received by a hot New Mexico desert. If that same amount of precipitation were to fall on cold northern Canada, it would be enough to sustain a conifer forest.

Dry climates usually receive their sparse rainfall during the summer months, when temperatures are higher and evaporation occurs more readily. However, this rainfall is often quite irregular. One location may go two years without a drop of rain, then receive four inches in a single downpour.

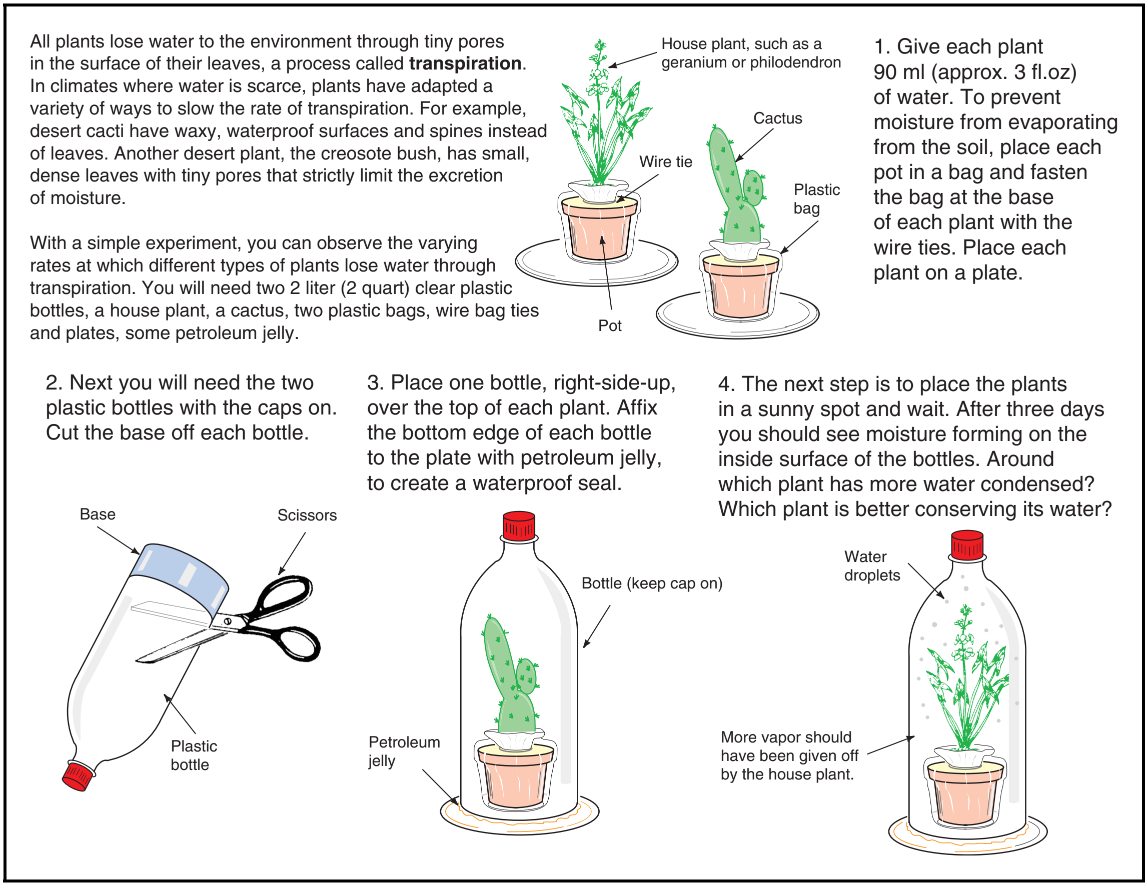
Desert Deserts are the world's driest regions. These true arid climates receive less than 10 inches (25 centimeters) of rainfall a year. Often, precipitation over these lands takes the form of virga, streamers of water that evaporate into the dry air before they even reach the ground.

Deserts come in hot and cool varieties. Hot deserts, which have no cool season, are the hottest places on Earth. Their mean temperature remains above 65°F (18°C) year-round. Cool deserts, on the other hand, have an annual mean temperature below 65°F and, for at least one month out of the year, a mean temperature below 45°F (7°C).

The daily temperature in both hot and cool deserts fluctuates greatly. The reason for this fluctuation is that little humidity is available to absorb incoming sunlight during the day and virtually no cloud cover to trap the heat escaping from the surface at night. In hot deserts, daytime temperatures commonly hover between 105 and 115°F (41 and 46°C) and sometimes exceed 120°F (49°C), while at night it cools off to around 75°F (24°C). Occasionally, during the winter months, the temperature at night in hot deserts drops below freezing. In cool deserts, afternoon temperatures in the summer often reach 105°F. However, it is not uncommon for nighttime temperatures in winter to dip below 30°F (–1°C).

The world's hot deserts are located in the subtropics between 15° and 30° latitude north and south, near the Tropic of Cancer and the Tropic of

Sonoran desert in the Saguaro National Monument in Tucson, Arizona. FIELD MARK PUBLICATIONS.



Plant water-loss experiment.

Capricorn. Also known as the horse latitudes, these regions contain a high-pressure belt where air from the equatorial region descends, bringing warmth and clear skies. During the summer months, the Sun is directly overhead and produces the searing heat for which these deserts are famous. Some of the deserts in this region include the Sahara of Africa; the Great Sandy Desert of Australia; and the deserts of the North American southwest and Mexico, such as the Mojave and the Sonoran.

Cool deserts are located far inland and removed from any source of water in the middle latitudes, which lie between the latitudes of 30° and 60°. Many of these are in the rain shadow of tall mountain ranges, where precipitation is often less than 5 inches (13 centimeters) annually. Examples of deserts in this category include the Atacama Desert in Chile at the base of the Andes Mountains; the Great Basin in Nevada at the base of the Sierra Nevada; the deserts of Nepal and northern India at the base of the Himalaya Mountains; and the Gobi in Asia.

Most deserts do have some vegetation although not a great deal. This vegetation takes the form of drought-resistant plants such as cacti, which store water in their stems and have waxy coverings that diminish transpiration, and scrubby plants like the creosote bush, which has an extensive root system. There are also a variety of wildflower species that pop up quickly following a rain only to drop their seeds and whither away once the soil dries.

Animals of the desert have adapted to the limited supply of water and food in many different ways. The camel, for instance, stores water and fat in its hump, reabsorbs moisture from exhaled air, and sweats only when its body reaches extremely high temperatures. The angulate tortoise of Africa stores water in its bladder, and reptiles retain moisture due to their thick, scaly skin. Other animals, such as snakes, spend the heat of the day in a burrow, while rabbits seek out the shade of a bush. Perhaps the ultimate example of an animal adapted to desert life is the kangaroo rat. Found in deserts of the American southwest, this rodent gets all the moisture it needs from solid food and can go its entire life without drinking a drop of water.

Steppe A steppe is a semiarid climate, meaning that it receives somewhat more rain than a desert. Steppes can be found along the edges of deserts and serve as transition zones between arid and moist areas. Annual precipitation in steppes generally measures between 8 and 20 inches (20 and 50 centimeters), all of which falls during a short wet season. This precipitation is enough to sustain short, coarse bunch grass called steppe (from which the climate gets its name), clumps of low bushes, sagebrush, and isolated trees.

Expansive steppes can be found in central Mexico, southern South America, northwest Africa, west central Asia, and surrounding the desert of central Australia. In the United States, regions with steppe climate are called prairies. These regions include the Great Plains (east of the Rocky Mountains), valleys on the northern boundaries of the Great Basin, and along the southern coasts of California.

An example of a city with a steppe climate is Denver, Colorado, which has an annual mean temperature of 50°F (10°C). Its monthly mean temperature fluctuates from 30°F (–1°C) in January to 75°F (24°C) in July, giving it an annual temperature range of 45°F (7°C).

Steppe grasslands in western North America. FMA, INC.

Denver receives 15 inches (38 centimeters) of precipitation yearly, most of which falls between April and July.

The large animals living in steppes are primarily migratory, grazing mammals. Examples of these include deer and antelope in the United States; gazelles and ostriches in Africa; camels in Asia; and rodents that live on or under the ground, such as prairie dogs in the United States, gerbils in Africa, and hamsters in Asia.

Subtropical climates Subtropical climates are those with distinct summer and winter seasons and sufficient rainfall to keep them from being classified as dry. At least eight months of the year they have mean temperatures above 50°F (10°C) and at least one month has a mean temperature below 65°F (18°C). An important criterion of a subtropical climate is that the winters are mild. The mean temperature of the coldest month always stays above 25°F (–4°C).

These climates are situated within a band running from about 25° to 40° north and south of the equator. This band begins at the edge of the tropics and extends through the warmer half of the middle latitudes, to the edge of the temperate zone. There are three distinct types of moist subtropical climates: humid subtropical, marine, and Mediterranean.

Humid subtropical The most outstanding characteristic of a humid subtropical climate is its hot, muggy summer. The mean temperature during the summer months is about 75° to 80°F (24 to 27°C). The nighttime temperature seldom drops below 70°F (21°C) and during the day it often rises to more than 100°F (38°C). Intense heat waves are not uncommon and sometimes last for weeks. The relative humidity is high, even during the heat of the day, which makes for even more oppressive conditions. The dew point (the temperature at which water condenses out of the air) is often above 75°F.

Winters are generally mild and, on the lower-latitude end (closest to the equator) of a humid subtropical region, it is rare for temperatures to fall below freezing. On the higher-latitude (poleward) end, frost and snow are more common, but heavy snowstorms are still rare. Conditions change rapidly in winter. One day's warm, sunny weather can give way to the next day's cold rain.

Rainfall is plentiful throughout the year, totaling between 30 and 65 inches (about 75 and 165 centimeters) annually. Afternoon thunderstorms are common in the summer, as is precipitation from the edge of tropical storms. Much of the rain and snow in winter is associated with eastward-moving storm fronts.

This type of climate is found along the east coasts of most continents, between 25° and 37° latitude. It covers the southeastern United States, eastern China, southern Japan, southeastern South America (Uruguay, Paraguay, and southern Brazil), and the southeastern coasts of Africa and Australia. These locations are mostly on the western sides of subtropical high-pressure systems, placing them in the path of maritime tropical air that originates near the equator and is directed toward the poles.

Since the growing season lasts from eight months to a year, depending on location, this climate is well suited for many types of agriculture. The natural plant cover consists of thick deciduous and coniferous woodlands at the eastern edge of these zones, graduating to prairies on the western edge.

There is a minor subset of humid subtropical climate, examples of which include Portugal and the Canadian Pacific coast, that have mild, rainy winters, and cool, dry, short summers. During winter in these places, the ocean winds keep the air warmer than it is farther inland. The average temperature for the warmest months in these regions never exceeds 72°F (22°C) and three times as much rain falls during the winter as during the summer.

Marine Marine climate, also known as Marine West Coast climate, features cool summers and mild winters, yet the summers are longer than they are in the humid subtropical climate of Pacific Canada. Precipitation is plentiful year-round in marine climates, and there is a relatively small annual temperature range. Some parts of the world with a marine climate are the west coasts of northern California, Washington, and Oregon; the British Isles; New Zealand; the west coast of France; and the southeast coast of South Africa.

This climate is characterized by the presence of low clouds, fog, and drizzle for much of the year, as well as regular rainfall and occasional snowfall. The temperatures are generally high enough that if snow does fall, it melts quickly. These conditions, plus relatively stable temperatures year-round, are largely the result of the prevailing westerly winds that bring ocean air into these regions.

On the U.S. northwest coast, rainfall is higher in the winter than in the summer. The reason for this pattern is the subtropical Pacific high-pressure system that directs storms away from the coast in the summer. It is common to find thick stands of coniferous and deciduous trees in marine climates.

Mediterranean The primary factor that distinguishes Mediterranean climates from other subtropical climates is that it has dry summers. In areas with a Mediterranean climate, there are four to six months each year with little or no rainfall. At least three times as much rain falls in the wettest (winter) month as in the driest (summer) month. Total rainfall for the year is between about 15 and 35 inches (38 and 89 centimeters).

The summer dryness is caused by subtropical high pressure systems located over the water, which produce sinking air and direct storms poleward, away from the coasts. The position of these highs shifts towards the equator in the summer, allowing mid-latitude storms (with plenty of rain) to enter the region.

The summer high temperatures are lowest at points nearest to the water's edge. This effect is caused by upwelling, the churning up of cold water from the depths of the ocean, which chills the coastal air. As one moves inland, the summers are hotter (and the winters are colder, too).

The largest region with a Mediterranean climate consists of the coastal lands surrounding the Mediterranean Sea. Specifically, this region includes the Iberian Peninsula (Spain and Portugal), southern France, most of Italy, western Serbia and Montenegro, Greece, southern

Scrubland atop this plateau in southern France is typical of a Mediterranean climate. ©SALLY A. MORGAN; ECO-SCENE/CORBIS.

Bulgaria, the coasts of Turkey and Israel, and the Mediterranean coast of northern Africa. This region's reputation for warm, sunny summers attracts crowds of tourists from around the world each year.

Other parts of the world with a Mediterranean climate include the central and southern California coast, the southwestern tip of Africa, the southeastern and southwestern edges of Australia, and a small area on the west coast of central Chile.

The irregular rainfall and preponderance of summer wildfires means that the only types of vegetation that can survive in this climate are shrubs, dwarf trees, and grasses. The shrubs have extensive root systems, enabling them to gather what little moisture exists in the soil. The leaves of Mediterranean plants also have moisture-conserving designs. For instance, some leaves have hard, waxy surfaces; some are hairy; and others curl up when it's dry. The olive tree has gray-colored leaves, which reflect sunlight.

Mediterranean vegetation is also adapted to periodic wildfires. After a fire, many will resprout from their roots. Some plant species, such as the knobcone pine, actually depend on fire for their propagation. The cones of these trees open and release seeds only in the extreme heat of a fire. If there is any doubt about the ability of scrubland vegetation to withstand wildfires, one only has to witness the rapid growth that follows in the wake of the burn.

The native animal inhabitants of these lands are deer, rabbits, wolves, and numerous rodents such as squirrels, voles, and mice. In some regions, like California and southern Europe, cows, goats, sheep, and other domesticated grazing animals are now the dominant species.

Temperate climates Temperate climates are those that have four distinct seasons. The criterion that differentiates them from subtropical (the next warmest) climates is that for a least one month of the year the mean temperature in a temperate climate is below 25°F (–4°C). Temperate climates can be distinguished from subpolar (the next coldest) climates in that they have at least one month in the year in which the mean temperature is above 70°F (21°C).

All temperate areas have warm, humid summers and cold, snowy winters, although the average monthly temperatures and precipitation levels vary considerably from one place to another. Total annual precipitation ranges from 20 to 40 inches (50 to 100 centimeters) and is steady throughout the year.

Temperate climates are situated mostly between 40° to 60° latitude, primarily in the Northern Hemisphere. They cover the northeastern United States, southern Canada, and parts of central Europe and central Asia. In the Southern Hemisphere, where there is very little land mass south of the 40th parallel, temperate climates exist only in the southeastern portion of Chile, the southern tip of Australia, and New Zealand.

A northern temperate spruce forest on Bonaventure Isle, Quebec, Canada. JLM VISUALS.

Toward the lower-latitude end of a zone of temperate climate, summers are hotter and more humid than they are in the higher latitudes. High temperatures in the summer are often over 90°F (32°C) in the lower latitudes, and there are five or six months of the year during which temperatures never dip below freezing. This means that the growing season is long enough to cultivate a variety of crops. In those same locations, the winter is cold and blustery with significant snowfall.

In the colder temperate areas, winter is harsher and longer, summer is milder and shorter, and spring and fall are merely quick transitions between winter and summer. Typically, there are only three to five months a year with no frost. During the summer, high temperatures rarely exceed 90°F (32°C) while in the winter the temperature may drop below –22°F (–30°C) and can remain below zero degrees for weeks on end.

The most common type of vegetation found in temperate areas is the deciduous forest. A deciduous forest contains trees such as oak, hickory, maple, beech, ash, and birch. In some areas there are also stands of conifers (evergreens) such as pine, spruce, and fir. In the autumn, a chemical transformation occurs within the leaves of deciduous trees, causing them to turn brilliant shades of red, orange, and yellow. In the spring, before the thick blanket of leaves has fully emerged, wildflowers dot the forest floor.

A great variety of birds, mammals, reptiles, and insects inhabit temperate areas. While many species of birds and some mammals migrate to warmer regions for the winter, other animals have developed methods of surviving through the cold months. Squirrels, for instance, store enough food in the summer and fall to last through the winter. Turtles find a deep, muddy burrow in which to hibernate. With many insect species, the adults die before the onset of winter, and their eggs hatch the following spring.

Subpolar climate The subpolar climate zone is a cold, northern climate, found generally between 50 and 70° north latitude. It is dominated by a nearly continuous coniferous forest called the "taiga" or "boreal forest." Specifically, this region includes Alaska, central and northern Canada (except for the northernmost fringe), northern Europe (except for the north of Scandinavia), and northern Asia (except for the northern and southern fringes of Siberia). There is no subpolar land in the Southern

Hemisphere because, except for the very southernmost tip of South America, no land exists at these latitudes.

Subpolar climate is characterized by long, harsh winters and short, cool summers, with a wide range of temperature variation between the coldest and warmest months. The factor that distinguishes subpolar climates from neighboring, colder polar climates is that subpolar climates have one to three months in which the mean temperature is above 50°F (10°C). There is no limit, however, defining the cold end of the subpolar temperature range. In northern Siberia, for instance, the coldest monthly average temperature sometimes drops below –35°F (–37°C).

The cold air of subpolar regions retains little moisture. Thus there is little cloud formation and hence, light precipitation. Most subpolar lands receive less than 20 inches (50 centimeters) of precipitation annually. While snowfall is light, the air is so cold that once the snow falls, it remains for months. Because of the low temperatures, large tracts of subpolar land contain permafrost, a layer of subterranean soil that remains frozen year-round.

The short growing season rules out agriculture in the region. The main type of vegetation is conifer trees, such as fir, spruce, larch, and pine, plus a few varieties of deciduous trees, such as birch and alder. Conifers are well-suited to this environment. Their tall, narrow, conical shape

Taiga in Wood Buffalo National Park in Alberta, Canada. ©RAYMOND GEHMAN/CORBIS.

encourages the snow to slide off them, and their needles don't require much moisture to grow.

Large tracts of subpolar land are covered with highly acidic wetlands called bogs. Bogs are comprised primarily of sphagnum moss, hardy grasses, insectivorous plants, pondweeds, water lilies, and algae, as well as a smattering of flowering plants such as blueberry and azalea. When the moss dies, it accumulates as peat, which in some bogs forms a bouncy, carpetlike layer several feet thick.

The mammals of the boreal forest include the lynx and various members of the weasel family (wolverine, fisher, pine martin, mink, ermine, and sable). These animals prey on snowshoe hares, red squirrels, lemmings, and voles. Beaver are abundant, and their dam-building habit is an important part of forest succession. Large mammals of the boreal forest include moose and elk. Insect-eating birds such as wood warblers are migratory, but seed-eating birds (finches and sparrows, evening grosbeak, pine siskin, and red crossbill) and omnivores (ravens) may be year-round residents. All of these birds may move south if food is scarce. Mosquitoes are abundant in the spring.

Polar climate The polar climate, which covers the extreme northern and southern portions of Earth, is the coldest in the world. The warmest month in these regions has an average temperature below 50°F (10°C). It is so cold near the poles because the sunlight strikes the surface there at a very steep angle and remains low in the sky even in the summer. This condition is in stark contrast to the world's hottest regions, where the Sun sometimes shines directly overhead.

The polar area extends, on its warmest boundary, to between 60° and 70° latitude. The coldest points are at 90° latitude, capping the North and South Poles. Lands with polar climates include: the northern reaches of North America, Europe, and Asia; all of Greenland; the northern half of Iceland; and Antarctica.

Polar regions receive less than 8 inches (20 centimeters) of precipitation annually, which is equivalent to that received by a desert. In a desert the air is warm enough for evaporation to exceed precipitation. In polar regions, however, the air is so cold that the meager rate of precipitation is still greater than the rate of evaporation, and the ground never dries out.

The polar climate is divided into two categories: tundra, which experiences a yearly thaw, and arctic, which remains a permanently frozen region.

Tundra Tundra comprises the majority of the polar land in the Northern Hemisphere, with the arctic being restricted to areas close to the North Pole. Due to the virtual absence of land between 50° and 70° latitude south, the only tundra in the Southern Hemisphere lies in narrow strips on the coasts of Antarctica.

In the tundra, the mean temperature of the warmest month is between 30 and 50°F (–1 and 10°C). While the tundra summers are cool, the winters are bitterly cold. An example of a tundra climate is Barter Island, Alaska, at 70° north latitude. The coldest month of the year at Barter Island is February, with an average monthly temperature of –20°F (–29°C). It has three months in which the average temperature is above freezing: in June the temperature reaches 35°F (2°C); and in July and August, 40°F (4°C). Throughout an average year, Barter Island receives about 7 inches (18 centimeters) of precipitation.

Beneath the tundra surface lies a layer of permafrost, frozen subterranean soil, hundreds of yards deep. In the summer the top few feet of soil thaw. Since the moisture can't penetrate the frozen ground below, the surface becomes muddy and swampy. The growing season is so short that only a limited number of small plant species dot the landscape. These include mosses, lichens, sedges, and dwarf trees. The trees are species of willow and birch; in warmer climates they grow several feet tall but in the tundra creep along the ground and are only a few inches tall.

A number of animal species have adapted to life in the tundra. Among them are waterfowl, most of which migrate south for the winter, and mammals with thick layers of insulating fat and fur. The ptarmigan and snowy owl are two birds that remain in the far north year-round. These birds each have a thick covering of feathers all over their body. The ptarmigan even has feathers on its feet. For protection from predators,

What to watch

Moviegoing audiences were captivated in 2005 by the astonishing documentary *March of the Penguins*, a film about the annual mating and child-rearing cycle of Antarctica's emperor penguins. Aside from the incredible appeal of the penguins themselves, one of the most astonishing things about the film was the Antarctic landscape itself, so different from those humans inhabit as to seem almost like another planet. The climate plays a central role in the lives of these unusual birds, and director Luc Jacquet provides a look at the climate rarely before seen. *March of the Penguins* won an Academy Award for Best Documentary Feature, and is available on DVD.

Polar bears thrive in the harsh polar climate. ©KENNAN WARD/CORBIS.

their feathers, like the fur of many animals, change color from brown in the summer to white in the winter.

Some small mammals, such as the arctic ground squirrel, survive the winter by hibernating. Heartier mammals, like the arctic fox, musk ox, caribou, and polar bear, remain active all winter.

Arctic The arctic is a barren land of snow and ice located around the poles in both hemispheres. There the average temperatures for every month are below freezing. In the Northern Hemisphere arctic lands include Ellesmere Island and the northern section of Baffin Island (these islands are part of the Canadian Archipelago) and the interior of Greenland, plus the seas between these lands. In the Southern Hemisphere it includes nearly the whole of Antarctica.

While temperatures vary greatly throughout the arctic, the coldest weather is found in Antarctica. Earth's lowest temperature, –128.6°F (–89°C), was recorded on July 26, 1983, at the Soviet research station Vostok in Antarctica. The station is located at 78° south latitude with an elevation of 11,400 feet (3,475 meters) above sea level. During Vostok's warmest month, December, the average temperature is –30°F (–34°C) and during its coldest month, August, the average temperature is –90°F (–68°C). The warmest temperature ever recorded there was –5.8°F (–21°C).

Antarctica is warmest on its outskirts and coldest in its interior. In the summer months, average temperatures range from 14 to 20°F (–10 to –7°C) near the seas and from about –5 to –20°F (–21 to –29°C) near the center of the continent. In the coldest months the outer areas have average temperatures about –20°F, while average temperatures in the interior are about –95°F (–71°C).

Conditions in the arctic region of the Northern Hemisphere are not much more hospitable. Average temperatures there are about –45°F (–43°C) in January, the coldest month, and about 10°F (–12°C) in July, the warmest month. The coldest temperature ever recorded in

Weather report: Emperor penguins

Emperor penguins are the only animals to breed in the winter on the coast of Antarctica. They can withstand colder temperatures than any other species. These birds maintain a body temperature of 100°F (38°C) even during the winter months, when the air temperature drops as low as –80°F (–62°C).

An emperor penguin is insulated by a thick layer of blubber. It also has waterproof feathers all over its body (even its bill and feet) except for its toes. The penguin is covered with more than seventy-seven feathers per square inch. A fluffy down at the base of each feather traps body heat.

The emperor penguin is the largest of any penguin species, standing 3 feet (just under 1 meter) tall and weighing about 88 pounds (40 kilograms). It also has the highest percentage of body fat of any penguin species and can survive up to four months without eating. The emperor penguin is so well insulated that it actually runs the risk of overheating during periods of physical activity!

An emperor penguin family in Antarctica. ©DLILLC/CORBIS.

Greenland was –87°F (–66°C) on January 9, 1954, at Northice, which is at a latitude of 78° north and an altitude of about 7,685 feet (2,340 meters). Farther south, at a latitude of 71° north, is Eismitte (which means "middle of the ice"). At this location, about 9,940 feet (3,030 meters) above sea level, the average temperature in February, the coldest month, is about –55°F (–48°C) and the average temperature in July, the warmest month, is about 10°F (–12°C).

Perhaps the only climatic factor more remarkable about the arctic than temperature is its patterns of sunlight. Because of the tilt of Earth's axis, day and night at the poles are each six months long. During the summer (March 21 to September 23 in the Northern Hemisphere and September 23 to March 21 in the Southern Hemisphere), the Sun never sets nor does it ever rise much above the horizon. The six months of winter, however, are shrouded in complete darkness. The exception to this pattern is the six weeks of twilight, centered around the spring and fall equinoxes, the days marking the start of spring and fall that are the two days of the year in which day and night are most similar in length. During the six weeks of twilight (from February 7 to March 21 and from September 23 to November 6), the Sun is constantly just below the horizon.

The bitter arctic cold is accentuated by blustery winds, sometimes over 100 mph (160 kph). Snowfall, however, is very light. These regions receive less than 4 inches (10 centimeters) of precipitation annually, most of that during the summer months.

The surface of arctic lands is a permanent ice layer, extending to a depth of thousands of feet. Thus, there is no plant growth. There are, however, some robust animal species that inhabit the mildest fringes of this icy world. Principal among them are emperor penguins, insulated from the elements by a thick layer of fat and a dense coat of feathers. This animal is able to withstand conditions colder than any other and is the only animal species that breeds during the Antarctic winter. Fifteen whale species and six seal species, as well as numerous species of fish, populate the seas surrounding Antarctica. The only animals to inhabit the arctic interior are tiny insects such as springtails and microscopic invertebrate worms such as nematodes and rotifers.

Mountain climates There is no inclusive definition of a mountain climate, also called a highland climate. The reason is that a mountain climate encompasses a whole series of climate types that are found at various points on the way up a mountain. The primary reason that conditions change as you ascend a mountain is that temperature decreases with altitude. Air pressure, humidity, precipitation, and winds also change with altitude. The climates on a mountain form pockets within the general climate of the surrounding region.

Mountain climates can resemble climates found at higher latitudes. In general, each 1,000-foot (300-meter) increase in elevation will produce a change in climate similar to traveling about 185 miles (298 kilometers) towards one of Earth's poles. For every 1,000 feet (300 meters) gained in altitude, the temperature falls about 3.6°F (2.0°C). However, mountain climates are not exact matches to climate zones at higher latitudes because many factors are different. For example, the effects of global atmospheric circulation, extratropical cyclones, and other weather systems are not as significant in mountain climates.

Scrub brush grows on a dry lake bed below the Caliente Mountains in California. ©JOSEPH SOHM/ VISIONS OF AMERICA/CORBIS.

A 13,000-foot-tall (3,960-meter-tall) mountain in the Sierra Nevada range, for example, encompasses five different climate types. A semiarid grassland surrounds the base of this mountain. Along the "foothills," the first 2,000 feet (610 meters), the grassland is gradually replaced by Mediterranean scrubland. From 3,000 to 6,000 feet (915 to 1,825 meters), there is the "montane zone," the climate resembles that of a northern temperate zone, with thick conifer forests. Above 6,000 feet, in the "subalpine zone," thinner stands of stunted conifers resemble a subpolar climate. This zone gives way to tundra at 9,000 feet (2,740 meters), in the "alpine zone." Finally, the mountain is capped with a permanent expanse of snow and ice.

Another notable feature of mountain climates is the uneven distribution of precipitation across a mountain or mountain range, known as rain shadow effect. Mountains have a relatively wet side, called the windward side, and a relatively dry side, called the leeward side. The windward side is the one encountered by approaching air masses. The windward side is on western slopes in the Northern Hemisphere and on eastern slopes in the Southern Hemisphere. The air rides upward along the mountainside, and as it rises, it cools. Once air reaches the dew point, condensation (the process by which water changes from gas to liquid) occurs and clouds form.

The animals that inhabit mountains are, for the most part, migratory. However, they do not follow typical north-south migratory paths. Rather they migrate up and down the mountain. They climb to higher elevations in the summer, when food is more abundant, and escape the harsh alpine winters by climbing down to warmer elevations. Among the wide variety of mountain animals are deer, bears, chipmunks, mountain goats, marmots, and many species of birds. Some animals are specially adapted to survive in

A key reference to: Climates of the United States

Within the continental United States, every climate is represented except the tropical, subpolar, and polar varieties. With 3,623,420 square miles (9,384,658 square kilometers) stretching from 49° latitude on the northernmost edge to 26° latitude on the southernmost edge, the United States contains perhaps a wider assortment of climates than any other nation. They are as follows:

- **Temperate**: northeastern states, from New York to Maine, Michigan, Iowa, Wisconsin, Minnesota, and the eastern portion of the Dakotas.
- **Humid subtropical**: southeastern states, from Pennsylvania to Missouri and every state to the south.
- **Semiarid**: states in the rain shadow of the Rocky Mountains, including Nebraska south through Texas and portions of Montana, Idaho, Wyoming, Colorado, and New Mexico.
- **Arid**: desert areas of New Mexico, Arizona, California, Utah, and Nevada.
- **Marine**: northwestern California and the western portions of Oregon and Washington.
- **Mediterranean**: west coasts of central and southern California.
- **Mountain**: portions of the west coast states (Washington through California) containing the Cascades and Sierra Nevadas, as well as portions of western and plains states containing the Rockies (Montana, Wyoming, Colorado, and New Mexico).

the oxygen-thin air found at high altitudes. One such animal is the guanaco, a relative of the llama, which has an unusually large heart and lungs.

Mountain climates are scattered throughout North America, South America, Africa, Europe, Asia, and the islands north of Australia. Examples of these climates include the Sierra Nevada and the Rocky Mountain ranges in the United States and Canada, the Sierra Madre Range in Mexico and Central America, the Andes in Chile and Peru, the Alps in Europe, and the Himalayas in southern Asia.

History of climate change Throughout Earth's 4.6 billion year existence, the global climate has undergone continuous change. Most of what scientists know about the history of climate change is limited to the most recent 10 percent of Earth's lifetime. The farther back in time, the fewer clues there are about the climate. However, by using the clues that do exist and drawing conclusions based on more recent data, scientists have been able to construct a climatic picture spanning the entire history of Earth.

There have been times when Earth has been alternately warmer and colder than it is today. There have also been several periods during which significant portions of the planet's surface have been covered with ice, periods called ice ages. Each ice age has brought about the extinction of numerous species of plants and animals. The result is that the process by which plants and animals have evolved has not been a smooth one. Rather it has been halted many times and jump-started with each new warm period.

The history of global climate change can be broken down into four main periods: Precambrian, Paleozoic, Mesozoic, and Cenozoic.

Precambrian era The Precambrian era began with the formation of Earth about 4.6 billion years ago and ended 570 million years ago. Earth began its existence as a ball of molten liquid rock. Within about 900 million years its surface cooled and solidified. Volcanic eruptions spewed forth gases, such as nitrogen, argon, water vapor, sulfur dioxide, and carbon dioxide, trapped beneath the rocky surface. These gases rose and mingled with hydrogen gas, a byproduct of Earth's formation from solar gases, to create the early atmosphere. The water vapor condensed into rain, which fell to the surface forming vast oceans. The rain washed most of the sulfur dioxide and carbon dioxide out of the atmosphere, and oceans have covered much of Earth's surface since.

Soon after the formation of the early atmosphere, the first forms of life appeared. These were anaerobic (capable of living without oxygen) bacteria. Then, about 3.5 billion years ago, these bacteria evolved into blue-green algae, which had the ability to photosynthesize. Photosynthesis is a process driven by the heat of the Sun in which an organism combines water and carbon dioxide to form a simple sugar. Oxygen is given off as a byproduct.

Over time, oxygen accumulated in the atmosphere. By 350 million years ago, the concentration of oxygen in the atmosphere reached its present value of 21 percent. Oxygen molecules (O2) then combined with free oxygen atoms, which were formed when sunlight broke apart oxygen molecules, to form ozone (O3). The ozone formed a separate atmospheric layer and fulfills the important function of absorbing the Sun's dangerous ultraviolet rays. The oxygen in the atmosphere, plus the protection provided by the ozone layer (the layer of Earth's atmosphere, 25 to 40 miles above ground, that filters out the Sun's harmful rays), encouraged the burst of biological diversity that marked the end of the Precambrian era.

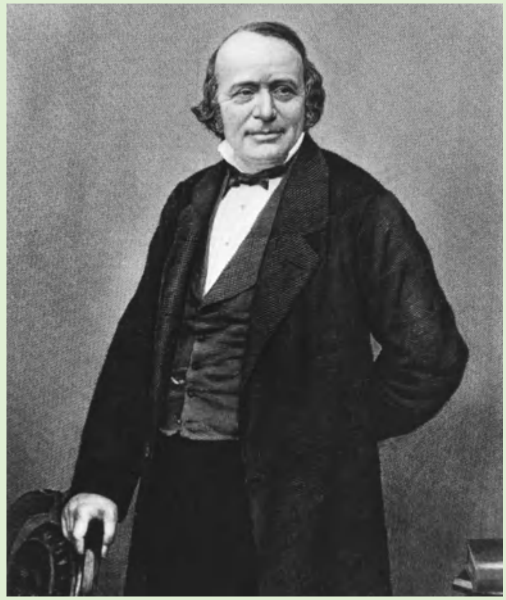
The Precambrian saw four ice ages. The first occurred somewhere between 2.7 billion and 2.3 billion years ago. Then Earth warmed up and was free of ice for almost a billion years. The second ice age took place between 950 and 890 million years ago; the third between 820 and 730 million years ago; and the fourth between 640 and 580 million years ago. In each case, some portion of Earth was iced over for about 100 million years.

Paleozoic era The Paleozoic era began with a dramatic increase in the number of marine animal species. It lasted from 570 to 225 million years ago. The Paleozoic era was significantly warmer than the Precambrian

Who's who: Jean Louis Agassiz, discoverer of ice ages

Swiss American naturalist, educator, and fossil expert Jean Louis Rodolphe Agassiz (pronounced "A-guh-see") (1807–73) was a pioneer of the theory that ice ages have occurred in Earth's history. He was not the first, however, to come up with this idea. That honor belongs to Scottish geologist James Hutton (1726–97), whose ideas were shunned by other scientists. Agassiz, who was more persuasive in his arguments about ice ages, is generally credited with developing the theory.

Agassiz grew up in the Swiss Alps and spent much of his time exploring their great heights. He studied the huge boulders on the mountains and felt that they must have been



Jean Louis Agassiz.

era, with the exception of two glacial periods. At the end of the first glacial period, around 400 million years ago, plants began to take hold on land.

The spread of plants across the land had a significant impact on climate. Primarily, it reduced the albedo (reflectivity) of Earth's surface by 10 to 15 percent. As a result, more sunlight was absorbed, which raised the planet's surface temperature.

During the last portion of this era, from 330 to 245 million years ago, temperatures fell again. About 250 million years ago, Earth's two supercontinents, called Laurussia (containing Greenland, North America, Scandinavia, and most of Russia) and Gondwana (containing most of the rest of the landmass), joined together. The newly formed supercontinent, Pangea, extended from the North Pole almost all the way to the South Pole.

Mesozoic era The Mesozoic era, which is often known as the age of the dinosaurs, lasted from 225 to 65 million years ago. In the latter half of this deposited there by glaciers. Thus, he began seeking evidence to prove that glaciers move.

A real breakthrough came in 1839 when Agassiz discovered that a house built upon a glacier had moved one mile during a ten-year period. This discovery prompted him to drive a line of stakes into the ice in order to trace their movement. In just a year he found that the stakes had moved into a U shape, with the stakes in the middle of the line showing the greatest change in position. Agassiz concluded that the glacier had moved the most slowly on the edges, where it was slowed by friction with the mountainside.

In 1840, Agassiz published his findings in a book entitled *Studies on Glaciers*. He wrote that within the past several thousand years, northern Europe had been covered by glaciers, in what he called a Great Ice Age. This notion was initially met with a great deal of skepticism in the scientific community.

In 1848, Agassiz became a professor of natural history at Harvard University. There he pursued many areas of study, principal among which was marine science. In 1859, he founded Harvard's Museum of Comparative Zoology. Meanwhile, Agassiz continued to search for evidence of ice ages in New England and around the Great Lakes. By the end of his lifetime, Agassiz's ice-age theory had gained a modest level of acceptance. It wasn't until the turn of the century that this concept became widely accepted.

era, Pangea split into two continents, one containing North America and the other containing Eurasia (Europe and Asia combined). About 100 million years ago, these landmasses further subdivided, roughly into the present continents. However, the landmasses were still situated very close together.

Throughout the Mesozoic era, temperatures everywhere on Earth were, on average, 11 to 18°F warmer than they are today. They were also relatively uniform across the planet. This was most likely due to the efficient distribution of heat from the equator to the poles by ocean currents and global winds. Landmasses, even by the end of the Mesozoic era, were not as widely dispersed across the globe as they are today. Thus, ocean currents (the major routes through which ocean water is circulated around the globe) and winds had a relatively clear path between the equator and the poles.

The Mesozoic era experienced a number of temperature swings, culminating in a sudden, brief ice age. This coincided with the extinction of about 70 percent of Earth's life-forms, including dinosaurs. According to one theory, an asteroid collided with Earth, creating a dust cloud that blocked out the Sun and brought about the ice age.

Cenozoic era: Pre-Holocene The Cenozoic era began 65 million years ago and continues to the present. Throughout this era, the continents have continued to drift, moving into their present configuration. The continental plates continue to move, and the process of super-continent formation and breakup will likely repeat several more times. This era is also characterized by the emergence of mammals, including humans, as the dominant animal group.

The Cenozoic era is divided into two parts: the pre-Holocene epoch, which stretches from the beginning of the Cenozoic until ten thousand years ago; and the Holocene epoch, which covers the most recent ten thousand years.

The pre-Holocene epoch, the early part of the Cenozoic era, was warmer than it is today, and there were no polar ice caps. Beginning about 55 million years ago, a long cooling trend began. This cooling occurred both gradually over time, and through a series of extremely cold periods. One of these cold spells took place about 50 million years ago, and another about 38 million years ago. The most recent was about 15

Glacier Bay National Park, Alaska. ©NEIL RABINOWITZ/CORBIS.

million years ago, the results of which can still be seen in the polar ice caps and the glaciers nestled in protected areas of tall mountains.

Over the last 2.4 million years there have been two dozen ice ages—times when the global temperature has plummeted sharply downward. At seven different points over the last 1.6 million years, ice covered up to 32 percent of Earth's surface. Scientists estimate that throughout this era new ice ages have begun about every hundred thousand years and have been interspersed with warmer, interglacial periods, each lasting at least ten thousand years.

Geological Time Scale

		Periods	
Phanerozoic	Cenozoic	Neogene	24 million
		Paleogene	65 million
	Mesozoic	Cretaceous	144 million
		Jurassic	206 million
		Triassic	248 million
	Paleozoic	Permian	290 million
		Carboniferous	354 million
		Devonian	417 million
		Silurian	443 million
		Ordovician	490 million
		Cambrian	540 million
Precambrian		Proterozoic	2.5 billion
		Archean	3.8 billion

The most recent ice age peaked about between twenty thousand years ago, when there were glaciers up to 10,000 feet (3,000 meters) thick over most of North America, northern Europe, northern Asia, as well as the southern portions of South America, Australia, and Africa. The sea level fell and exposed large areas of land that are currently submerged, such as the Bering land bridge, which connected the eastern tip of Siberia with the western tip of Alaska.

This era was followed by a warm period, beginning fourteen thousand years ago. By eight thousand years ago—most of the ice had melted and between seven and five thousand years ago—the world was about 5°F warmer than it is today. The sea level rose and the current shape of continents emerged.

Cenozoic era: Holocene The Holocene epoch began approximately ten thousand years ago. Extensive climatic data exist for this time period. The history of human civilization begins during this post–ice age period, about six thousand years ago.

About five thousand years ago, when Earth was slightly warmer and wetter than it is today, agriculture was developed, and the earliest cities were established in Egypt and Mesopotamia (now part of Iraq). There was a relatively cool period that began about 900 BCE and lasted until about 500 CE, which resulted in crop failures. There are also indications that beginning about 800 CE there was a prolonged drought, which in all likelihood contributed to the fall of the great Mayan civilization in Mexico and Central America.

In the Middle Ages (500 to 1500 CE), the global climate was similar to today's. During that time, the civilizations of Europe flourished, and the Vikings colonized Iceland and Greenland. However, a cold spell began at the end of the thirteenth century. Summer after summer was cold and wet, which caused famine throughout Europe.

Conditions were more moderate during the fifteenth century and then became colder again between about 1500 and 1850, a period referred to as the Little Ice Age. Rather than being continuously cold, the Little Ice Age consisted of a series of cold spells, each up to thirty years long, separated by warmer years. For the most part, this period was characterized by bitterly cold winters and cold, wet summers. The canals of Holland, as well as the Baltic Sea and the River Thames in England, were continuously covered with layers of ice several inches thick. Food became scarce throughout Europe, the mountain glaciers increased in size, and the colonists in Greenland and Iceland perished.

After the Little Ice Age, temperatures warmed. In the years since 1850, however, significant fluctuations have occurred in global temperatures. About a dozen cool periods have alternated with warmer periods. From 1900 to the present, there has been a 1°F increase in global temperature. Scientists now think that this increase constitutes part of a trend of human-influenced global warming and is not merely a natural part of Earth's continually changing climate.

There are various ways of looking at the Holocene epoch. Some consider it a warm period, since ice exists only at the polar regions, covering 10 percent of the planet. Others believe the world is still in the final stages of the most recent ice age. What most scientists do agree on, however, is that another ice age is in store for the future.

Reasons for climate change In an attempt to find some order in the series of climatic shifts that describes the history of Earth, scientists have sought to define a pattern of warm-cool cycles that repeat after a given period of time. They have, however, been largely unsuccessful. The proposed cycles either don't apply to all times in the past or don't hold true for all parts of the world.

One problem in determining patterns of climatic change is that many factors are involved. Some of those factors affect Earth's climate for millennia while others affect it only for decades. In addition, some factors, such as Earth's shifting orbit around the Sun, are predictable and regular, while others, such as collisions with large objects in space, are not.

Human activity constitutes a whole category of factors affecting climate change in the recent past and present. Deforestation, the burning of fossil fuels, and acid precipitation (rain and snow that are made more acidic when carbon, sulfur, and nitrogen oxides in the air dissolve into water) and smog (a layer of hazy, brown air pollution at Earth‘s surface) caused by industrial emissions are among the real or potential agents of climate change.

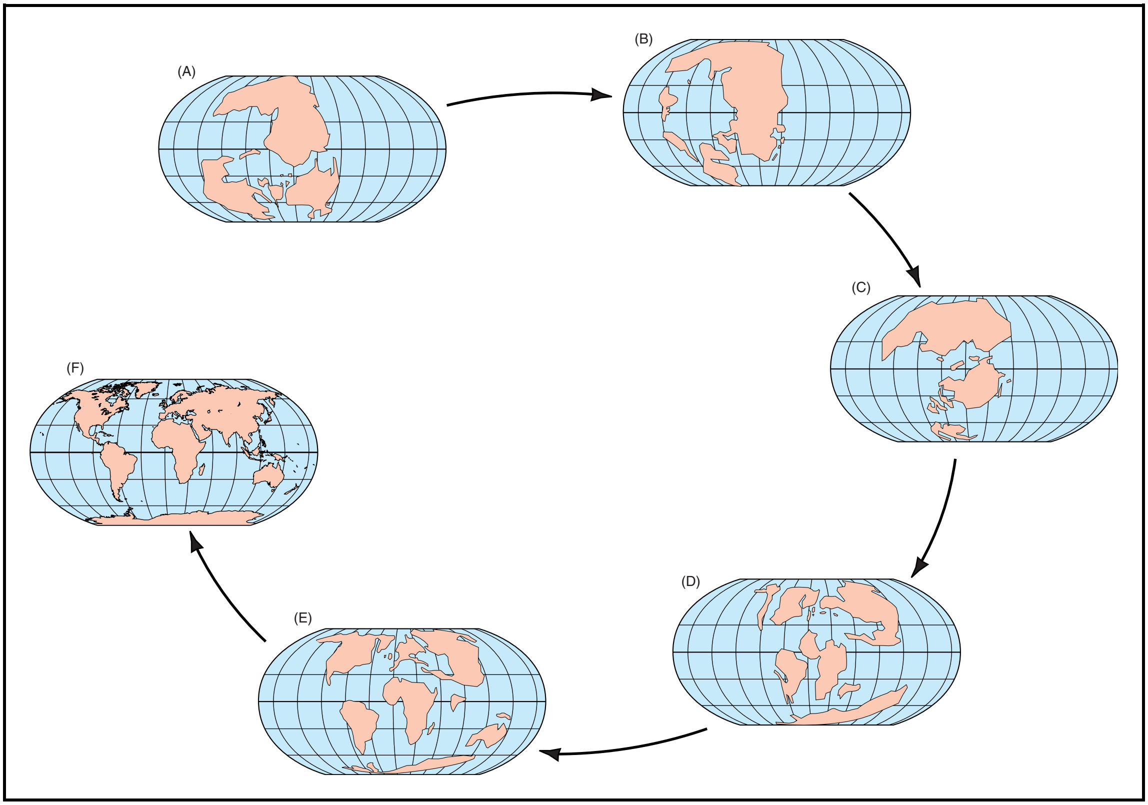
What follows is a discussion of a handful of forces that have affected the climate of Earth throughout its history: continental drift; shifts in Earth's orbit; volcanoes; asteroids and comets; and solar variability. Another phenomena that is currently being studied as a possible factor in long-term climate change is El Niño/Southern Oscillation (ENSO).

Continental drift The continental drift theory was first suggested by German meteorologist Alfred Wegener in 1915. That theory states that all land on Earth was joined together in one huge continent 200 to 250 million years ago. Then, over the years, forces deep within Earth's core caused the land to break apart. Continents moved away from one another and drifted around the globe. This motion is predicted to continue indefinitely into the future.

Evidence of continental drift can be found in the fossils of dinosaurs and other mammals that migrated across once-connected landmasses and in the fossilized remains of tropical plants beneath polar ice sheets. Another piece of evidence that landmasses were once connected is that shapes of the continents fit together like pieces of a jigsaw puzzle. The Atlantic coastlines of Africa and South America are the most striking examples of this phenomenon. In addition, satellites are able to record the subtle, extremely slow movements of the continents today.

Continental drift is believed to affect both the climates of individual continents and the climate of the entire planet. The climates of the individual continents have been altered by their gradual, but radical, change in position around Earth. For instance, parts of Europe and Asia that once sat on the equator are now at high latitudes in the Northern Hemisphere. India moved to its current low-latitude Northern Hemisphere position from one deep in the Southern Hemisphere. Glaciers once covered parts of Africa, and Antarctica gradually slid from warmer latitudes to the South Pole.

On a global level, the position of landmasses affects how the heat from the Sun is distributed around Earth. When the continents were joined



Continental drift. This diagram illustrates the distribution of landmasses at certain points throughout Earth's history. (A) 320 million years ago; (B) 250 million years ago; (C) 135 million years ago; (D) 100 million years ago; (E) 45 million years ago; (F) Present.

together, ocean currents and global winds produced a different pattern of global heat distribution than they do at present. Global climatic conditions 200 to 250 million years ago were more uniform than they are today. As the continents separated and dispersed around the globe, greater extremes in climatic conditions began to appear around the world.

Another consequence of continental drift has been the formation of mountain ranges. When landmasses come together, the land is forced upward. Examples of mountain ranges formed in this way are the Rocky Mountains, the Andes, the Tibetan Plateau, and the Himalayas. Mountain ranges affect temperatures, winds, and rainfall over limited areas. Very tall ranges, particularly those with north-south configurations, can influence air circulation patterns over very large areas.

The Tibetan Plateau is a prime example of this phenomenon. Formed 50 million years ago by the collision of the Indian and Asian continents, this plateau is one of the world's tallest and widest mountain ranges. It affects wind patterns across the entire Northern Hemisphere. Fossil records show that almost immediately following the formation of the Tibetan Plateau, the climate of the Northern Hemisphere cooled and large glaciers formed. The presence of glaciers led to further cooling. Snow accumulates on the ice, which reflects sunlight rather than absorbing it.

Another aspect of continental drift that affects global climate is the distribution of landmasses at various latitudes. For instance, as land moved away from the tropics and toward the poles, tropical oceans replaced the land. These bodies of water absorbed huge amounts of incoming heat, which led to global cooling. Also, the movement of continents into polar regions provided a surface on which ice layers could accumulate.

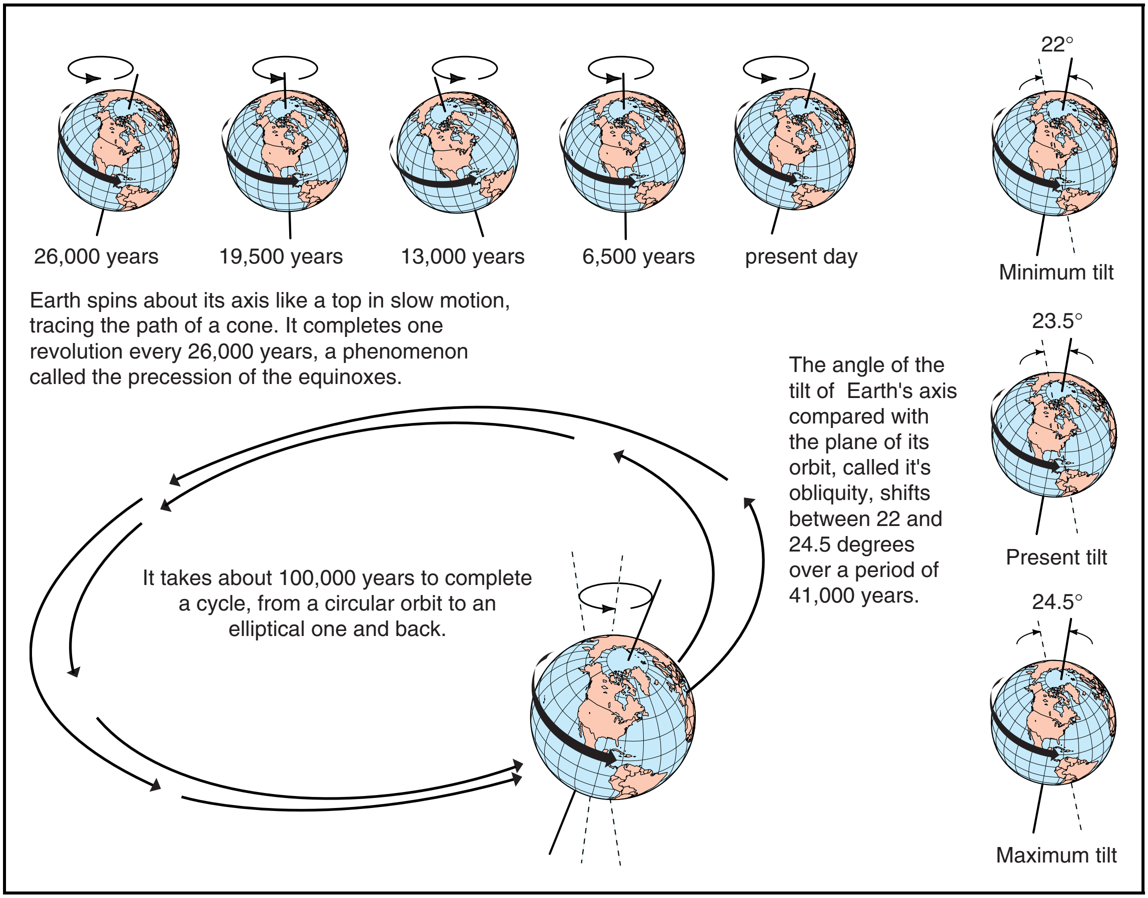
Earth's orbit In the 1930s, the Yugoslavian astronomer Milutin Milankovitch (pronounced "muh-LAN-kuh-vich") (1879–1958) proposed a theory to explain changes in Earth's climate. He listed three factors that could affect the planet's climate: the shape of Earth's orbit, and the angle and direction of Earth's axis.

The shape of Earth's orbit around the Sun changes over long periods of time. At times, the orbit is nearly a perfect circle. At other times, it has a more elliptical shape (like an egg). The alternating change in the shape of Earth's orbit is called eccentricity. The eccentricity of Earth's orbit occurs in a regular cycle—from circular to elliptical to circular again—that takes about one hundred thousand years.

When the orbit is circular, there is less variation in the levels of solar energy received by Earth throughout the year than when it's elliptical. At present, the orbit is in a stage of low eccentricity, meaning that it is nearly circular. Earth receives only 7 percent more solar energy in January, when Earth is closest to the Sun, than July, when it is farthest from the Sun. In contrast, when the orbit is highly eccentric, the solar energy received at points closest to and farthest from the Sun will differ by up to 20 percent. In addition, a more elliptical orbit means the summers and winters are longer, and springs and falls are shorter.

The second orbital factor that affects climate is the wobbling of Earth about its axis of rotation. Earth's axis is tilted in relation to the plane of its orbit around the Sun. This effect is what causes the Northern and Southern Hemispheres to each receive different amounts of sunlight throughout the year.

Earth spins like a top in slow motion, so that its axis traces the path of a cone. It wobbles its way through one complete revolution every



The three components of the Milankovitch theory.

twenty-six thousand years, a phenomenon called the precession of the equinoxes. This means that every thirteen thousand years the seasons are gradually reversed. Eventually, unless the calendar is adjusted, the Northern Hemisphere will experience winter in July and the Southern Hemisphere, in January. Precession also influences Earth's distance from the Sun at different seasons. When it's winter in the Northern Hemisphere in July, Earth will also be at its closest point to the Sun in that month.

The third variable affecting Earth's climate is the angle of the tilt of Earth's axis compared to the plane of its orbit. This angle is called obliquity. Over the course of forty-one thousand years, this angle fluctuates between 22 degrees and 24.5 degrees. It is currently 23.5 degrees. When the angle is smaller, sunlight strikes various points on Earth more evenly, and the seasonal differences are smaller. That is, winters are milder and summers are cooler. Yet when the angle is larger, there is a greater variation in the level of solar radiation received across Earth, and seasons are more pronounced.

The smaller angle of tilt tends to favor the formation of glaciers in polar regions. The reason for this effect is that when winters are warmer, the air holds more water and snowfall is heavier. That snow then has a greater probability of remaining on the ground during the cool summer.

Evidence has been found in deep ocean sediments that strongly support Milankovitch's theory. By analyzing the chemical composition of these sediments, scientists have deduced that glaciers have advanced and retreated in roughly 100,000 year cycles over the last 800,000 years. Within those cycles, glacier formation occurs in secondary cycles, reaching peaks every 26,000 and 41,000 years. These time intervals correspond to the cycles of the three types of orbital variation described here.

Volcanoes In the early stages of Earth's history, thousands of volcanoes dotted the planet's surface. These volcanoes underwent frequent, large eruptions that had a significant impact on the climate. In addition to releasing gases that rose up and formed Earth's atmosphere, these eruptions sometimes spewed out ash and dust so thick that they very nearly blocked out the Sun. Volcanic eruptions have probably been the catalysts for some periods of glaciation.

While volcanic eruptions still occur today, they are far fewer in number and intensity than they once were. A very large volcanic eruption today affects global climate only for a few years. For example, in 1815 the Indonesian volcano Mount Tambora erupted. Dust from the eruption was carried around the world by upper-air winds. In conjunction with smaller eruptions of other volcanoes over the preceding four years, the Tambora event led to a decrease in global temperature. For example, a severe cold spell in 1816 earned that year the nickname "the year without a summer."

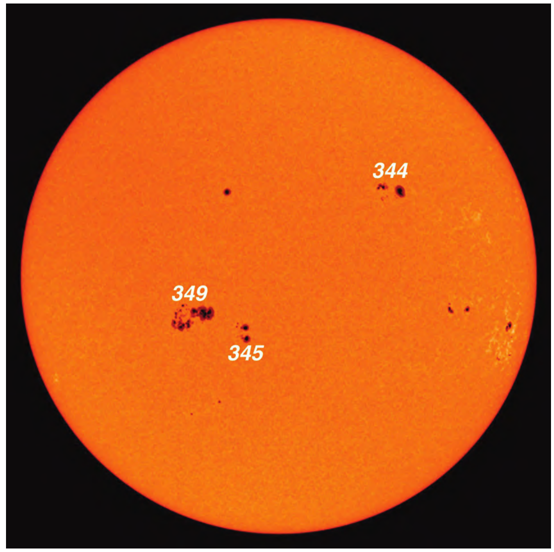
The eruptions with the gravest climatic consequences are those rich in sulfur gases. Even after the ash and dust clears from the atmosphere, sulfur oxides continue to react with water vapor to produce sulfuric acid particles. These particles collect and form a heavy layer of haze. This layer can persist in the upper atmosphere for years, reflecting a portion of the incoming solar radiation. The result is a global decrease in temperature.

A pillar of lava and volcanic ash belches from Mt. Vesuvius in Italy in 1944. © BETTMANN/CORBIS.

Asteroids and comets Throughout Earth's history, there have been five very abrupt and dramatic changes in global climate, occurring 500 million years ago, 430 million years ago, 225 million years ago, 190 million years ago, and 65 million years ago. One possible explanation for these changes is that large, rocky bodies from space, such as an asteroid or comet (together known as bolides) crashed into Earth. Many scientists believe that the extinction of the dinosaurs, which came about 65 million years ago, was caused by a collision with an object from space.

It has been calculated that the impact of an asteroid at least 6 miles (10 kilometers) across, traveling at a speed of at least 12 miles (20 kilometers) per second, would produce a crater about 95 miles (150 kilometers) in diameter. It would release energy equivalent to that of four billion atomic bombs similar to those dropped on Hiroshima, Japan, heating the atmosphere to temperatures of 3,600 to 5,400°F (about 2,000 to 3,000°C). Another result of this energy release would be the production of huge concentrations of nitric and nitrous acids. These acids would react with and destroy the ozone layer. They would fall to the ground as highly acidic rain, destroying plants and animals.

If the object from space were to fall on land, a thick dust cloud would rise up and potentially block out all sunlight for several months.



Sunspot activity on the surface of the Sun. ©NASA/EPA/CORBIS.

Following an early wave of wildfires caused by the high temperatures, any surviving plants and animals would be killed off during a long, dark period of cold weather during which virtually all sunlight would be blocked from Earth by a thick dust cloud.

It is more likely that a bolide would fall into the ocean, since oceans cover almost three-quarters of Earth's surface. In this case, the bolide impact would stir up carbonate-rich sediments and produce vast quantities of carbon dioxide. An increase of carbon dioxide in the air serves to trap reradiated infrared radiation from Earth's surface, leading to an increased greenhouse effect, which is the warming of Earth due to the presence of gases that trap heat.

The possibility of such a collision happening within our lifetime is remote. However, it has become more of a concern following the July 1994 crash of fragments of Comet Shoemaker-Levy into Jupiter. These collisions, which occurred over several days, caused disturbances on an Earth-sized area of the giant gaseous planet's atmosphere. Had the same impact occurred on Earth, the results would probably have been disastrous.

Solar variability It has long been established that the amount of energy emitted by the Sun varies slightly over the years. In recent years, scientists have made correlations between changes in cycles of solar output and particular weather patterns. While there have been several theories linking solar variation to long-term climate change, many more years of data collection will be necessary before such links can be proven. However, the evidence collected thus far presents a compelling case for the link between solar variability and climate change—at least climate change on the scale of decades.

The variation in solar output is primarily based on cycles of sunspot activity. Sunspots are dark areas of magnetic disturbance on the Sun's surface. It has been shown that when the number and size of sunspots is at a maximum, which occurs roughly every eleven years, the Sun's energy output is highest. This heightened solar output is due to an increase in bright areas, called faculae, which form around the sunspots.

Measurements taken on board satellites by special instruments called radiometers have shown that 0.1 percent, and possibly up to 0.4 percent, more solar energy reaches Earth during a sunspot maximum than during a sunspot minimum. (A sunspot maximum is a period of the greatest number of sunspots; a sunspot minimum is a period in which there are the smallest number of sunspots.) The length of sunspot cycles varies over time, from seven to seventeen years. A growing body of evidence supports a link between the length of sunspot cycles and temperature patterns around the world. It has been shown over the last century that global temperatures, in general, are higher during shorter sunspot cycles than during longer sunspot cycles. In addition, a reduction in the amount of sea ice around Iceland, another sign of warming, has been noted during shorter sunspot cycles.

Another piece of evidence linking sunspots and global temperatures is that the period of lowest sunspot activity in several centuries coincided with the coolest period in several centuries. Between 1645 and 1715, the stretch of years known as the Maunder minimum (named for British solar astronomer E. W. Maunder who discovered it in the late 1880s), sunspot activity was at a very low level. It is even possible there were no sunspots at all during this period. The period between 1645 to 1716 was also the coldest part of the Little Ice Age.

Ways to measure climate change A paleoclimatologist, a scientist who studies climates of the past, uses a wide variety of methods. The first step in learning about climates of the past is to discover objects that were formed long ago and to put an accurate date on those objects. Then the challenge is to extract information from the objects that describe the climate at that time.

Many types of materials, both on Earth's surface and embedded far underground, that have been preserved over thousands and millions of years provide clues about Earth's past. Paleoclimatologists use these materials in a variety of ways.

Rocks and rock formations The oldest rocks on Earth are about 3.9 billion years old. These rocks are the only objects that still exist from the earliest period in the Earth's history, the Precambrian era. Thus, scientists must rely entirely on rocks to learn about the climate of that time.

To determine the age of rocks, paleoclimatologists use a technique developed in the late 1800s called radioactive dating. This can be used for rocks that contain radioactive elements, such as uranium, radium, and potassium. Radioactive nuclei exist in an unstable configuration and emit high-energy particles (alpha particles or positrons) over time, to achieve greater stability. When the parent nuclei shed alpha particles, or decay, they transform into daughter nuclei (in the case of a uranium parent, the daughter is lead).

The age of a sample is determined by comparing the percentage of parent nuclei to daughter nuclei. Since scientists know the rate at which radioactive elements decay, they can predict how long ago the sample was entirely made of parent atoms—in other words, when the sample was formed.

A similar technique is called carbon dating. This involves the analysis of radioactive carbon, which is produced in small amounts continuously over time in the atmosphere by cosmic rays (invisible, high-energy particles that bombard Earth from space). Radioactive carbon, like normal carbon, becomes assimilated into green plants through photosynthesis. Radioactive carbon is unstable because its nuclei contain too many neutrons. To achieve stability, the nucleus transmutes into nitrogen. Given the rate of decay of radioactive carbon it's possible to determine the age of a given sample.

Once scientists have established the age of a sample, they can study it for clues about the climate at that time. First, the shape of a rock tells them about the medium in which it once existed. For example, rocks with rounded surfaces probably once existed in a body of water, and rocks with eroded (worn-away) surfaces were probably once covered by glaciers.

To take this a step further, if rounded rocks from the same time period are found all over Earth, it can be assumed that the average temperature at that time was above freezing. The presence of surface water also indicates the existence of some form of atmosphere, without which water would quickly evaporate away. By the same token, if eroded rocks of the same age are found at far-flung locations, this signals that an ice age was in progress.

Fossils of primitive organisms begin showing up in rocks dated about 3.8 billion years ago. Studying fossils provides information not only about the progression of life-forms at different time periods but also about the climate. For instance, rocks formed during cooler times, such as ice ages, have few or no fossils embedded within them. In contrast, rocks that were formed during warmer times contain fossils in far greater numbers.

A particularly valuable source of evidence of climate change is rock formations made from layers of particles, deposited incrementally and hardened over time. An analysis of samples of each layer of a rock formation provides information about Earth's climate at that point in history. Of particular interest are the fossils within each layer, which constitute a timeline of the emergence of various species.

The presence of marine animals in a given layer indicates that at that time the region was covered with water. By studying the chemical composition of fossilized shells, the primary ingredient of which is calcium carbonate, it's even possible to determine the relative warmth of the water. Oxygen in calcium carbonate exists in two forms: oxygen-16, which is by far the most plentiful, and oxygen-18 (the number refers to how many neutrons the atom possesses). It has been found that during periods of glaciation, the concentration of oxygen-18 increases in the oceans. Thus, the ratio of oxygen-18 to oxygen-16 in fossilized shells gives an approximation of the water temperature.

Ice cores Ice cores drilled into the 2-mile-thick polar ice caps provide unique insights into climates of the past. The ice has been accumulating in layers, one year at a time, for thousands of years. Though individual layers of ice can be counted for the last 50,000 years in Greenland, patterns can be discerned from this ice that yield information as far back as 250,000 years. In Antarctica precipitation is so meager that annual layers of ice cannot be distinguished from one another. However, information contained in the thick layer describes conditions for as far back as 500,000 years ago.

The layers of ice contain many types of climatic evidence, all perfectly preserved. For instance, the thickness of a layer tells how much precipitation fell during a given year. That, in turn, yields information about temperature, since greater levels of precipitation fall during warmer times.

Chemicals detected within the ice are also clues to the air temperature at the time of the precipitation The approximate temperature during a particular period can be determined by comparing ratios of oxygen-16 and oxygen-18 present in a given medium.

By determining the nature of the dust contained within ice cores from the North Pole, it's possible to determine the origin of that dust. That, in turn, provides information about the wind patterns at that time. This type of evidence is not useful in South Pole ice cores, since Antarctica is surrounded by oceans, and is a great distance from all other landmasses.

In addition, air bubbles can be analyzed for the composition of the atmosphere. The timing of volcanic eruptions can be inferred from the presence of high levels of acidity in the ice. When volcanoes erupt, they emit dust and gases that are highly acidic.

A scientist takes a core sample of ice in Antarctica. ©MORTON BEEBE/CORBIS.

Ocean and lake sediments The sediments collected from the bottoms of oceans and lakes contain information about the global climate dating back millions of years. The sediment accumulates in

A cross-section of a tree trunk shows rings of annual growth. ©DOUG WILSON/CORBIS.

layers, much as rock formations and ice do. The age of sediment layers is determined using chemical analysis.

Embedded within the layers of sediment are fossils of tiny marine organisms that have evolved and become extinct over time. Each species was adapted only to a narrow range of water temperatures. Therefore, the presence of a species in a given layer of sediment reveals the ocean temperature at that time.

Pollen has also settled in layers on ocean and lake floors. Pollen provides clues to past conditions because every plant species requires a particular set of conditions for survival. The first step in pollen analysis is to identify the pollen species. The next step is to determine its age by finding the age of the surrounding sediment. Studying the times in which particular plant species inhabited a given location teaches scientists about that location's climatic history.

For example, a recent study of a bog in northern Minnesota turned up pollen of fourteen plant types dating back eleven thousand years. In the oldest layer, the greatest pollen concentration was spruce. Since spruce trees inhabit cold habitats, it could be inferred that at that time conditions were cold. The next layer yielded primarily pine pollen. Since pine trees grow in warmer regions than do spruce, conditions must have been warmer then. In the next layer, dated eighty-five hundred years ago, oak pollen was widespread. Oak grows in drier conditions than does either spruce or pine, which means that conditions must have been drier at that time. By examining the pollen within each layer, it was possible to construct a climatological history of the bog.

Tree rings Dendrochronology, the study of the annual growth of rings of trees, is another important component of paleoclimatology. Trees are the oldest living entities on Earth. Some bristlecone pines that are still alive today date back to the time of Julius Caesar.

As trees grow, they add new cells to the center of their trunk each year. These cells force the previous years' growth outward, forming concentric rings with the oldest ring on the outer edge. A tree's woody material acts like a library of climatic data, creating a record for each year of its lifetime. This information can be found in living trees, dead (but not rotten) trees, and tree stumps.

In order to assess the overall conditions of a given year, the width of that year's growth ring is measured. In warm, wet years, trees grow more (and have wider growth rings) than in cool, dry years. Hence, the difference in the width of growth rings is an indicator of climate.

In order to separate the effect of temperature from that of precipitation, it is necessary to examine trees growing at the edge of their temperature or rainfall range. An example of this is the fir trees growing at the edge of the subpolar zone in Canada. Since temperatures are quite cold every year, an increase in growth from one year to the next would be due almost entirely to precipitation. To study temperature, consider the case of Joshua trees in the heart of a North American desert. There rainfall is continuously very light, so variations in the width of tree rings would be caused by temperature changes.

Experiment: Create a weather "log"

You, too, can be a dendrochronologist. All you have to do is locate a slice of a tree trunk. You can use the stump of a recently cut tree or seek out a log that hasn't yet been split, from a firewood seller. Just be certain that you know the year in which the tree was cut and, if you're using a log, find out where it's from.

First count the rings on the face of the log to determine the age of the tree (a tree adds a new ring of growth each year, with the most recent year's growth in the center.) Then study the width of each ring. Remember that trees grow more in warmer and wetter years, resulting in wider growth rings.

Now you're ready to construct a basic climatic history for the area in which the tree grew. On a piece of paper, create two columns: one for the year and the other for the conditions. For years in which the ring is skinny, write "cold/dry." For years in which the ring is wide, write "warm/wet."

[*See Also* **Climate Change and Global Warming; Human Influences on Weather and Climate**]

For More Information

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Clouds

Clouds are formed when air cools to its dew point or becomes saturated, at which point the air cannot hold any more water vapor, and water droplets condense. There are many different conditions under which this occurs, producing a variety of cloud types. The force with which the air rises, the topography (features of the surface), and the temperature at the surface and at various altitudes are among the factors that influence whether a cloud will be small or large, thick or thin, flat or bumpy, and whether it will produce precipitation.

Cloud classification systems

The first scientific method of classifying clouds was devised in 1803 by English naturalist and pharmacist Luke Howard (1772–1864). In an article entitled "On the Modifications of Clouds," Howard assigned Latin names to four different cloud categories, based on appearance: cumuliform ("piled") for puffy, heaped-up clouds; cirriform ("hair-like") for thin, wispy, feathery swirls of clouds; stratiform ("layered") for continuous, flat sheets or layers of clouds; and nimbus ("cloud") for dark rain clouds. He then used combinations of these names to describe other clouds. For instance, nimbostratus is a rain-producing, layered cloud, and stratocumulus is a continuous cloud sheet punctuated by bumps.

This system of cloud classification was revised in 1874, at the first meeting of the International Meteorological Congress. There it was decided to use Howard's cloud names as a starting point for a classification system that placed clouds into ten categories, based on their height in the sky as well as their appearance. In 1896, the Congress published the *International Cloud Atlas,* the general outline for the system still in use today.

WORDS TO KNOW

calvus: "bald"; upper part of a cloud is losing its rounded, cauliflower-like outline and becoming diffuse and fibrous. Applies to Cu, Cb.

capillatus: "having hair"; cloud with cirriform, streaky structure on its upper edges. Applies to Cb.

castellanus: "castlelike"; vertical extensions. Applies to Cc, Ac, Sc, Ci.

congestus: "congested"; upper parts piled up and sharply defined; resembles a head of cauliflower. Applies to Cu.

fibratus: "fibrous"; hairlike strands with no hooks or curls at the end. Applies to Ci, Cs.

floccus: "flock of wool"; small tufts with ragged undersides. Applies to Cu, Ci, Cc, Ac.

fractus: "fractured"; broken up, ragged edges. Applies to St, Ci, Cu (it is used as a prefix in the case of Cu "fractocumulus").

humilis: "humble, lowly"; small, flattened appearance. Applies to Cu.

incus: "anvil," or fan-shaped; spreading, smooth or fibrous mass at the top of a cloud. Applies to Cb.

intortis: "intertwined"; entangled, fibrous strands. Applies to Ci.

lenticularis: "lens-shaped"; elongated, or almond-shaped with well-defined outlines. Applies to Cs, Cc, Ac, Sc.

mammatus: "breast, udder"; pouches of water droplets that hang from the underside of a cloud. Applies to Cb, Ci, Cc, Ac, As, Sc.

mediocris: "mediocre"; moderate vertical development with lumpy tops. Applies to Cu.

nebulosus: "nebulous"; thin, hazy veil. Applies to Cs, As, St.

pileus: "felt cap"; small cap- or hood-shaped formation perched above or attached to the top of a cloud. Applies to Cu, Cb.

spissatus: "tightly packed"; icy formations at the top of a vertical cloud that are dense enough to block out the Sun. Applies to Ci.

stratiformis: "covering, blanket"; thick layer. Applies to Ac, Sc, Cc.

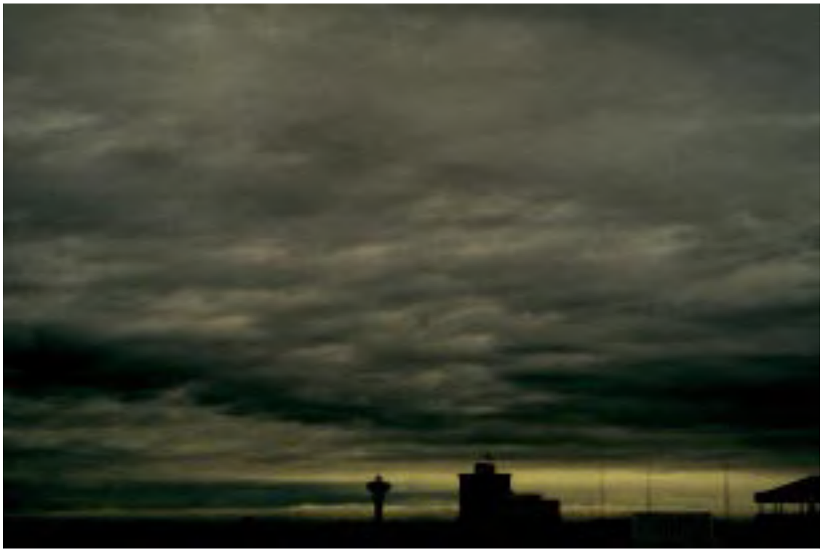
translucidus: "translucent"; transparent layer covering a large part of the sky, through which the Sun or Moon shines. Applies to St, As.

troposphere: the lowest atmospheric layer, where clouds exist and virtually all weather occurs.

uncinus: "hook-shaped"; fibers creating the pattern called "mare's tail." Applies to Ci.

undulatus: "undulating"; wavelike formation within patches, layers, or sheets of clouds. Applies to Ac, As, Cc.

Low clouds are those with a base below 6,500 feet (2 kilometers); middle clouds are those with a base between 6,500 and 23,000 feet (2 and 7 kilometers); and high clouds are those with a base between 16,000 and 43,000 feet (5 kilometers and 13 kilometers). It's important to remember that, for classification purposes, it is the bottom, or base, of a cloud that determines its height.



A layer of stratocumulus clouds over Seattle, Washington. FMA, INC.

You may notice that there is some overlap between the altitude of cloud bases in the middle- and high-cloud categories. The altitude at which clouds form depends on air temperature. On warm days and in warmer locations, medium and high clouds form at higher altitudes than they do on cold days.

This list of cloud-base altitudes pertains only to the middle latitudes, or temperate regions, which lie between 30° and 60° north and south of the equator. In the tropics, the bases of middle and high clouds form at higher altitudes than they do in temperate regions. In the polar regions these cloud bases form at the lower altitudes than they do in temperate regions.

There also exists a fourth group of clouds, the tops of which may extend to the edge of the troposphere, the lowest layer of the atmosphere. These clouds are called towering cumuliform clouds. Sometimes towering cumuliform clouds are placed with other clouds in the low category, since their bases

Four Major Cloud Groups and Their Types

High Clouds	Middle Clouds	Low Clouds	Clouds with Vertical Development
Cirrus (Cs) Cirrostratus (Cs) Cirrocumulus (Cc)	Altostratus (As) Altocumulus (Ac)	Stratus (St) Stratocumulus (Sc) Nimbostratus (Ns)	Cumulus (Cu) Cumulonimbus (Cb)

Experiment: Make a cloud in a bottle

For this experiment you will need a large glass jar (like a pickle or mayonnaise jar), a metal baking tray full of ice cubes, a piece of black paper, and matches.

First, affix the black paper to the back of the outside of the jar, so your cloud will be easier to see. Next, fill the jar about one-quarter full with hot water (but not boiling water, because this can crack the glass). Then carefully light a match, hold it over the jar opening for a few seconds, and drop it into the jar. Quickly place the tray of ice on top of the jar and observe what happens inside the jar.

This experiment reproduces the circumstances under which clouds are formed. Namely, the surface is warmed, the lowest layer of air rises, and water changes from gas to a liquid as the air cools. This process is called condensation. The smoke from the match provides the condensation nuclei, which are small particles around which water droplets form.

form below 10,000 feet (3 kilometers). In most classification schemes, however, including the one in this book, cumuliform clouds are placed in a category of their own, called vertical clouds.

The ten basic categories of clouds, arranged by base height and appearance, are called genera. Each genus (singular form of "genera") is subdivided into species.

Low clouds

Low clouds are almost always composed of liquid water droplets. When the temperature drops below 23°F (–5°C), however, these clouds may also contain ice crystals. There are three genera of low-lying clouds: stratocumulus, stratus, and nimbostratus.

Stratocumulus (Sc) Stratocumulus (pronounced stray-toe-KYOOM-yuh-luss) is a common type of cloud. As its name suggests, stratocumulus is a layered, puffy hybrid of a cloud. The puffiness is a result of warm air rising above the base of the cloud and condensing at higher altitudes. Stratocumulus ranges in color from white to dark gray, depending on its thickness.

Stratocumulus forms wide, shallow layers and may blanket the entire sky or may have breaks through which blue patches are visible. It may appear as a series of distinct, yet touching, rounded masses. Sometimes those masses appear in rows.

The presence of stratocumulus is an indicator of high levels of moisture in the lower levels of the troposphere. It is formed either when pockets of warm air rise to the dew point or when a warm air mass is pushed upward by an advancing front, the dividing line between two air masses. Usually, stratocumulus clouds do not produce precipitation. However, when these clouds become thick enough, they may bring light drizzle or snow.

Stratus (St) The second type of low cloud, stratus (pronounced STRAY-tuss), is that gloomy, gray, featureless sheet of cloud that covers the entire sky. It is common worldwide and is noted for blanketing coastal

Stratus clouds swirl through downtown Chicago, Illinois, some actually forming as the moist Lake Michigan air rises up and over the taller buildings. FMA, INC.

and mountainous areas for long periods of time. Stratus may produce drizzle or, if it's cold enough, light snow.

Stratus formation takes place at a lower altitude than any other cloud type. Stratus is most often a shallow layer of cloud, sometimes appearing nearly transparent. It may develop to a maximum thickness of 1,500 feet (450 meters). A stratus sheet typically covers an area of hundreds of square miles across.

Stratus clouds are usually formed by the rising of a large mass of moist air. In some cases, however, stratus is formed when a layer of fog (a cloud that forms near the ground), is warmed by the Sun, and then rises from the ground. Alternately, the rising fog may create a layer of stratus that is uneven and puffy, more accurately described as stratocumulus.

Nimbostratus (Ns) Finally, there are wet-looking nimbostratus (pronounced nim-bo-STRAY-tuss) clouds. These clouds are similar to stratus clouds in that they form a gray layer that covers all or a large part of the sky. Nimbostratus clouds, however, are thicker and darker than stratus clouds. They are often jagged at the base, a result of being blown about by the wind. Nimbostratus clouds may fuse with stratocumulus clouds below or altostratus clouds above, making their upper and lower edges difficult to distinguish.

Nimbostratus often brings continuous, light to heavy precipitation that lasts more than twelve hours. This precipitation may evaporate and

The Sun shines dimly through altostratus clouds. FMA, INC.

produce a low-lying cloud or fog, further reducing visibility on the ground. The base of a nimbostratus cloud may form as high as 13,000 feet (4 kilometers) above ground. For this reason, nimbostratus is sometimes classified as part of the middle group of clouds.

Middle clouds

Middle clouds are those with bases that form about 6,500 feet (2 kilometers) to 23,000 feet (7 kilometers) above Earth's surface. The temperature of the air at this elevation is usually between 32°F (0°C) and –13°F (–25°C). Thus, these clouds contain supercooled water, which remains in a liquid state below freezing point, or a combination of supercooled water and ice. There are two types of middle clouds: altocumulus and altostratus.

Altocumulus (Ac) Altocumulus (pronounced all-toe-KYOOM-yuh-luss) clouds are puffy masses, the bases of which are higher than ordinary cumulus clouds. Altocumulus clouds often appear in parallel rows or waves, comprised of thousands of small clouds, and may be several layers thick. These clouds are noted for the picturesque patterns they form. They are produced by the lifting of warm air that often precedes an advancing cold front, the line behind which a cold air mass is advancing.

An undercast layer of altocumulus clouds, through which a dense covering of smoke has penetrated from a forest fire raging below (seen from beneath the wing of an airplane). FMA, INC.

Within a single altocumulus cloud, one will find areas of light and dark gray and even white. The edges of each puffy mass are pronounced, indicating the presence of water droplets.

Altocumulus clouds are produced in a similar fashion to altostratus clouds, namely by the uplift of a large air mass and the resulting condensation of water droplets. The difference between the two processes has to do with air stability. When the atmosphere is unstable around the dew point, warm air continues to rise and condense. This leads to the formation of altocumulus. When the air is stable, altostratus is formed.

When warm air rises far above the base of altocumulus clouds, the puffy masses appear tall and are described as little castles. When little castles are present in the morning on a warm, humid day, it is a sign that afternoon thunderstorms are likely.

Altostratus (As) The Latin prefix *alto-* means "high" and *stratus* means "sheetlike." Thus, altostratus (pronounced all-toe-STRAY-tuss) clouds are flat sheets, the base of which is higher than ordinary stratus clouds. Similar to stratus, this plain layer of cloud covers the entire sky.

Altostratus is a white, gray, or blue-gray uniform cloud sheet that may, like stratus, blanket an area as large as hundreds of square miles. It is generally thin enough that a dim outline of the Sun (called a "watery sun") or Moon can be seen through it. Sometimes, however, it is thick enough to entirely block our view of the Sun or Moon.

A mixture of stratocumulus and altocumulus cloud fragments.
FMA, INC.

Unlike altostratus, nimbostratus, a darker gray, is so thick that it always hides the Sun. Also, nimbostratus looks textured whereas altostratus is more likely to look smooth. Altostratus can be told from stratus because stratus is the lower and darker of the two.

Altostratus clouds are produced when a large air mass rises, often pushed upward by an incoming front, and cools to the dew point. When a layer of altostratus is relatively thin, it does not generally yield precipitation. However, when it is thick enough, it will produce rain and snow over an extensive area. Altostratus clouds often precede an advancing storm system.

High clouds

High clouds are those with bases situated more than 20,000 feet (6 kilometers) above Earth's surface. They are formed when water condenses out of the air at high altitudes. In very cold weather in the middle latitudes they may form at altitudes as low as 16,000 feet (5 kilometers). The temperature of the air where high clouds form is generally below –13°F (–25°C), and the moisture content is low. Thus, these clouds are composed mostly of ice crystals, with small amounts of liquid water. This gives them their thin, wispy appearance.

Cirrus (Ci) The most common cirriform clouds are cirrus (pronounced SEER-us). These clouds are created by windblown ice crystals and are so

Cirrus clouds cover the sky over the rocky shoreline of Peter Island, British Virgin Islands. ©TODD GIPSTEIN/CORBIS.

thin as to be nearly transparent. Cirrus clouds may resemble long streamers, feathery patches, strands of hair with a curl at the end, or a number of other distinctive shapes. The wispy appearance of some cirrus clouds have earned them the nickname "mares' tails."

Cirrus clouds may appear in small patches or extensive areas of the sky. In the former case, they are associated with fair weather. These clouds are carried across the sky from west to east by the prevailing winds, the winds blowing in the direction that is observed most often during a given time period. Sailors used to measure the speed of winds aloft, which blow in the middle and upper layers of the troposphere, by the appearance of cirrus clouds: the longer the streamers, the faster the wind.

When the cirrus cover grows thicker in the west and takes on a crisscross pattern, it means that warm air is advancing at high altitudes. This is the first sign of an approaching warm front. After that, one can expect to see the development of a thick layer of cirrostratus. Clouds will develop at progressively lower heights as the rain approaches.

Cirrostratus (Cs) Cirrostratus (pronounced seer-oh-STRAY-tuss) clouds are a higher, thinner version of altostratus clouds. They cover all or part of the sky in a sheet thin enough that the Sun or Moon are clearly visible through them. When these clouds are present there is often a halo,

Cirrocumulus clouds stretch across a blue sky. FMA, INC.

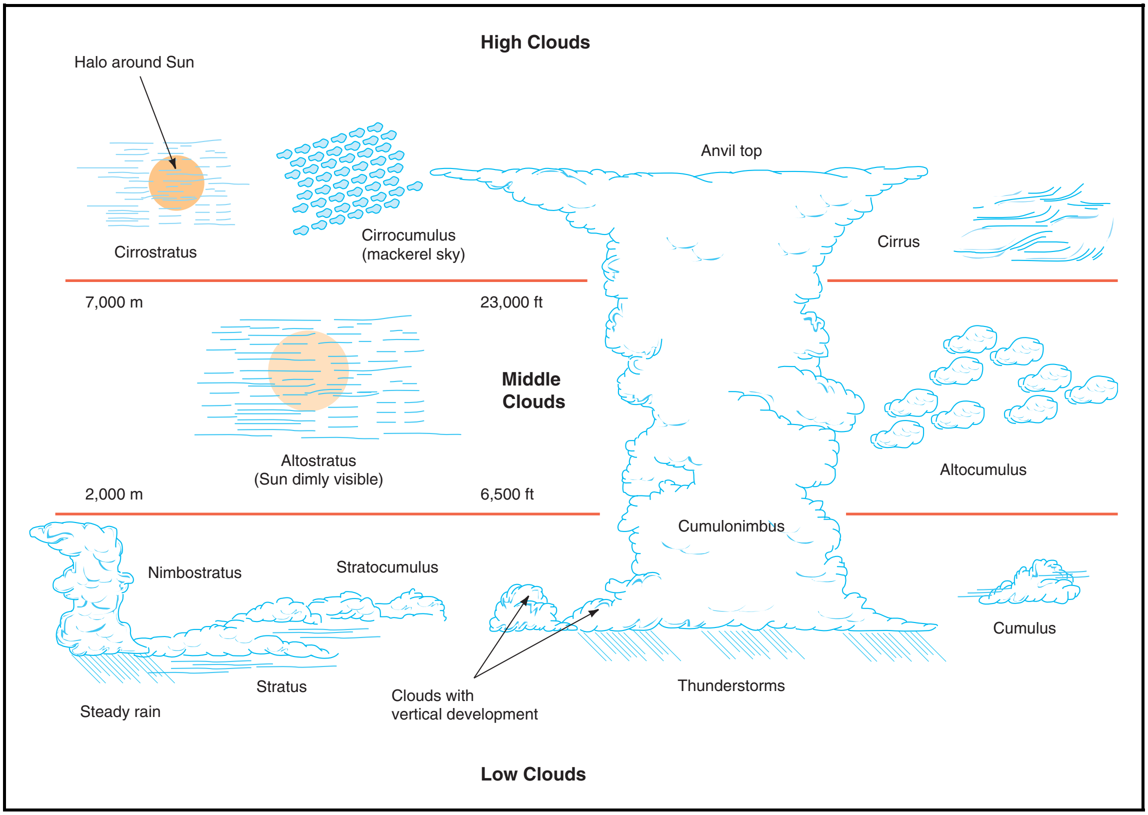
a ring of light, around the Sun or Moon. The halo is produced by the refraction, or bending, of light through the ice crystals within the clouds. In some cases, when cirrostratus clouds are nearly transparent, a halo is all that marks their presence. When these clouds are thicker, they appear as a milky white sheet across the sky.

Cirrostratus clouds are formed by a large-scale, gentle lifting of moist air to great heights. This rising air is a result of convergence, the flow of winds inward toward an area on the surface.

Cirrostratus is thinner and lighter in color than altostratus. Another way to tell the two cloud types apart is that only cirrostratus allows enough sunlight to pass through to create shadows on the ground.

Snow rarely falls from cirrostratus clouds, and when it does, it usually takes the form of virga, meaning it evaporates before it hits the ground. A layer of cirrostratus clouds that's growing thicker often represents the leading edge of a warm front. If a band of middle clouds shows up next, you can expect rain or snow in the next twelve to twenty-four hours.

Cirrocumulus (Cc) The most uncommon type of cirriform clouds is cirrocumulus (pronounced seer-oh-KYOOM-yuh-luss). These are small, white, rounded, and puffy clouds. They may occur individually or in patterns resembling rippled waves or the scales of a fish (the latter is



The base heights of the ten genera of clouds.

termed "mackerel sky"). Cirrocumulus is noted for its distinctive patterns and for the beautiful shades of red and yellow it takes on during sunrises and sunsets.

Cirrocumulus clouds resemble altocumulus clouds but exist at higher altitudes. The two cloud types can be told apart because cirrocumulus clouds are even-colored, as opposed to altocumulus clouds, in which some areas are darker than others. Also, cirrocumulus clouds have smaller individual puffs than do altocumulus clouds.

Cirrocumulus clouds usually cover a small portion of the sky; only rarely do they cover the entire sky. They generally form thin layers and block very little sunlight. In fact, similar to the case of cirrostratus clouds, enough sunlight shines through cirrocumulus cloud for shadows to appear on the ground.

Cirrocumulus itself does not yield precipitation. However, if the cloud layer begins to thicken it may indicate that a front is on the way.

Vertical clouds

The clouds included in this category are the products of sudden, forceful uplifts of small pockets of warm air. To produce a vertical cloud, the air must be thrust upward at a speed of about 70 miles per hour (mph) or 113 kilometers per hour (kph). This can happen either by convection, the upward motion of a heated air mass, or by frontal uplift, in which the warm air mass rises due to an approaching cold air mass. In contrast, the uplift of air that produces other cloud types usually occurs at a rate of less than 1 mph (1.6 kph).

The base of a vertical cloud is usually between 3,600 and 6,600 feet (1 and 2 kilometers) above the ground. These clouds are found in all parts of the world except Antarctica, where surface temperatures are so cold that convection can not take place.

Within this category are cumuliform clouds, including cumulus and cumulonimbus (thunderstorm clouds). It's important to note, however, that altostratus and nimbostratus demonstrate varying degrees of vertical development, and for that reason are also sometimes considered vertical clouds.

Towering cumulus clouds. COURTESY OF WALTER A. LYONS.

Cumulus clouds seen from an airplane. FMA, INC.

Cumulus (Cu) Cumulus (pronounced KYOOM-yuh-luss) clouds are quite easy to recognize. Formed on humid days, they look like white or light-gray cotton puffballs of various shapes set against the blue sky. They are typically about a half-mile wide, and their edges are clearly defined.

Cumulus can be distinguished from stratocumulus because cumulus clouds exist singly while stratocumulus clouds exist in groups or rows. While cumulus clouds have rounded tops, stratocumulus clouds have relatively flat tops.

Cumulus clouds are produced by convection, the rising of pockets of warm air. This occurs as the Sun warms the ground and the layer of the air above it. The warm air rises, forming a low pressure area. Surrounding air flows in and is also warmed. This process continues until a convection cell is formed. As the air rises, it expands and cools. If it cools below the dew point, clouds will form. Cumulus clouds usually begin forming in the morning and grow throughout the day. They reach their tallest point at the warmest time of day, which is generally midafternoon. In the evening, they begin to dissipate.

As long as the atmosphere is unstable (the ascending air parcel, a small portion of air with a consistent temperature, is warmer than the ambient air) at the height of the cloud base, the cumulus cloud will continue to develop vertically. The top of a cumulus cloud indicates the

Cumulus mediocris clouds dot the sky in eastern Colorado.
FMA, INC.

limit of rising air. Cumulus clouds typically grow to only moderate heights and are associated with fair weather.

When the air is particularly unstable and strong convection occurs, a cumulus cloud can reach great heights. As it surges upward, it passes through the intermediate stage of cumulus mediocris, a medium-sized cumulus with a lumpy top, and then may become cumulus congestus, which is shaped like a head of cauliflower. During this stage, cumulus clouds grow wider and often run into one another, forming a line of towering rain clouds. If the vertical growth of a cumulus congestus continues, it will evolve into a cumulonimbus, or thunderstorm cloud.

Cumulonimbus (Cb) While the dark base of a cumulonimbus (pronounced KYOOM-yuh-low-NIM-bus) can form as low as 1,000 feet (300 meters) above the ground, its top may reach 39,000 feet (12 kilometers), which is well into the upper reaches of the troposphere. In the tropics and subtropics, the top of the largest species of thunderstorm clouds, cumulonimbus incus, a fully developed cumulonimbus that reaches the top of the troposphere, can surge beyond the troposphere and into the stratosphere, the second-layer of the atmosphere.

A cumulonimbus cloud will keep growing taller as long as both convection and atmospheric instability persist. The atmosphere is considered unstable when the temperature of the surrounding air drops with

The classic cumulonimbus clouds with an anvil-like top. COURTESY WALTER A. LYONS.

increasing altitude, at a faster-than-average rate. On average, air temperature drops 3.6°F for every 1,000 feet (6.5° per kilometer) one ascends.

If a cumulonimbus cloud extends into the stratosphere, it will encounter a reversal in the cooling trend: Temperature in the stratosphere rises with altitude. This change brings a halt to the cloud's vertical growth. If the updrafts, upward-blowing columns of air, continue within the cloud, it will grow outward. Ice crystals at its top will then be sheared off by the jet stream, the fastest upper-air winds, and fan outward into a wedge-shaped mass, forming cumulonimbus incus. This cloud is so-named because its top is similar in appearance to a blacksmith's anvil, the Latin name for which is *incus.* Cumulonimbus incus clouds may appear singly or in ominous-looking rows called squall lines.

Ice that shears off the top of this cloud's anvil may form layers of cirrus and cirrostratus clouds that cover an area hundreds of miles downwind. For this reason, cumulonimbus is also referred to as a cloud factory.

The lower portions of a cumulonimbus cloud contain liquid water, the middle portions contain both water and ice, and the top is made entirely of ice crystals. Therefore, one cloud can simultaneously produce different forms of precipitation, including rain, snow, and hail, in great quantities.

A cumulonimbus cloud is a giant storehouse of energy. Within it are powerful updrafts and downdrafts of wind, blowing at speeds greater than 55 mph (88 kph). Thunder, lightning, and tornadoes all may accompany storms produced by cumulonimbus clouds.

Approximate Height of Cloud Bases Above the Surface for Various Locations

Cloud Group	Tropical Region	Temperate Region	Polar Region
High	6,000 to 18,000 m (20,000 to 60,000 ft)	5,000 to 13,000 m (16,000 to 43,000 ft)	3,000 to 8,000 m (10,000 to 26,000 ft)
Middle	2,000 to 8,000 m (6,500 to 26,000 ft)	2,000 to 7,000 m (6,500 to 23,000 ft)	2,000 to 4,000 m (6,500 to 13,000 ft)
Low	surface to 2,000 m (0 to 6,500 ft)	surface to 2,000 m (0 to 6,500 ft)	surface to 2,000 m (0 to 6,500 ft)

Variations in cloud base heights

The range of altitudes listed in the previous section for middle and high clouds applies only to the middle latitudes, or temperate regions. The bases of middle and high clouds form at highest elevations in tropical regions (30° south to 30° north) and lowest elevations in the polar regions (60° to 90°, north and south).

Specifically, the bases of middle clouds form from 6,500 to 13,000 feet (2 to 4 kilometers) in the polar regions; 6,500 feet to 23,000 feet (2 to 7 kilometers) in the temperate regions; and 6,500 to 26,000 feet (2 to 8 kilometers) in the tropical regions. The bases of high clouds form from 10,000 to 26,000 feet (3 to 8 kilometers) in the polar regions; 16,000 feet to 43,000 feet (5 to 13 kilometers) in the temperate regions; and 20,000 to 60,000 feet (6 to 18 kilometers) in the tropical regions. The base height of low clouds is unaffected by latitude.

These variations in cloud base height are due to temperature. Polar air is generally colder than temperate or tropical air at equal elevations throughout the troposphere. Thus, air cools to its dew point relatively close to the ground in the polar regions, whereas it must travel to greater heights before condensation occurs in the tropics. For instance, cirrus clouds, high clouds made of ice crystals, can form as low as 10,000 feet (3 kilometers) in polar regions, whereas they will form only at twice that height in the tropics.

The ranges of cloud base heights also show some variation within a given geographic region due to the season and time of day. Again, the cause of this variation is air temperature. In the winter, middle and high clouds form at lower heights than they do in summer. Cloud base height, on average, is highest in midafternoon when the air is warmest and lowest at night when the air is coldest.

Cloud species

To review, the ten basic groups, or genera, of clouds are stratocumulus, stratus, nimbostratus, altocumulus, altostratus, cirrus, cirrostratus, cirrocumulus, cumulus, and cumulonimbus. Within each genus (the singular of genera), there is one or more species. Species are highly defined types of clouds.

Much can be learned about a cloud by translating its species name from the Latin. For instance, *lenticularis* means "lens" and describes a lens-shaped cloud; *fractus* means "fractured" and describes a cloud with irregular or ragged edges; and *pileus* means "piled up" and refers to clouds with a caplike formation on top.

Some clouds species are subdivided into varieties. One way to name a variety is to list more than one species name after the genus name. An example of this is *Cumulus congestus pileus,* a cauliflower-shaped, sprouting cumulus cloud with a smooth, caplike cloud above it.

Examples of common species

What follows are descriptions of some common cloud species, identified by both their genus and species names.

Cumulonimbus calvus clouds boil upwards over the Nebraska prairie on a hot summer day. FMA, INC.

A key reference to: Learning to identify clouds

Being presented with a long list of cloud types, with Latin names no less, can prove overwhelming. Here are some helpful hints for identifying clouds.

When you look up at the clouds, first look for general characteristics. Ask yourself these questions: Are the clouds flat or bumpy? Do they form a solid sheet or are they individual with distinct edges? Are they white, light-gray, or dark gray? How much of the sky is covered: Is it completely overcast, can you see patches of blue, or is it mostly blue with a few clouds? Do the clouds appear to be low to the ground or high in the sky?

By comparing your answers with the descriptions given for the ten cloud genera, you should be able to identify the genera of the clouds you're looking at. After becoming reasonably successful at this, you'll be ready to start identifying cloud species. This skill requires a familiarity with the descriptions of common species. When watching the sky, one should carry a good field guide or cloud atlas. These books provide pictures of clouds alongside their names and written descriptions.

Stratus fractus Nicknamed "scud," this cloud type is the ragged underside of a stratus or nimbostratus that has separated from the parent cloud above it. Stratus fractus often appears before or after a rain- or snow-shower. The cloud gets its shredded appearance from being blown about by the wind.

Stratocumulus stratiformis This stratocumulus has puffy cloud segments that have grown together into a solid, thick, lumpy sheet. Stratocumulus stratiformis may produce precipitation heavier than a drizzle, which is unusual for a stratocumulus cloud.

Altocumulus undulatus Altocumulus undulatus takes the form of parallel rows of altocumulus clouds. They may appear in patches or cover most or all of the sky. Sometimes the rows are very close together and resemble the ripples created by dropping a pebble into still water.

The rows are produced by the action of two stacked vertical layers of air, each moving in a different direction. The upper layer of air is the colder of the two. The warm air then rises to the height of the upper layer and cools, causing moisture to condense from it. At the same time, the cold air descends into the warm layer, causing the water in its path to evaporate, or turn from a liquid into a gas. This evaporation results in cloudless rows where the cold air has traveled, interspersed with cloudy rows where the warm air has traveled.

Altostratus translucidus Altostratus translucidus is a moderately thick, featureless cloud cover that produces a visual effect known as "watery sky," sometimes called "watery sun." Watery sun is when the Sun looks like a bright, blurry ball set against a gray backdrop. The Sun appears much as it would when viewing it through frosted glass. A layer of altostratus translucidus is thicker in some parts than in others. The thickest parts of this cloud may totally obscure the Sun.

Altocumulus undulatus clouds. FMA, INC.

Cirrus uncinus This picturesque form of high, ice-crystal cloud looks as if it were painted on the sky with fine brush strokes. Cirrus uncinus, with its series of hook-shaped filaments, has been nicknamed "mares' tails." It also has been described as commas in the sky.

The distinctive look of these clouds is created by the wind. The clouds develop when ice crystals within the clouds grow. The clouds become heavier and begin to descend. They are then whipped by strong winds below, sometimes jet stream winds, and spread horizontally across the sky. The clouds' hooked tails indicate the direction of winds aloft.

Cirrus floccus Cirrus floccus resemble small cumulus clouds, high in the sky. These delicate, woolly-looking tufts are formed when warm air continues rising past the base of a cirrus cloud, depositing condensation above. Falling ice crystals, which look like hazy veils, trail beneath the clouds and are blown horizontally by the wind.

Cumulus humilis These clouds are the smallest species of cumulus cloud. They look like small tufts of cotton. Cumulus humilis are formed by weak convection currents. This pattern stands in contrast to other species of cumulus, in which convection is stronger and produces taller clouds. Cumulus humilis is also formed during the breakup of a layer of stratocumulus.

These clouds are relatively flat on the bottom, rounded on top, and wider than they are tall. They are generally associated with fair weather.

Cirrus uncinus clouds. FMA, INC.

Cumulus humilis clouds may grow throughout the day, as the Sun heats the surface and warm air pockets continue rising. They may evolve into cumulus mediocris and cumulus congestus and, under the right conditions, into a cumulonimbus thunderhead.

Fractocumulus Fractocumulus is a cumulus cloud with tattered edges. Sometimes small fragments begin to break off this cloud. The fragments may hang on the edge of the parent cloud or may separate entirely and hover nearby.

Fractocumulus often represents an intermediate step in the development of a cumulus cloud, either as it is beginning to form or beginning to dissipate. Fractocumulus may appear white or gray, depending on the Sun's position in the sky and the thickness of the cloud.

Unusual clouds

In the following descriptions of some unusual cloud formations, three of the following six examples (pileus, mammatus, and lenticular) have been introduced in the species list above. Each of these formations can occur in multiple genera. The other three examples (banner, Kelvin-Helmholtz, and contrails) will showcase clouds that are formed under special conditions and are not included in our species list.

Cumulus humilus clouds. FMA, INC.

Pileus clouds Pileus clouds, also known as cap clouds, are smooth formations found at the top of cumulus congestus or cumulonimbus clouds. A pileus cloud is formed by strong updrafts associated with a growing cumuliform cloud. These updrafts, which reach speeds of 20 to 30 mph (32 to 48 kph), force a parcel of air sharply upward. The air parcel travels along the side of the cumuliform cloud and over the top. It settles above the cloud, where the moisture within the air condenses into a flat, elongated cloud.

If the cumuliform cloud continues to grow taller, it will touch the pileus cloud, making it appear that the cumuliform cloud is wearing a pileus cap.

Mammatus clouds These distinctive, beautiful formations are often associated with severe weather. They most commonly develop on the underside of the anvil of a mature cumulonimbus cloud. They also form infrequently underneath altostratus, altocumuluscirrus, cirrocumulus, and stratocumulus clouds.

Mammatus clouds are round pouches of moisture. They appear in clusters, hanging down from and covering the underside of a cloud. They typically develop on a cumulonimbus cloud after the worst part of a thunderstorm has passed. Contrary to popular belief, the presence of mammatus rarely signals a tornado. The formation of mammatus beneath cloud types

Cumulonimbus mammatus clouds advancing ahead of a summer evening thundershower in downtown Minneapolis, Minnesota. FMA, INC.

other than cumulonimbus is a sign that thicker clouds and rain showers are either approaching or retreating.

Mammatus clouds are formed under the unusual conditions of warm, moist air traveling downward, a sort of reverse convection. The process works like this: When a thunderstorm cloud reaches the top (or occasionally surpasses the top) of the troposphere, it quits growing vertically and spreads horizontally, creating an anvil, or flattened formation at the top of a mature cumulonimbus. Pockets of warm air continue to rise to the top of the cloud and travel horizontally along the top of the anvil. Due to the large concentration of ice crystals and water droplets suspended in these pockets of air, they are heavier than the surrounding air and begin to fall.

Normally, air becomes warmer as it descends, causing the moisture within it to evaporate. However, in this case, the falling air pockets contain so much moisture that any heat gained while descending is expended in the process of evaporation. If more heat is lost than gained during the descent, the air pockets actually become cooler than the surrounding air. In that case, the moisture within them condenses once again. When this condensation occurs at the base of the anvil, it forms the structures known as mammatus clouds.

Lenticular clouds Lenticular clouds are part of a class of mountain-wave clouds, also called orographic clouds. They are generated when moist wind crosses over a mountain range. The wind blows along the surface of the westward, or windward, mountain side of the mountain, over the top, and down the eastward, or leeward side. As a result, a wavelike pattern of winds is set into motion. That pattern continues for several miles downwind of the mountaintop.

As the air moves upward toward the crest of a wave, it cools. If it is carrying sufficient moisture, clouds will form. The air then flows downward toward the trough of the wave, during which it warms and clouds

Standing lenticular cloud saucers over the Colorado Rockies. FMA, INC.

evaporate. This motion results in the formation of lenticular clouds at the wave's peaks, while clouds are absent in the troughs.

If alternating moist layers and dry layers of air exist above the mountains, these lens-shaped clouds will form one on top of another, resembling a stack of pancakes. As long as the wind continues moving through the wave at a constant rate, the clouds will remain stationary.

Lenticular clouds are a common sight over most mountain ranges. The most spectacular lenticular clouds are formed over the largest mountain ranges, such as the Himalayas, the Andes, and the Rockies.

Banner clouds Banner clouds also belong to the class of mountain-wave clouds. They are so-named because they look like banners waving from mountaintops.

A banner cloud is also sometimes referred to as a smoking mountain. It forms at a mountain's peak and drapes down over its leeward slope. A banner cloud, like a lenticular cloud, is a product of the wavelike motion of the wind across a mountain range. The reason that a banner cloud forms specifically on a mountaintop, however, has to do with changes in air pressure, or the force exerted by the weight of the air.

A banner cloud forms because air pressure builds on the windward side and subsides on the leeward side of a mountain. The windward high-pressure area is formed by the amassing of air as it travels upward, along a

Banner cloud streaming off a small peak ear Cape Town, South Africa. FMA, INC.

mountainside. As a result, pressure drops on the windward side. Condensation (and cloud formation) occurs more readily in areas of low pressure.

The most famous banner clouds are those that often adorn the peaks of Mount Everest in the Himalayas and the Matterhorn in the Swiss Alps.

Kelvin-Helmholtz clouds Kelvin-Helmholtz clouds are cirrus clouds that look like breaking ocean waves or narrow, horizontal corkscrew spirals. They are comprised of a series of eddies (small parcels of air that flow in a pattern different from the general airflow). Since they dissipate within a couple of minutes of forming, they are rarely seen.

Kelvin-Helmholtz clouds are the product of a strong wind shear. Wind shear refers to the rate of change of wind speed, or wind direction, over a set distance. The formation of Kelvin-Helmholtz clouds requires the presence of two vertical air layers of different densities that travel at different speeds. The upper layer must be the warmer and less dense of the two. Given a great enough wind shear, eddies will develop where the two air layers meet.

Kelvin-Helmholtz clouds were named for Scottish physicist Baron Kelvin (1824–1907) and German physicist Hermann von Helmholtz (1821–94), the two scientists who were the first to describe this pattern of eddies in fluids in the late nineteenth century.

Contrails Contrails are the only cloud type covered in this chapter that are not naturally occurring. These clouds are cirruslike markings spread

A thin chain of Kelvin-Helmholtz billow clouds in the sky downwind of the Colorado Rockies. FMA, INC.

across the sky by aircraft flying at 16,500 feet (5 kilometer) or higher. "Contrails" is an abbreviation for "condensation trails."

A contrail is the frozen trail of water droplets emitted by an aircraft's exhaust. At high levels of the troposphere, or low levels of the stratosphere where large aircraft travel, the air temperature is typically below –68°F (–56°C). At this temperature, water droplets freeze within seconds, appearing white against the blue sky.

When the surrounding air is relatively dry, these artificial clouds are thin, dissipate quickly, and are generally not visible from the ground.

Contrails formed in air with a high relative humidity, however, are thicker than their dry-air counterparts. They may remain visible in the sky for a half hour or more, particularly if winds are light. During this time, they may spread apart, forming a sheetlike cloud.

A thick, persistent contrail is a sign of moisture in the upper air. This sign is often the first clue that a frontal system, a weather pattern that accompanies an advancing front, is approaching.

Cloud identification and forecasting

Certain types of clouds, and especially sequences of clouds that develop over time, are reliable indicators of weather to come. Their usefulness for forecasting is greatly improved when wind speed is also considered. Once one has a familiarity with the basic cloud types, all it takes is regular

Jet plane contrails. FMA, INC.

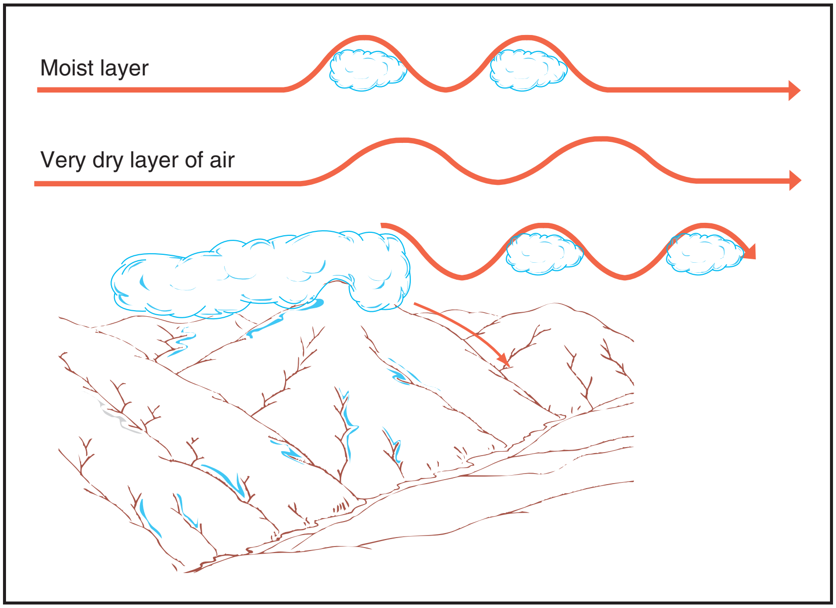
observations of the sky to predict when the weather will be fair, wet, or stormy, as well as whether the air will become warmer or colder.

Fair- and foul-weather clouds The discussions of high, middle, and low clouds earlier in this chapter described which types of precipitation, if any, are associated with each cloud genus. What follows is a summary of the weather implications of the major cloud types.

The fairest-weather clouds are high clouds. These are cirriform clouds composed of ice crystals. They rarely produce precipitation that reaches the ground. When rain or snow does fall from these clouds, it usually takes the form of virga, or fall streaks, rain that evaporates as it falls.

When cirrus clouds thicken, however, they often represent the leading edge of a frontal system, usually a warm front. If this is the case, one can expect to see the formation of progressively lower layers of clouds and precipitation within the next twenty-four hours.

Next comes the middle clouds: altostratus and altocumulus. These clouds often form in advance of a storm. Only when they exist in thick layers will these clouds yield precipitation. The presence of altocumulus castellanus, in the morning on a warm, humid day signifies the likelihood of afternoon thunderstorms.



Mountain-wave clouds.

Low clouds are the most likely to produce steady rain or snow. Stratus may do nothing more than hang in the air like a gloomy, gray blanket, or it may yield light precipitation that sometimes lasts for days. A thick layer of stratocumulus, which is often the leading edge of a cold front, may bring light drizzle or snow. The rainiest of the low clouds is nimbostratus, which often produces continuous, light to heavy precipitation for longer than twelve hours.

The final category, vertical clouds, can do just about anything. They range from cumulus humilis, the fairest of all fair-weather clouds, to cumulonimbus incus, the king of the thunderstorm clouds. The degree of raininess or snowiness of these clouds depends on their degree of vertical development: the taller the cloud, the more likely that it will produce precipitation. When cumuliform clouds yield precipitation, it is usually localized, heavy, and short-lived.

Wind direction After identifying the types of clouds in the sky, the next step in predicting the weather is to determine the direction of the surface winds. It is also important to note if, and how, the winds are shifting. Wind direction is important because the wind carries along the moisture that produces clouds and precipitation. For this reason, a change in the wind direction usually signals a change in the weather.

Altocumulus castellanus clouds.
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Cloud sequences and fronts The first sign of an approaching cold front or warm front is that cirriform clouds appear high in the sky. Next come middle clouds, then low clouds. These clouds become progressively darker, eventually bringing precipitation. Once the front passes, the sky clears. The specifics of this general sequence of events are different for cold fronts than they are for warm fronts.

Cold fronts A cold front, the leading edge of a relatively cold air mass, advances more quickly than does a warm front. It generally takes five to seven days to pass completely through an area. The first sign of a cold front is the appearance of cirrus clouds, which remain in the sky for as long as several days.

After that, one can expect the development of any number of sequences of clouds. This pattern depends on the speed with which the front is moving. In general, however, the next type of cloud to form is cirrocumulus, followed by either altocumulus or altostratus. Then comes a layer of stratocumulus which becomes progressively thicker. Rain clouds, nimbostratus or cumulonimbus, are next on the scene.

The intensity of precipitation brought by the rain clouds depends on the strength of the front. The strength of the front, in turn, is determined by the contrast in temperature between the two air masses: the colder air mass being ushered in by the cold front and the warmer air mass that is being displaced. Storms are fueled by the contrast of warm and cold air. The greater the temperature difference, the more severe the storm.

Thus, the final stage of a cold front's passage through an area can be marked by anything from an overcast sky and drizzle to a series of two or three thunderstorms. When the front has passed, blue skies and colder air remain.

Warm fronts A warm front moves along more slowly than a cold front and is much gentler in its approach. Whereas a cold front pushes its way into a warm air mass, thrusting the warm air above it, a warm front overtakes a cold air mass by gliding above the cold air and nudging it along. The upper, leading edge of a warm front can arrive at a given location up to 1,000 miles (1,600 kilometers) and several days before its base arrives.

Because a warm front moves so slowly, its leading edge produces an extensive sequence of cloud types. Initially there are wispy cirrus clouds. These spread out across the sky into cirrus spissatus. Next comes a layer of either rippled cirrocumulus (called "mackerel sky") or cirrostratus. After that come the middle clouds: altostratus followed by altocumulus. As moisture continues to condense at lower levels, stratocumulus and sometimes stratus appear.

As the base of the warm front approaches, rain clouds—nimbostratus or, infrequently, cumulonimbus—form. Whereas the precipitation associated with a warm front is usually lighter than that associated with a cold front, it can last for several days, and it may be heavy at times. When the front has passed completely, the sky clears and the temperature rises.

[*See Also* **Weather: An Introduction**]

Weather report: Keep a cloud journal

Try your hand at forecasting by the clouds. Each morning and evening for a week, make a sketch of the clouds you see and attempt to identify them by genus and species. For each journal entry, make predictions about which types of clouds will appear next, as well as whether it will rain or snow. Your predictions should be based on the sequence of cloud types that have appeared since the start of your journal. For each entry, note whether your previous prediction came true.

For More Information

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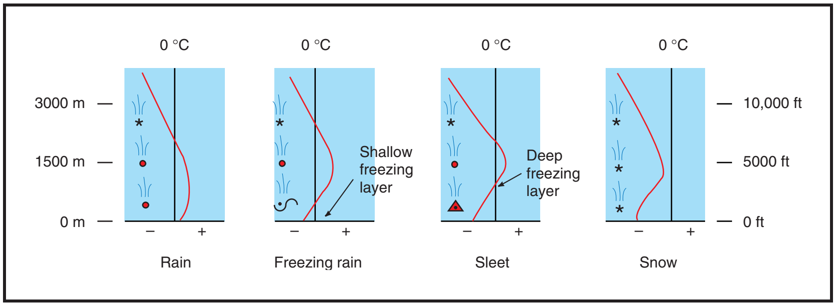
Precipitation

Precipitation is defined as any form of water that originates in the clouds and falls toward the ground. By this definition, precipitation includes rain, snow, and ice. Each of the three main forms of precipitation can be broken down into specific categories, according to the temperature of the air layers through which the precipitation passes, the size of the individual water particles, and the intensity with which it falls.

Most precipitation (except in the tropics) originates in clouds as ice crystals. As an ice crystal descends through a cloud, it grows by collecting water vapor and droplets of supercooled water, which remains in the liquid state below the freezing point. In the process, the ice crystal takes on the shape of a snowflake, a lump of snow or ice, or in severe thunderstorms, hail. What happens next depends on the air temperature at various heights throughout the ice crystal's descent.

If the air temperature remains below freezing throughout the entire descent, the precipitation will reach the ground in the frozen state as snow. If the ice crystal passes through a layer of air above the freezing point of water, the ice crystal will melt and fall as rain. However, if the melting raindrop passes through a freezing layer, it will refreeze and reach the ground as ice pellets, or frozen raindrops. Finally, if the ice crystal melts, only to reenter freezing air just at ground level, it will strike the ground as freezing rain.

Rain Each raindrop is made up of a million or so microscopic cloud droplets. The average raindrop measures 0.04 to 0.24 inches (0.10 to 0.61 centimeters) in diameter. Raindrops that are larger than average become unstable and tend to break apart into smaller raindrops. "Rain" is defined as liquid water that falls from the sky. A rain waterdrop must be larger than 0.02 inches (0.05 centimeters). Precipitation consisting of anything smaller than that is called drizzle.



Vertical air temperature profiles through which various forms of precipitation descend.

The main sources of rain are thick clouds with high bases, namely nimbostratus and cumulonimbus clouds. Occasionally rain falls from a thick layer of altostratus or tall cumulus clouds.

Some raindrops form in warm clouds, clouds that are too warm for ice crystals to form. Although raindrops also collide with water droplets as they descend through a cloud, the collisions are less likely to result in coalescence (the process by which an ice crystal grows larger). Hence, water drops do not grow as large as their ice-crystal counterparts. Raindrops from warm clouds are usually less than 0.08 inches (0.2 centimeters) in diameter.

The exception to this rule are raindrops that form in towering cumulus or cumulonimbus clouds in the tropics. In those clouds, where strong updrafts (columns of air blowing upward, inside a vertical cloud) exist, a water drop may be blown from the bottom to the top of the cloud several times, growing larger each time, until it finally falls to the ground. Raindrops up to 0.32 inches (0.8 centimeters) in diameter have been found falling from such clouds in Hawaii.

Visibility in the air improves following a rainfall because precipitation has a cleansing effect on the air. Water droplets in the air form around condensation nuclei, tiny particles of dust and debris. When precipitation falls, it removes these particles from the air.

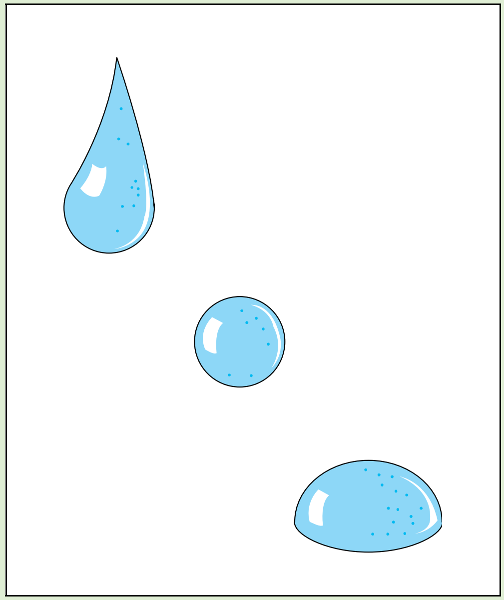
Drizzle Drizzle is precipitation made up of drops that are between 0.008 inches (0.02 centimeters) and 0.02 inches (0.05 centimeters) in diameter. These drops are just barely large enough to overcome the upward force of air resistance. Once they do, they slowly drift downward, sometimes taking over an hour to travel from the cloud to the ground.

Weather report: The shape of a raindrop

Contrary to popular belief, raindrops are not tear-shaped or pear-shaped. Raindrops vary in shape between a sphere and a lump, depending on their size.

Small raindrops, less than 0.08 inches (0.2 centimeters) in diameter, are nearly spherical. Raindrops with diameters greater than 0.08 inches look saucer-shaped, flattened at the bottom and rounded on the top. They are wider than they are tall. Large raindrops have been said to resemble falling parachutes, mushroom caps, and hamburger buns.

The shape of a raindrop is caused by surface tension and air resistance. Surface tension is the attraction between water molecules at the surface. Surface tension forces molecules into the configuration with the smallest surface area, which is a sphere. In larger raindrops, this shape is distorted by the effect of air pressure (the pressure exerted by the weight of air over a given area of Earth's surface). Air pressure is felt most strongly on the bottom of the drop and most weakly on the sides of the drop. It pushes the bottom upward, flattening it, while allowing the sides to expand.



If a raindrop becomes larger than 0.25 inches (0.6 centimeters) in diameter, it will flatten out even more. At the same time it will become pinched on the top, into a bow-tie shape. The two halves of the bow tie will bulge and become more pronounced until the drop divides into two smaller spherical drops.

Drizzle is produced in two ways. It falls from stratus clouds, which are low and exist in shallow layers less than 1.5 miles (about 2.5 kilometers) thick. In stratus clouds, water drops have far less opportunity to grow by coalescence than they do in rain-producing clouds. Drizzle can also form as it begins as rain, descends through dry air, and partially evaporates. By the time the raindrops reach the ground, they have been reduced to the size of drizzle.

Drizzle may fall constantly, even for an entire day. The heaviest drizzle is produced where warm, moist air rises along the side of a

Virga, or falling rain that evaporates in the air. FMA, INC.

mountain and forms mountain-wave clouds. Drizzle that falls from these clouds can produce 0.4 inches (1 centimeter) of water per day.

The drops in drizzle fall very close together, which reduces visibility. In a heavy drizzle, it may be possible to see only five-sixteenths of a mile (0.5 kilometer) ahead.

Virga When humidity is very low, rain or snow may completely evaporate into the air during its descent. This creates streaks of falling water, called virga. Virga looks like dark fringes extending from the base of a cloud.

Virga often sets the stage for heavier precipitation. It does this by increasing the humidity of the air into which it evaporates. Thus, water or ice that falls may subsequently make it to the ground. Virga can also provide additional condensation nuclei for another cloud.

Showers A shower is a spell of heavy, localized rainfall that occurs only in warm weather. Showers fall from towering cumuliform clouds, which are produced by strong convection currents (the circular movements of gas or liquid between hot and cold areas). Convection is the rising of pockets of warm air that occurs when Earth's surface is heated.

A shower occurs only while the shower- producing cumuliform cloud is overhead. It can last anywhere from two minutes to a half hour, depending on wind speed and the size of the cloud. In an area where a

Orographic stratus, a type of mountain wave cloud: thick stratus clouds form over the slopes of Maui in the Hawaiian Islands as moist, tropical trade wind air is forced upwards. FMA, INC.

series of cumuliform clouds exist, several showers may occur, separated by dry, even sunny, periods.

The area being showered at any given time is no larger than 4 to 5 square miles (10 to 13 square kilometers). Rain, in contrast, can fall on an area larger than 100 square miles (260 square kilometers) at a time and can last all day.

Towering cumuliform clouds give rise to showers because they are able to generate large quantities of raindrops quickly. Ice crystals or water drops bounce between the top and bottom of the cloud numerous times, growing larger by coalescence on each trip. In most cases, by the time an ice crystal reaches the bottom of the cloud, the air is warm enough to cause the ice to melt.

When a water drop becomes too large, it breaks apart, forming smaller drops. These drops, in turn, get blown to the top of the cloud, and the process of coalescence is repeated. A chain reaction ensues, producing more and more drops. This reaction continues until the updrafts weaken or change direction. Then a sudden, heavy shower falls.

The heaviest showers are called cloudbursts. To qualify as a cloudburst, precipitation must fall at a rate of 4 inches (10 centimeters) or more per hour. The heaviest showers occur in the tropics, where the air is warm and moist, and powerful convection currents produce huge thunderstorm clouds.

A key reference to: Measuring the intensity of rainfall

The intensity of precipitation is the amount of water that falls over a given period of time. For instance, a cloudburst is the most intense form of rainfall because it releases a large amount of water to the ground in a very short period of time. On the other hand, a steady rain may produce the same amount of water as a cloudburst, but since it falls over a longer period, it has a lower intensity.

The following are commonly accepted definitions for categories of rainfall, based on intensity:

- Heavy rain: greater than 0.3 inches (0.75 centimeters) of water falls per hour. Heavy rain appears to fall in sheets and greatly reduces visibility.
- Moderate rain: between 0.1 and 0.3 inches (0.25 and 0.76 centimeters) of water falls per hour. While the rain does not fall in sheets, it still falls too fast to see individual raindrops.
- Light rain: less than 0.1 inches (0.25 centimeters) of water falls per hour. Individual raindrops can be seen.
- Trace: rainfall is too light to measure.

The intensity of drizzle, which produces very small quantities of water, is measured in terms of visibility.

- Heavy drizzle: visibility is restricted to 0.31 miles (0.5 kilometers).
- Moderate drizzle: visibility is between 0.31 and 0.62 miles (0.5 and 1 kilometer).
- Light drizzle: visibility is greater than 0.62 miles (1 kilometer).

Freezing rain Freezing rain, as its name suggests, is rain that freezes on the ground. Freezing rain begins its journey to the surface as snow. As the snow descends, it encounters a layer of warm air and melts. Then, just above the ground, it travels through a shallow layer of subfreezing air. The raindrops don't have time to refreeze but remain in the liquid state at temperatures below freezing. In other words, they become supercooled.

When the supercooled liquid makes contact with a cold surface, it spreads out and then freezes. It forms a layer of clear, smooth ice called glaze. If drizzle becomes supercooled and then freezes on the ground, it is known as freezing drizzle. Freezing rain creates a beautiful, but hazardous, coating of ice on trees, power lines, and roads.

Freezing rain occurs most often in the winter, following a cold night in which the ground rapidly loses heat to the atmosphere through radiational cooling. As a result, an inversion is produced. An inversion exists when a layer of cold air is found next to the ground and a warmer layer of air lies above.

A heavy downpour of freezing rain is called an ice storm. While the layer of glaze deposited by freezing rain is usually less than an inch thick, it can be much thicker in ice storms. For instance, an ice storm in northern Idaho in January 1961 produced an 8-inch-thick (20-centimeter-thick) layer of glaze. It has been estimated that during a severe ice storm, a 50-foot-tall (15-meter-tall) evergreen tree with an average width of 20 feet (6 meters) may be loaded down with five tons of ice.

In an ice storm, it is common for tree limbs and power and telephone lines to be knocked down. The ice is very difficult to drive on and causes traffic accidents. Over 85 percent of the deaths that occur in ice storms are traffic related.

A layer of glaze coats trees and shrubs following an ice storm. COURTESY PHILLIS ENGLEBERT.

One of the most severe ice storms on record struck a huge area, from Mississippi to New England, in January 1983. That storm resulted in an estimated 25 deaths and cut off power to more than 250,000 people.

Freezing rain is common in hilly or mountainous areas, where cold air sinks into the valleys. In the Appalachian mountains of Pennsylvania and West Virginia, freezing rain can fall on localized areas for long periods of time. The ice deposited by freezing rain usually melts within a few hours, although occasionally it can persist for days. The record for the longest-lasting glaze was set in 1969. In that year, ice remained on the trees for six weeks in Connecticut.

Snow Snow is precipitation that is common during the winter in middle latitudes (the regions between 30° and 60°, north and south) and year-round on mountaintops. Its basic unit is the snowflake, which consists of many ice crystals joined to each other. Like raindrops, snowflakes come in various shapes and sizes. Like rain, snow is categorized by the intensity with which it falls: from the lightest form, flurries, to the heaviest form, a blizzard.

In order to qualify as snow, precipitation must remain frozen when it reaches the ground. This does not mean, however, that it can snow only when the surface air temperature is at or below freezing.

Weather report: Rainmaking

People throughout the ages have sought ways to bring rain to moisture-deprived areas. In the 1800s and early 1900s people tried, unsuccessfully, to produce rain by ringing church bells or firing cannons into the air. In the mid-1940s, scientists began testing an experimental method called cloud seeding. Cloud seeding involves injecting particles into a cloud, which act as freezing nuclei. Cloud droplets adhere to the particles and fall to the ground as precipitation.

A requirement of cloud seeding is that clouds are already present. Those clouds must be tall enough so that their upper portions extend into regions where temperatures are below freezing. In other words, they must be cold clouds. That is because the droplets that stick to the injected particles must be supercooled, meaning they exist in the liquid state at temperatures below freezing. Supercooled water droplets are found only in cold clouds.

The earliest cloud seeding experiments, performed in 1946 by atmospheric scientist Vincent Schaefer, involved dropping crushed dry ice (carbon dioxide) pellets into the top of a cloud from an airplane. Since dry ice is extremely cold (–108°F or –78°C), it cools the air around it, which produces more condensation. The dry ice pellets also act as freezing nuclei. In one experiment, Schaefer dropped three pounds of ground dry ice into an altocumulus cloud. Five minutes later, snow began falling from that cloud. The following year one of Schaefer's colleagues, Bernard Vonnegut, discovered that silver iodide makes a better cloud seeding agent than dry ice.

The 1950s saw a boom of rainmaking operations in drought-stricken areas around the world that experienced extended periods of abnormal dryness. These operations failed, however, to produce a significant increase in precipitation. Furthermore, they provoked the objections of many people who were concerned with the broader implications of manipulating the atmosphere. Would cloud seeding irreversibly alter the Earth's water cycle? Would it lead to uncontrollable flooding or prolonged droughts?

Despite these concerns, at the end of the 1950s a U.S. federal research program was launched on cloud seeding and other forms of weather modification. Government agencies and private

Rather, snow can remain frozen at temperatures above freezing for distances up to 1,000 feet (300 meters) without melting. The exact air temperature at which snow turns to rain depends on the humidity of the air.

At the beginning of a snowfall, when temperatures are above freezing, snow may turn to rain as it falls. If air is dry, rain rapidly evaporates into it. The process of evaporation (in which water changes from a liquid to a gas) draws heat from the air, leaving the air cooler than before the evaporation began.

As snow continues to fall from the cloud, it encounters lower temperatures, although temperatures may still be above freezing. If the snow enters companies conducted many experiments, with inconclusive results.

Cloud seeding was the center of controversy more than once in the 1970s. In 1972, a spate of cloud seeding was followed by a flash flood (a sudden, intense, localized flooding caused by persistent, heavy rainfall or the failure of a levee or dam) in Rapid City, South Dakota, in which more than two hundred people lost their lives. While the cloud seeding and the flash flood may or may not have been linked, the tragedy was enough to deter people from further rainmaking experiments there. Cloud seeding was also a questionable practice used by the U.S. military during the Vietnam War. After the flooding of the Ho Chi Minh Trail, which supposedly came about as a result of cloud seeding by the U.S. military, the U.S. Senate called the practice into question.

Does cloud seeding really work? More than sixty years after the first cloud-seeding experiment this question is still hotly debated. Some studies suggest that, under particular circumstances, cloud seeding can increase precipitation by 5 to 20 percent.

Some of the most impressive results have been obtained by seeding cumulus clouds. As droplets freeze to the injected particles, they release latent heat (the energy that is either absorbed by or released by a substance as it undergoes a phase change), which fuels the upward expansion of the clouds. When a cumulus cloud develops vertically, it lasts longer and is more likely to produce precipitation. Another way in which cloud seeding seems to be effective is by seeding winter clouds that are already producing precipitation. This practice has been shown to increase the amount of snow falling from those clouds.

On the flip side, by overseeding a cloud, it's possible to reduce precipitation. When too many freezing nuclei are present, they remain too small to fall to the ground—even after all available supercooled droplets have frozen onto the freezing nuclei. The moisture in the cloud will then evaporate. For this reason, overseeding is used at airports to dissipate thick fog (clouds that form near the ground).

The practice of cloud seeding continues to the present day. Current expectations of what cloud seeding can produce, however, are quite humble compared to the expectations of researchers in the 1940s and 1950s. In the United States, cloud seeding is performed mainly in California. There, the goal of cloud seeding is to slightly increase the amount of rainfall or snowfall produced by storms.

above-freezing temperatures, it begins to melt. Water from the edge of a snowflake rapidly evaporates into the air, further cooling the air, as well as cooling the snowflake.

If cooled below the freezing point by the evaporative process, the snowflake will reach the ground intact. If not, it will melt, and some of the water will evaporate, further lowering the air temperature. As long as air remains unsaturated (with less than 100 percent relative humidity, a measure of humidity as a percentage of the total moisture a given volume of air, at a particular temperature, can hold), the cooling process will continue. However, once air becomes saturated (has 100 percent relative humidity), no net evaporation will occur, and cooling will cease.

Weather report: Ice and aircraft

Freezing rain and supercooled water droplets within clouds pose major hazards to aircraft. As an aircraft travels through clouds where the temperature is between 10 and 32°F (–12 and 0°C), it encounters a mixture of ice crystals and supercooled droplets. Where supercooled raindrops or large droplets in clouds come in contact with an aircraft, they spread out and form an even coating of ice called glaze. Where the small droplets strike an aircraft, they freeze immediately without spreading, trapping air bubbles. The second type of icy coating, which appears white and weighs less than glaze, is called rime.

A layer of glaze, and to a lesser extent a layer of rime, affects an aircraft in several ways. First, it makes the plane heavy—sometimes so heavy that it is literally pulled from the sky. Second, if ice forms on the plane's wing or fuselage, it provides wind resistance and alters the plane's aerodynamics. If the engine's air intake opening is iced over, it can lead to a loss of power. Ice can also cause the failure of brakes, landing gear, or instruments.

Ice poses the greatest danger to small, single- or twin-engine planes. Ice affects jet airliners to a lesser extent since those planes spend most of their time above the clouds. Nonetheless, airline pilots are given warnings of, and strive to avoid, clouds that may contain supercooled droplets. As an added precaution, the wings of an aircraft are usually de-iced, meaning they are sprayed with a type of antifreeze before take-off.

Snowflakes The first person to study the intricate detail and uniqueness of snowflakes extensively was an American farmer named Wilson Bentley (1865–1931). Beginning in 1880, when he was just fifteen years old, Bentley placed snowflakes under a microscope and photographed them. He continued this work for fifty years, making thousands of photographs. In 1931 he published a book with W. J. Humphreys, entitled *Snow Crystals,* which contained more than 2,300 photos of snow and frost.

One thing that all snowflakes have in common is a hexagonal (six-sided) configuration. The structure of the ice crystals that make up a snowflake is also hexagonal. In fact, this basic shape can be traced back to water molecules. Because of the electrical attraction between water molecules, they take a hexagonal shape when they freeze.

A snowflake begins its existence as an ice crystal within a cold cloud. As it bounces between the bottom and top of the cloud, it grows by coalescence with supercooled water drops or by deposition, the freezing of water vapor molecules directly onto the ice crystal. As the ice crystal grows, it bonds with other ice crystals and assumes the shape of a snowflake (also called a snow crystal). When the snowflake becomes heavy enough, it descends to the surface.

Snowflakes can exist in flat, platelike forms; long, six-sided columns; or needles that are two hundred times longer than they are wide. They may also form starry shapes, called sector plates. When a sector plate accumulates moisture, it may develop feathery branches on its arms. In

Snow mounds in a snowbelt downwind of the Great Lakes. COURTESY WALTER A. LYONS.

this way, the most distinctive and most common snowflake, the dendrite, is formed. As dendrites travel through the cloud, they may combine with other dendrites, forming a wide array of complex patterns.

The shape of a snowflake depends upon the air temperature within the cloud where it is formed.

- Below –8°F (–22°C), snowflakes are hollow columns.
- Between –8 and 3°F (–22 and –16°C), they are sector plates.
- Between 3 and 10°F (–16 and –12°C), they are dendrites.
- Between 10 and 14°F (–12 and –10°C), they are sector plates.
- Between 14 and 21°F (–10 and –6°C), they are hollow columns.
- Between 21 and 25°F (–6 and –4°C), they are needles.
- Over 25°F (–4°C), they are thin hexagonal plates.

Why are dendrites the most common form of snowflake, given that they only form within a narrow range of temperatures (10 and 14°F or –12 and –10°C)? The reason is that dendrites form more rapidly than do other snowflake types.

In the dendrite-forming temperature range, the difference in vapor pressure (the pressure exerted by a vapor when it is in equilibrium with its liquid or solid) between water droplets and ice crystals is greatest. Vapor pressure is the pressure exerted by a vapor when it is in equilibrium with

Question: Why do we salt icy roads?

Salt is applied to snowy, icy roads because it melts ice and prevents the water from refreezing. Compared to other materials that are used to combat slippery roadways, such as sand and cinders, salt is relatively cheap and easy to apply. For these reasons, salt has been the road de-icing agent of choice since the 1960s.

The chemical composition of salt used on roads is sodium chloride (NaCl). When it comes in contact with water molecules, NaCl breaks down into one positively charged sodium ion (NA+2) and two negatively charged chloride ions (Cl–). A water molecule consists of one oxygen atom (O–2) and two hydrogen atoms (H+). The positively charged hydrogen atoms are drawn to the negatively charged chloride atoms. Negatively charged oxygen atoms are drawn to the sodium atoms.

Sodium chloride thus causes the components of individual water molecules to disassociate. It bonds with the hydrogen and oxygen atoms so that hydrogen and oxygen are not free to recombine into water. The sodium and chloride ions also draw water molecules away from one another. Salt both prevents liquid water molecules from forming ice crystals and breaks up existing ice crystals.

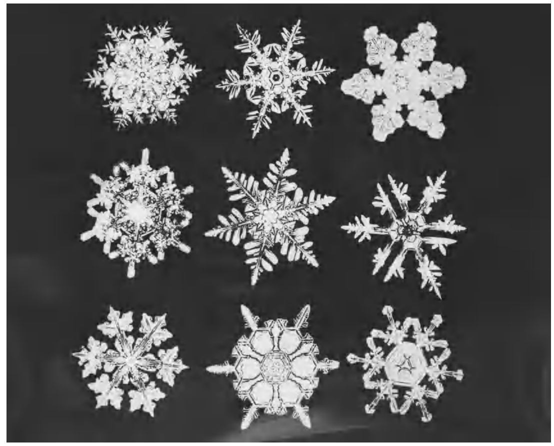
Sodium chloride lowers the freezing point of water from 32°F (0°C) to 20°F (–7°C). At temperatures below 20°F, salt is no longer effective at melting ice.

Whereas salt provides an efficient means of melting snow and ice on roads, and has greatly contributed to highway safety, it also has a downside. Salt is bad for the environment. It kills vegetation along the side of the road and can seep down into wells, making the water undrinkable. Salt also causes vehicles to rust and bridges to corrode. For these reasons, salt is only applied in the minimum quantities necessary to get the job done.

its liquid or solid. Vapor pressure is greater over the surface of a water droplet than it is over the surface of an ice crystal. Similar to air, water molecules migrate from an area of high pressure to an area where pressure is lower. Thus, when a water droplet comes in contact with an ice crystal, water molecules leave the water droplet and freeze onto the ice crystal. The greater the difference in vapor pressure between water and ice, the more rapidly ice crystal growth occurs.

The size of a snowflake depends upon the temperature of the air as the snowflake descends. When a snowflake falls through air in which the temperature is above freezing, it melts around the edges. A film of water forms that acts like glue. It causes snowflakes that come in contact with one another to stick together, producing large, soggy snowflakes, 2 to 4 inches (5 to 10 centimeters) or larger in diameter. These snowflakes stick to surfaces and are heavy to shovel.

In contrast, snowflakes that fall through very cold dry air do not readily stick together. They are small and powdery when they hit the ground. This snow makes for ideal skiing conditions.



Snowflakes come in a variety of patterns. ©BETTMANN/CORBIS.

Snow grains and snow pellets Snow grains are the frozen equivalent of drizzle. They are small, soft white grains of ice that form within stratus clouds and fall to the ground in only small amounts. Snow grains are elongated and generally have diameters less than 0.04 inches (0.1 centimeters). Because they are so light, they fall very slowly and land gently, without bouncing or shattering.

In contrast to snow grains, snow pellets fall rapidly and bounce high off the ground. These white pieces of icy matter, also called graupel or soft hail, measure between 0.08 and 0.2 inches (0.2 and 0.5 centimeters) in diameter. Snow pellets fall in showers and feel brittle and crunchy underfoot.

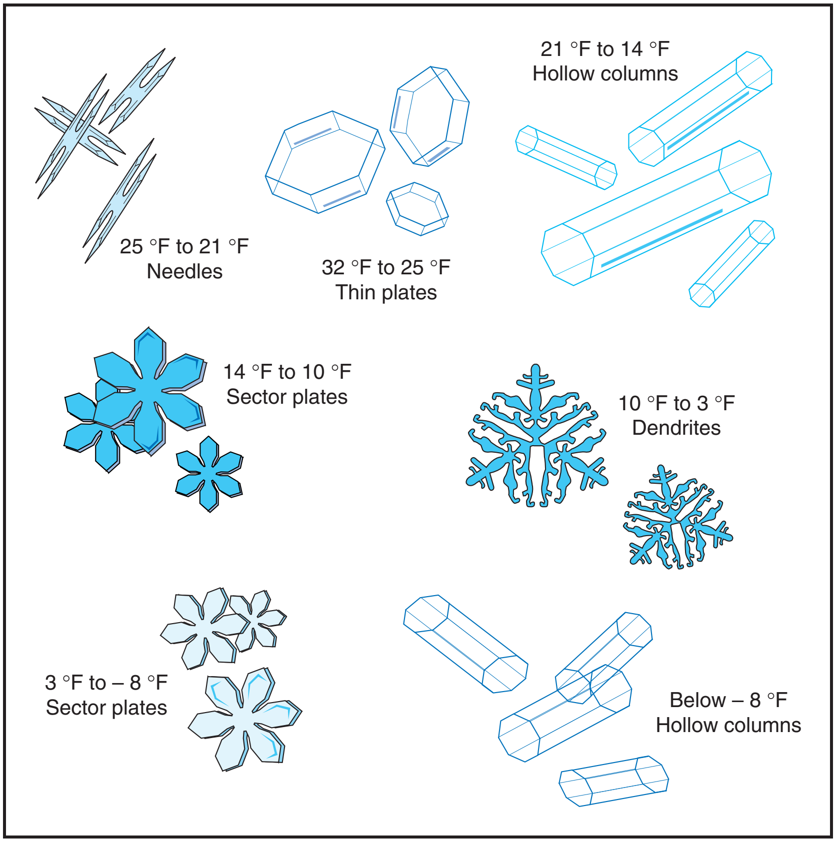
Snow pellets form within towering cumuliform clouds, where the atmosphere is very unstable. This instability occurs when air temperature drops rapidly with height. The top of the cloud, where temperatures are lowest, is inhabited mostly by ice crystals. The ice crystals grow by the deposition of water vapor onto them and take on the shape of snowflakes.

As a snowflake travels downward into the warmer, middle region of the cloud, it encounters supercooled water droplets. In what is known as riming, the droplets freeze to the snowflake, trapping numerous air pockets in the process. If riming occurs to a great enough extent, the snowflake will be transformed into a lumpy, white pellet of snow called graupel. It is in this form that precipitation reaches the surface.

Intensity of snowfall The lightest form of snowfall is flurries. Flurries are brief and intermittent and originate in cumuliform clouds. While they produce very little accumulation, flurries may interfere with visibility.

A heavier and more persistent snowfall, which most people think of as snow, comes from nimbostratus and altostratus clouds. This snowfall may continue steadily for several hours.

A brief but heavy snow shower is called a snow squall. Snow squalls, like flurries usually originate in cumuliform clouds. Snow squalls can be



The shapes of snowflakes at various temperatures.

compared in intensity to summer rain showers and are accompanied by strong surface winds.

Heavy snow is defined as that which reduces visibility to 0.3 miles (0.5 kilometers). Heavy snow, on average, yields 4 inches (10 centimeters) or more in a twelve-hour period or 6 inches (15 centimeters) or more in a twenty-four hour period. However, the amount of snow accumulation deemed heavy varies from one geographic area to another. For instance, in places where accumulations of 4 inches during a twelve-hour period are common, snow may not be considered heavy until more than 6 inches have accumulated during that period. On the other hand, where any accumulation of snowfall is rare, an accumulation of 2 to 3 inches (5 to 8 centimeters) in a twelve-hour period may be considered heavy.

Snow can also be classified by how it behaves on the surface. For instance, drifting snow is loose snow that has been swept by strong winds into large piles, or drifts. Blowing snow is snow that has been lifted off the surface by the wind and blown about in the air. Blowing snow may reduce visibility in a manner similar to that which occurs in a heavy snowfall. A ground blizzard is the condition that results when snow continues to drift and blow after a snowfall has ended.

Blizzards A blizzard is the most severe type of winter storm. It is characterized by strong winds, large quantities of snow, and low temperatures. The National Weather Service defines a blizzard as a snowstorm with winds of 35 mph (56 kph) or greater. The temperature is generally 20°F (–7°C) or lower. The falling and blowing of fine powdery snow greatly reduces visibility, often to less than a quarter of a mile and sometimes to just a few yards.

When a blizzard strikes, it can bring traffic to a standstill, strand motorists, and shut down entire cities. Prolonged exposure to a blizzard can cause frostbite (the freezing of the skin), hypothermia (a condition characterized by a drop in core body temperature from the normal 98.6°F to below 95°F), and even death. Some people have actually suffocated to death during blizzards by choking on fine, powdery snow.

A severe blizzard is a blizzard in which wind speeds exceed 45 mph (72 kph), the snowfall is heavy, and the temperature is no higher than 10°F (–12°C). When falling, drifting, and blowing snow reduce visibility to almost zero, the condition is called a whiteout. Everything appears white, making the ground and sky indistinguishable. People stranded in such conditions can easily become disoriented and lose their way.

Can two snowflakes be alike?

To answer this question, a definition of "alike" is required. "Alike" can mean that two snowflakes are the same, molecule for molecule, throughout. By this definition, the answer is no, two snowflakes cannot be alike. First of all, a snowflake contains over 180 billion water molecules. These molecules come together under many different conditions, making it all but impossible for any two snowflakes to have an identical configuration. In addition, water molecules are constantly freezing to and evaporating from snowflakes, meaning that snowflakes are constantly changing at the molecular level.

An alternate definition of "alike" is "identical in appearance." By this definition, the answer is yes, two snowflakes can be alike. This fact was discovered in 1989 by Nancy Knight, a cloud physicist with the National Center for Atmospheric Research. Knight collected snow samples while on board a research aircraft at a height of 20,000 feet (6 kilometers) over Wausau, Wisconsin. She discovered two hollow-column snowflakes, both 250 microns long and 170 microns wide (a micron is one-millionth of a meter—by way of comparison, a human hair is about 100 microns in diameter), proving that snowflakes can be identical in appearance. To this day, however, there is no record of identical dendrites.

Avalanches An avalanche is the cascading of at least 100,000 tons of snow down a steep slope. It occurs when stress is placed on a weak layer of

Weather report: Lake-effect snow

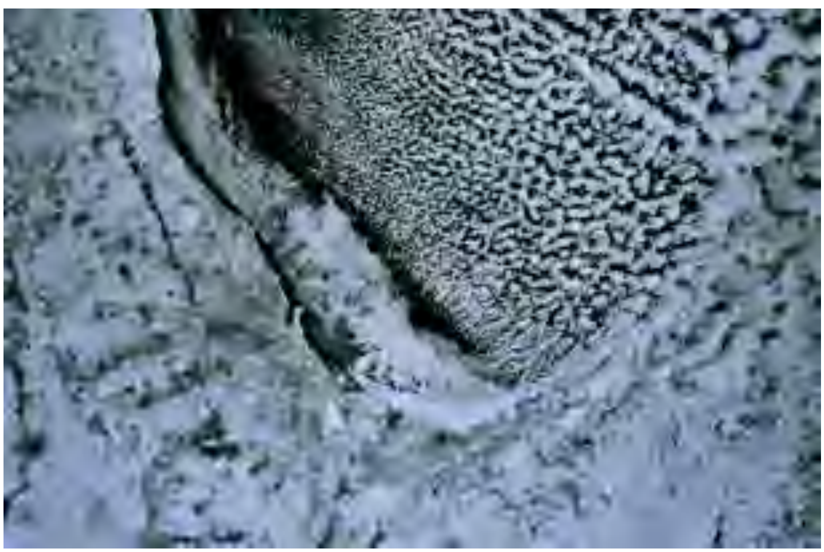
Lake-effect snow is the name given to the heavy snowfalls that occur along the shorelines of the Great Lakes. The process that gives rise to lake-effect snow begins when dry, polar air masses, informally called Alberta Clippers, sweep down from Canada. As this air travels across the Great Lakes, evaporation in the form of steam fog raises the humidity of the air considerably. Clouds form and deposit heavy snowfall on the land downwind of the Great Lakes.

In January 1959, 51 inches (130 centimeters) of lake-effect snow fell during a sixteen-hour period on Bennetts Bridge, New York, on the southern shore of Lake Ontario. Lake-effect snow fell on Buffalo, New York, for forty straight days during the winter of 1976–77.

snow. For an avalanche to occur, snow on the ground must be layered in such a way that it is structurally unstable. For instance, a loose layer of snow may be sandwiched between two more compact layers.

Every time new snow falls, it places additional weight and pressure on the existing snow. At some point, this pressure may give rise to a fracture (break) across the blanket of snow, down to the weakest layer. As soon as any additional stress is added, a slab of snow breaks off and goes hurtling down the slope, The additional stress may take the form of more snow, a strong gust of wind, the weight of a skier, or even a loud noise.

Avalanches are extremely destructive. They bury everything in their path, even cities, in a matter of seconds. The largest avalanches occur in the Andes, the Himalayas, and the mountains of Alaska. However it is in the Alps, where valley regions are heavily populated, that avalanches pose the greatest danger to humans.



A Landsat image shows lines of intense lake-effect snow squalls heading for northern Indiana and lower Michigan during a blustery outbreak of frigid arctic air moving across Lake Michigan. FMA, INC.

A heavy snowfall covers the landscape. ©TIM THOMPSON/CORBIS.

A key reference to: Winter storm alerts and safety procedures

The National Weather Service issues winter storm alerts whenever snowfall is anticipated to be heavy enough to create dangerous travel conditions. There are four different types of these alerts based on the seriousness of the storm, defined as follows:

- A winter weather advisory states that snow, sleet, freezing rain, or high winds may be on the way. It advises people to exercise caution when traveling.
- A winter storm watch states that at least 6 inches of snow and an ice storm may be on the way. It advises people to limit their travels and to exercise great caution if they must venture onto the roads.
- A winter storm warning states that a storm, including heavy snow and possibly ice, has already begun or will soon begin. It advises people not to travel, except in an emergency.
- A blizzard warning states that a blizzard—including heavy snow, low temperatures, and winds of at least 35 mph (56 kph)—is on the way. The combination of heavy snowfall and low clouds make it appear that the ground and sky are a continuous white sheet (called a whiteout), making travel nearly impossible. This warning advises people to remain indoors.

Safety procedures:
If you live in an area affected by winter storms, it is wise to take the following precautions at the start of the season:

- Store extra blankets and warm clothing and boots at home for every member of the family.
- Put together a supplies kit for your home containing first aid materials, a battery-powered flashlight, a battery-powered radio, extra batteries, nonperishable food, a nonelectric can opener, and bottled water.
- Store a similar supplies kit, plus the following equipment, in the trunk of your car: a shovel, a bag of sand, tire chains, jumper cables, and a piece of brightly colored cloth to tie to your antenna.
- Keep your car's gas tank full to prevent the fuel line from freezing.

If you must go outside during a winter storm, follow these rules:

- Wear several layers of lightweight clothing, gloves, a hat, and a scarf covering your mouth.
- Walk carefully over icy ground.
- When shoveling, take frequent breaks to avoid overexertion.
- If you must drive, inform someone of your route, destination, and expected time of arrival.

If you get stranded in your car during a winter storm:

- Stay with your car. Tie the brightly colored cloth to your antenna so rescuers can spot you. Don't attempt to walk away. It's easy to become disoriented and lose your way in a snowstorm.
- Only start the car and turn on the heater for ten minutes each hour. When the car is running, leave on the inside light so you can be spotted. When the car is not running, periodically check the tailpipe and clear it of snow, if necessary. If your tailpipe is blocked, dangerous fumes can back up into the car.
- Move your arms and legs continuously to stay warm and maintain your blood circulation.
- Let in fresh air by slightly opening the window that's opposite the direction of the blowing wind.

In the United States, between twelve hundred and eighteen hundred avalanches are reported each year. Most of these occur in the western states. When taking into account avalanches that go unnoticed or unreported, the actual number is much higher.

Colorado has the highest death rate caused by avalanches, with six to eight fatalities a year. Most of the people killed are skiers or snowmobilers. The best way to stay out of an avalanche's path is to avoid snow-covered slopes at angles steeper than 30 degrees.

Ice Ice pellets and hailstones are the two forms of precipitation that fall to the ground as hard, mostly transparent pieces of ice. Ice pellets and hailstones have little else in common besides their composition.

Ice pellets Ice pellets are frozen raindrops. They are formed by precipitation that passes first through a warm layer of air and melts, then reenters a layer of freezing air and refreezes. The precipitation reaches the ground as tiny pellets of ice.

Ice pellets differ from freezing rain in the depth of the layer of freezing air through which they pass. Ice pellets encounter the freezing air at a higher elevation than does freezing rain. Thus, ice pellets have time to freeze *before* they hit the ground, while freezing rain freezes only *on contact* with the cold ground.

In the United States, ice pellets are also referred to as sleet. Sleet is a confusing term, however, since this word is used in Australia and Great Britain to refer to a mixture of rain and wet snow. Even in the United States, sleet is often used by the news media to describe slushy precipitation. For this reason, this text will use the term "ice pellets" instead of "sleet."

Ice pellets measure only 0.2 inches (0.5 centimeters) in diameter, are irregular in shape, and bounce when they hit a surface. Ice pellets can also be identified by the ping sound they make when they strike a glass or metal surface. An accumulation of ice pellets can create hazardous driving and walking conditions.

Weather report: Snow rollers

On rare occasions, Mother Nature gives us a hand in building a snowman by creating snow rollers. A snow roller is a lumpy, spherical or cylindrical mass of snow, generally less than 1 foot in diameter. It is created only under a very particular set of conditions. First, there must be a layer of smooth, hard, crusty old snow on the ground. Then, a light layer of new snow falls on top of the old snow. Finally, a strong warm wind blows in, rapidly raising the temperature.

This wind literally lifts up a patch of snow and rolls it along the surface snow, which is warm and sticky. This process continues until the accumulated snow becomes too heavy to be rolled any farther.

One place where snow rollers have been witnessed is in Boulder, Colorado. They are created by the strong, warm Chinook winds, or dry, warm winds that blow down the eastern slopes of the Rocky Mountains.

WORDS TO KNOW

accretion: the process by which a hailstone grows larger, by gradually accumulating cloud droplets as it travels through a cloud.

coalescence: the process by which an ice crystal grows larger. The ice crystal collides and sticks together with water droplets as the ice crystal travels down through a cloud.

condensation: the process by which water changes from a gas to a liquid.

condensation nucleus: a tiny solid particle around which condensation of water vapor occurs.

convection: the upward motion of an air mass or air parcel that has been heated.

deposition: the process by which water changes directly from a gas to a solid, without first going through the liquid phase.

downdraft: a downward blast of air from a thunderstorm cloud felt at the surface as a cool gust.

drizzle: precipitation formed by raindrops between 0.008 inches and 0.02 inches in diameter.

freezing nuclei: a tiny particle of ice or other solid onto which supercooled water droplets can freeze.

supercooled water: water that remains in the liquid state below the freezing point.

updraft: a column of air blowing upward inside a vertical cloud.

Hailstones Hailstones are a larger and potentially much more destructive form of frozen precipitation than ice pellets. They have either a smooth or jagged surface and are either totally or partially transparent. While most hailstones are pea-sized, they may reach the size of softballs.

Large hailstones have been responsible for destroying crops, breaking windows, and denting cars. They have also caused numerous human and animal deaths. The largest single hailstone on record was about the size of a cantaloupe. It measured 7 inches (18 centimeters) in diameter and 18.75 inches (48 centimeters) in circumference, with a weight of just under 1 pound (.45 kilograms). It fell on Aurora, Nebraska, on June 22, 2003. The heaviest hailstone on record in the United States measured 5.5 inches (14 centimeters) in diameter and 17 inches (43 centimeters) in circumference, with a weight of 1.7 pounds (.77 kilograms). It fell on Coffeyville, Kansas, on September 3, 1970.

Hailstones are formed within cumulonimbus clouds during intense thunderstorms. A hailstone forms around a small particle, called an embryo. Objects that can act as embryos include ice crystals, frozen raindrops, graupel, dirt, or even insects. There have also been reports of larger organisms, such as frogs, being swept up in a tornado (a rapidly spinning column of air that extends from a thunderstorm cloud to the ground) and returning to Earth with a hailstone formed around them.

As an embryo travels through a cloud, it is coated by cloud droplets and grows larger by accretion (gradual accumulation). On reaching the bottom of the cloud, the developing hailstone is blown back up to the top by powerful updrafts. It repeats its journey down and up through the cloud many times. In the case of very strong updrafts, this process may last several minutes. When the hailstone becomes heavy enough to overcome the force of the updraft, it falls to the ground.

Thunderstorms, and hence hailstones, are warm-weather phenomena. As a hailstone descends toward the surface and encounters warm air, it begins to melt. Small hailstones may melt completely in the air. Hailstones that are large enough, however, melt only partially and reach the ground in the frozen state. In the tropics, where the air is very warm, hail always melts before reaching the ground, turning to rain.

When sliced in half, a hailstone resembles an onion, with a pattern of concentric rings. The number of rings is equal to the number of trips the hailstone made through the cloud. Up to twenty-five rings have been counted in large hailstones.

Layers of a hailstone alternate between clear ice and white ice, called rime. The clear layers are formed when the hailstone is in warmer air, in the lower portion of the cloud. There, supercooled water droplets are plentiful. They form a layer of water around the hailstone, which slowly freezes when the hailstone returns to the colder, upper portion of the cloud.

The milky white layers are formed in the upper, freezing portion of the cloud, where supercooled droplets are scarcer and freeze directly onto the hailstone by the process of riming. In a manner similar to the process by which a graupel is formed, the droplets trap air bubbles when they freeze to the hailstone.

Weather report: Hail alley

Hail alley is the region of North America where hail frequently damages crops. It covers a north-south belt from Alberta, Canada, to Texas. It extends westward to the Rockies and eastward to the Mississippi River. Hailstorms occur with the greatest frequency in the Great Plains states. There, hail falls accompany 10 percent of all thunderstorms.

A hailstorm can flatten an entire field in minutes. Hail damage to crops in the United States alone tops $700 million per year. To guard against the chance that a single storm can wipe out an entire year's earnings, farmers in hail alley spend large sums of money on hail insurance. Illinois farmers top the list of insurance buyers, purchasing over $600 million worth of liability coverage annually.

A Kansas man displays softball-sized hailstones. © JIM REED/CORBIS.

The accumulation of hailstones during a thunderstorm can be considerable. One of the largest hail falls on record reached a depth of 18 inches (46 centimeters) and occurred in Selden, Kansas, in June 1959. Occasionally, snowplows must be taken out of summer storage to clear roads of hailstones. This was the case in September 1988, in Milwaukee, Wisconsin, when hailstone drifts reached 18 inches. In August 1980, snowplows were required to remove hailstone drifts 6 feet (2 meters) deep in Orient, Iowa.

The hailstorms that have caused the greatest toll in terms of human life have occurred in Asia. In 1888, in northern India, hail killed 246 people. In 1932, in southeast China, a hailstorm claimed about two hundred lives and injured thousands. In 1986, in Bangladesh, a storm that produced some very unusual hailstones weighing more than 2 pounds (1 kilogram) each killed ninety-two people. In the United States, only two deaths have been attributed to hail in the last century.

If you are caught in a thunderstorm, watch for these warning signs of hail: a green tinge develops at the base of the cloud or the rain begins to take on a whitish color. If you witness either of these signs, it is time to collect your family and pets and move indoors.

[*See Also* **Clouds; Forecasting; Weather: An Introduction**]

For More Information

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Avalanche

An avalanche is a large mass of snow, ice, rocks, soil, or a combination of these elements that moves suddenly and swiftly down a mountain slope, pulled by the force of gravity. It destroys nearly everything in its path. The most common type of avalanche is a snow avalanche. An estimated 100,000 snow avalanches occur in the United States each year. Ice and debris avalanches, while they occur less frequently, are far more dangerous and cause greater damage than snow avalanches.

The Mount Huascarán avalanche of 1962

In the early evening of January 10, 1962, a huge mass of ice measuring about 2.5 million cubic yards (1.9 million cubic meters; the size of a football stadium filled from bottom to top) and weighing approximately 3 million tons (2.7 million metric tons; the weight of six thousand steam locomotives) broke loose from the glacier-capped peak of Mount Huascarán (pronounced wass-ka-RON), the tallest mountain in Peru. As the ice mass hurtled down the cliff face toward the populated valley below, it gained speed and grew in size, picking up rocks and other debris. After traveling nearly 10 miles (16 kilometers) in eight minutes, the mass came to a halt. In its wake, it left a carpet of ice, mud, and rock that covered ten villages and towns, ten thousand livestock, and almost four thousand people.

Mount Huascarán (*Nevado Huascarán* in Spanish) is part of the Andes, a 5,000-mile-long (8,045-kilometers-long) mountain system along the western coast of South America. The Andes, which run through seven countries—Argentina, Chile, Bolivia, Peru, Ecuador, Colombia, and Venezuela—are very tall. The mountain system contains many peaks that exceed 20,000 feet (6,100 meters) in height—that is thirteen times as tall as the world's tallest building. The only mountain range that exceeds the Andes in average elevation is the Himalayas. Some of the highest peaks in the Andes, including Mount Huascarán, are volcanoes (although most are dormant).

WORDS TO KNOW

acid rain: rain that is made more acidic by sulfuric and/or nitric acid in the air, due to the burning of fossil fuels.

Andes: mountain range extending more than 5,000 miles (8,045 kilometers) along the western coast of South America.

Alps: mountain system composed of more than fifteen principle mountain ranges that extends in an arc for almost 660 miles (1,060 kilometers) across south-central Europe.

avalanche path: the course an avalanche takes down a slope, composed of a starting zone, a track, and a runout zone.

avalanche wind: a cloudlike mixture of snow particles and air pushed ahead of a slab avalanche as it races downward.

clear-cutting: the logging practice of harvesting all trees from vast forest tracts.

glacier: slowly flowing masses of ice created by years of snowfall and cold temperatures.

leeward: the side of a mountain facing the direction toward which the wind is blowing (in the United States, the eastern side). Cold air descends and produces dry conditions on this side.

loose-snow avalanche: avalanche composed of loosely packed snow that begins at a single point and slides down a slope, fanning out in the shape of an inverted V.

plate tectonics: the geologic theory that Earth's crust is composed of rigid plates that float toward or away from each other, either directly or indirectly creating the major geologic features on the planet's surface.

Richter scale: scale that measures the magnitude of an earthquake or size of ground waves generated at the earthquake's source.

slab avalanche: avalanche that begins when fracture lines develop in a snowpack and a large surface plate breaks away, then crumbles into blocks as it falls down a slope.

windward: the side of a mountain facing the direction from which the wind is blowing (in the United States, the western side). Warm air ascends, forms clouds, and yields precipitation on this side.

According to the geological theory known as plate tectonics, the Andes began to form millions of years ago when two plates or sections of Earth's crust advanced toward each other. Upon contact, one plate rode up and over the other, causing the land to rise. To this day, the plates continue to move, and the Andes continue to rise. The continual movement of the plates beneath the Andes makes the area geologically unstable, and earthquakes are common.

The climate in the Andes varies greatly, depending on both altitude (height above sea level) and latitude (distance north or south of the equator measured in degrees). There are hot regions, alpine meadows, glaciers, and a variety of climate types in between. Glaciers form where

Debris from the 1962 Mt. Huascarán avalanche is explored. ©BETTMANN/ CORBIS.

the winter snowfall exceeds the summer snowmelt, such as in high mountainous areas or polar regions.

In the Andes, glaciers occupy about 1,900 square miles (4,921 square kilometers). A section in the Peruvian Andes that has a large number of glaciers is called the White Mountains (*Cordillera Blanca* in Spanish). Named for the ice caps that persist even in the heat of summer, the White Mountains contain dozens of spectacular peaks towering above 19,686 feet (3,000 meters). Mount Huascarán is one of them.

A few years prior to the 1962 disaster, Peruvian geologists had completed a study of the hundreds of glaciers that punctuate the Andes. They had officially labeled the mass of ice atop Mount Huascarán Glacier No. 511. (Since glaciers dot the tops of so many peaks in the White Mountains, geologists assigned them numbers rather than names.)

Glacier no. 511 loomed over a peaceful valley Glacier No. 511 regularly advanced and retreated with the seasons, creeping forward a few inches each day when fed by winter storms, then retreating slightly during the hot days of summer. Most people living in the valley below the White Mountains simply ignored the glacier—it had always been a part of their landscape. Others relied on the glacier for a source of income. Several Native American families, descendants of the great Inca civilization that had thrived in South America until the Spanish conquest in 1532, regarded the glacier as a type of ice factory. They would scale Mount

Bodies of Mt. Huascarán avalanche victims are identified. ©BETTMANN/ CORBIS.

Huascarán and chip blocks of ice from the glacier, wrap the ice in grass to prevent it from melting, and carry the blocks on their backs into the villages below. There they would sell the ice to restaurants and stores.

West of the White Mountains is a dark and dry section of the Andes known as the Black Mountains (*Cordillera Negra* in Spanish). Between the White and Black Mountains lies a deep and narrow valley called the Corridor of Greenery (*Callejón de Huailas* in Spanish). This valley, colored by rich green vegetation, is considered by many to be one of the world's most beautiful places. The Santa River (*Rio Santa* in Spanish) flows along the valley floor, framed by tall palm trees whose arching green leaves contrast vividly with the icy white glaciers above. Tourist books refer to this area as the "Switzerland of Peru," since it resembles the Swiss Alps, a section of the great European mountain system renowned for its beauty (and its avalanches as well).

The Corridor of Greenery, lying 750 miles (1,207 kilometers) south of the equator, is located in the Southern Hemisphere. Thus, summer begins in January. At only 9,000 feet (2,743 meters) above sea level—an entire 2.5 miles (4.0 kilometers) below the looming glacier—the valley receives the full effect of the warm equatorial sunshine. Valley residents raise sheep for their wool, and from the wool make handwoven blankets and clothing. They also grow fruit, grain, and vegetables in the fertile land along the Santa River.

The formula behind the disaster Numerous factors tragically combined to send a piece of Glacier No. 511 sliding down the mountain and slamming into the valley below. The glacier had recently grown in thickness due to freak, heavy snowstorms. Several unseasonably hot summer days followed, melting the newly fallen snow. The extreme changes in temperature caused the surface of the glacier to develop cracks, into which flowed melted snow. Increasingly, more surface meltwater flowed downward, creating small streams that seeped to the bottom of the glacier and loosened its hold on the solid rock beneath. The glacier became increasingly unstable.

Geologists do not know for certain which single event forced a massive hunk of the glacier to break off. Some theorize that rocks slid down onto the vulnerable region of the glacier from a rocky peak overhead. Whatever the trigger, at 6:13 PM, as Glacier No. 511 glittered in the setting Sun, an enormous mass of ice broke loose and became the start of a fast-moving, deadly avalanche.

Ripping huge rocks from the cliff face, the falling ice crashed onto a lower section of the glacier 3,000 feet (914 meters) below. The mixture of ice, rock, and snow—preceded by a powdery white cloud—gathered speed as it skidded down the sloped surface of the 2-mile-long (3.2-kilometer-long) glacier. After sliding across the glacier's surface, the speeding ice mass roared into the mouth of the funnel-like valley canyon at more than 65 miles (105 kilometers) per hour.

An eyewitness to the disaster, a man who lived in the nearby city of Yungay, thought he saw a cloud turning golden in the Sun's fading light as he looked at Mount Huascarán. However, he quickly realized, as he told a reporter for *National Geographic* magazine, that "the cloud was flying downhill."

Slamming against the canyon walls, the avalanche cut away house-sized blocks of granite and carried them along in a 150-foot-high (46-meter-high) wall of ice, rock, and mud. The moving mass also kicked up hurricane-strength gusts of wind along its sides. The avalanche's size and momentum

Reports from the past: Ancient avalanches

The Alps, a mountain system extending about 660 miles (1,060 kilometers) across south-central Europe, is renowned for its many glaciers and magnificent scenery. Behind its beauty, however, lies the ever-present threat of avalanches, which have destroyed villages and claimed lives in the region for thousands of years.

Although no written records remain, historians believe many men in the army of Carthaginian general Hannibal (247–183 BCE) died as a result of avalanches. In 218 BCE, during the Second Punic War, Hannibal and his army set out to invade Rome-controlled Italy by crossing the Alps. Historians speculate that during this feat, one of the most remarkable in military history, nearly half of Hannibal's men perished, many smothered by avalanches.

The first written record of avalanches in the Alps appeared nearly two thousand years ago. Greek geographer and historian Strabo (c. 63 BCE–after CE 21) wrote in his *Geographia* that crossing the Alps was dangerous because of ice that fell from the tops of the mountains.

increased as it collected whatever debris lay in its path—topsoil, boulders, even sheep and llamas. Moving swiftly downward, the avalanche created friction along its bottom surface, which in turn melted thousands of tons of ice. The entire mass took on a white, soupy look.

The powerful avalanche scarred the walls of the canyon as it zigzagged downward like a bobsled bouncing against the sides of its track. In a later investigation of the disaster, geologists discovered five separate points of impact where the avalanche had rebounded off the canyon walls. The avalanche gained such force during its descent that it climbed hills as high as 275 feet (84 meters) and even left a 6,000-ton (5,442-metric ton) boulder balanced on top of a ridge.

The thunderous impact of the falling ice was heard and felt by people living in the villages sprinkled throughout the Corridor of Greenery. One person who was at the scene told a *National Geographic* reporter that the sound of the avalanche was a roar "like that of ten thousand beasts."

The first victims At 6:15 PM, bloated with debris from the canyon floor and walls, the avalanche struck the first of several villages that lay in its path. Pacucco, Yanamachico, and other nearby mountain villages were quickly engulfed. More than eight hundred people were killed; only eight survived. At the moment of impact, the avalanche was twice its original size and traveling at nearly 100 miles (160 kilometers) per hour. Based on the speed and weight of the ice mass, the victims probably died immediately, even before realizing what was happening. Men returning from tending sheep in the fields, women cooking supper, and children playing outdoors were all instantly crushed when the avalanche poured over them.

The avalanche then continued moving toward the more populated region of the valley floor. Fortunately, as the valley became less steep, the speed of the avalanche slowed to about 60 miles (97 kilometers) per hour.

The avalanche remained a lethal force, however, having grown to five times its original size—a volume approximately equal to seven Empire State Buildings. Although a steep bank of land redirected the avalanche away from the city of Yungay, the avalanche raced toward the town of Ranrahirca, with a population of nearly 3,000.

The avalanche struck as the evening lights came on At 6:00 PM, Ranrahirca town electrician Ricardo Olivera had arrived at the town's power station to turn on the electricity for the evening. Mayor Alfonso Caballero stopped by the station to watch the lights come on, then continued his evening walk. Within a few minutes, both men heard the thunder of the approaching avalanche. They raced to their homes to warn their families. Meanwhile, panicked crowds of people jammed the streets. Many townspeople pushed their way toward the church, which they believed would be strong enough to withstand the force of the avalanche. Mayor Caballero safely reached his home, but the oncoming avalanche's roar drowned his shouts of warning to his sister inside. As the electrician Olivera reached his home, he came across two little girls from his neighborhood. Grabbing each one, he tried to pull them to safety on a side street.

Just eight minutes after Olivera had turned on the lights, the avalanche reached Ranrahirca. As the avalanche swept over the town, dust filled the air, choking and blinding the residents. The 40-foot-high (12-meter-high) wall of ice and rock knocked away a corner of Caballero's house, but both the mayor and his sister were spared. Olivera, too, was unharmed, but the edge of the avalanche snatched the two young children from his grasp. They, like members of Olivera's family, were buried beneath tons of ice. The people in the church were also buried as an icy sheet more than twice as tall as the church's steeple overtook them. In the span of just a few moments, between 2,400 and 2,700 people were killed; fewer than 100

Eyewitness report: An English avalanche?

In England, a country noted more for rain than for snow, avalanches are rare—but they do occur. The country's most devastating avalanche struck on December 27, 1836, in the town of Lewes in Sussex, an area in southern England. Heavy snow had begun to fall on the town three days earlier. Meanwhile, strong easterly winds blew back and forth over Cliffe Hill on the outskirts of town. The snow and winds combined to create a cornice or projection of snow that hung over the edge of the hill, some 200 feet (61 meters) above a row of houses below.

The next day residents saw the overhanging snow, but considered it more beautiful than threatening. Two days later, after the warmth of the sun had created a crack in the overhang, one man tried to warn the residents of the impending danger, but they did not listen. That afternoon, the snow cornice broke free and an avalanche buried the houses below, killing eight people.

Afterward, to commemorate the event, a tavern named the Snowdrop Inn was built on the site of the mishap.

people were spared. Most of the survivors lived or worked on the outskirts of the town, beyond the avalanche's route.

The avalanche then spread out like a huge fan on the valley floor. The enormous mass of ice and rock spilled into the Santa River, climbing 100 feet (30 meters) up the opposite bank and creating a dam that produced flood waters more than 15 feet (5 meters) deep. There, at 6:20 PM, nearly 10 miles (16 kilometers) from where it had started, the avalanche stopped. In its wake nearly four thousand people lay dead, most of them buried under the massive pile of ice, mud, and rock. Some bodies were later discovered more than 100 miles (160 kilometers) downstream, where the Santa River empties into the Pacific Ocean.

Relief efforts were futile Because the avalanche had destroyed telephone and other communication lines in the area, word of the disaster was slow in getting out. Hours passed before government helicopters hovered over the huge stretch of icy white debris, dropping off soldiers to provide help. Medical supplies, doctors, and nurses were transported by airplanes to a small airport in an area untouched by the avalanche. Ranrahirca, which had been a thriving community with cobblestone streets and buildings with red-tiled roofs, lay buried beneath 40 to 60 feet (12 to 18 meters) of mud and rock. There were only about twelve injured people to treat; the rest of the avalanche victims had died. Relief teams quickly realized there was little they could do.

In addition to the great human loss, about ten thousand livestock lay beneath the rocky cover of mud. Rescue workers feared that decomposing animals and human bodies would soon contaminate the region's water supply with disease-carrying germs. Temporary medical clinics were quickly set up to administer vaccinations. Survivors were given shots to protect them against typhoid fever, a deadly disease transmitted by contaminated food or water. To prevent the spread of typhus—another deadly disease typically spread by fleas, lice, or mites—insecticides were sprayed on the remaining trees and plants in the valley.

Two days after the avalanche, U.S. president John F. Kennedy sent a telegram to Peruvian president Manuel Prado y Ugarteche offering the sympathies of all Americans. President Kennedy also asked James Loeb, the U.S. ambassador to Peru, to determine what emergency aid the United States could provide. Unfortunately, since there were so few survivors, there was little assistance any individual or country could offer.

The slow recovery Fearing that a second avalanche could occur, survivors and rescue workers salvaged belongings and began to clear roads. A refugee center was set up in a high school building that was spared by the avalanche; wooden planks were used to create a temporary footbridge across the wide stretch of muddy rock. Bulldozers were used to clear mud and debris. As the ice melted over the next few weeks, some bodies were unearthed from the mud and, when possible, identified and buried. Since most people were torn to pieces by the powerful impact of the avalanche, the thawing mess became a gruesome scene of scattered body parts.

Local legend suggests that the beautiful mountains around the Corridor of Greenery have hurled down deadly avalanches of ice and snow on past occasions. In fact, in the Native American language Quechua, Ranrahirca means "Hill of Many Stones." Months after the disaster, Mayor Caballero issued a proclamation declaring that a new town of Ranrahirca would someday be built. In honor of the lives lost on that tragic day, the new town's main avenue was to be called the Street of January Tenth.

Recent events: The 1998–99 Swiss avalanche

No country in the world has more of an interest in avalanche research than Switzerland. More than 50 percent of Switzerland's population lives in avalanche terrain. During the 1998–99 avalanche season, the Swiss suffered through their worst avalanche season in forty-five years. Hundreds of major avalanches took place in the Swiss Alps, killing thiry-six people and causing more than $100 million in damages.

The worst of these avalanches took place in the resort town of Evolène in southwest Switzerland, where heavy rain and snowfall triggered an avalanche that killed twelve people. The damage was so severe that the mayor and local security chief were later convicted of failing to take appropriate precautions, such as evacuating houses and closing roads.

Because of its population's vulnerability to avalanches, the Swiss government invests significant resources in the study of avalanches. At the Swiss Federal Institute for Snow and Avalanche Research (the SLF), located in Davos, a small town in eastern Switzerland about 92 miles (147 kilometers) from Zurich, scientists oversee a network of electronic monitors that collect meteorological data that help predict when and where avalanches will take place. Based on this data, the SLF sends out avalanche bulletins advising citizens of avalanche conditions and warning of extreme situations as much as seventy-two hours in advance.

Watch this: "Avalanche!"

In 1997, the PBS program *NOVA* broadcast an episode called "Avalanche!," a look at avalanches and the scientists who study them. According to the show, avalanches are ferocious enough to have earned the nickname "white death." Avalanches are also an increasing problem as skiers, backpackers and snowmobile-riders venture into previously undisturbed back country, where the risk of avalanche is higher.

The show explains the science of avalanches and also follows a team of scientists as they try to learn more about avalanches as they happen. The scientists are so dedicated to understanding and exploring avalanches that at one point in the show an avalanche buries them alive!

Disaster struck once again A mere eight years after the 1962 disaster, a much larger tragedy befell the Corridor of Greenery. On May 31, 1970, a forty-five-second earthquake with a magnitude of 7.8 on the Richter scale caused a huge amount of rock and glacial ice to break off the west face of Mount Huascarán and plummet down toward the valley. Within three minutes, almost 80 million cubic yards (61 million cubic meters) of ice, rock, water, and debris traveled nearly 11 miles (18 kilometers). Traveling at an average speed of 100 miles (160 kilometers) per hour, the avalanche completely buried the city of Yungay (spared in 1962) and nearly a dozen villages, killing almost 20,000 people in the Corridor of Greenery. (Overall, the earthquake claimed a total of 70,000 lives across an area of about 32,370 square miles [83,000 square kilometers].)

Dangerous science: What causes avalanches?

While any movement of snow, ice, rocks, or mud down the slope of a mountain or hill can be considered an avalanche, the term is most often used to describe the rapid downward movement of a vast quantity of snow. (The movement of rocks and mud is more commonly known as a landslide.) Scientists estimate that as many as one million avalanches take place around the world each year. Of these, most occur in the Alps in Austria, France, Italy, and Switzerland. In the mountainous western region of the United States, approximately 100,000 avalanches tumble down each year (most of them are in the Rocky Mountains). The number of avalanches in the United States is small in comparison to the number in the Alps and the Andes.

Snow avalanches take on many forms but are generally placed into two categories: loose-snow and slab. Slab avalanches are, by far, the more common and more deadly of the two.

Loose-snow avalanches A loose-snow avalanche (also called a pure avalanche) is, as its name implies, composed of snowflakes or snow crystals that are loosely packed. The crystals behave much like dry sand:

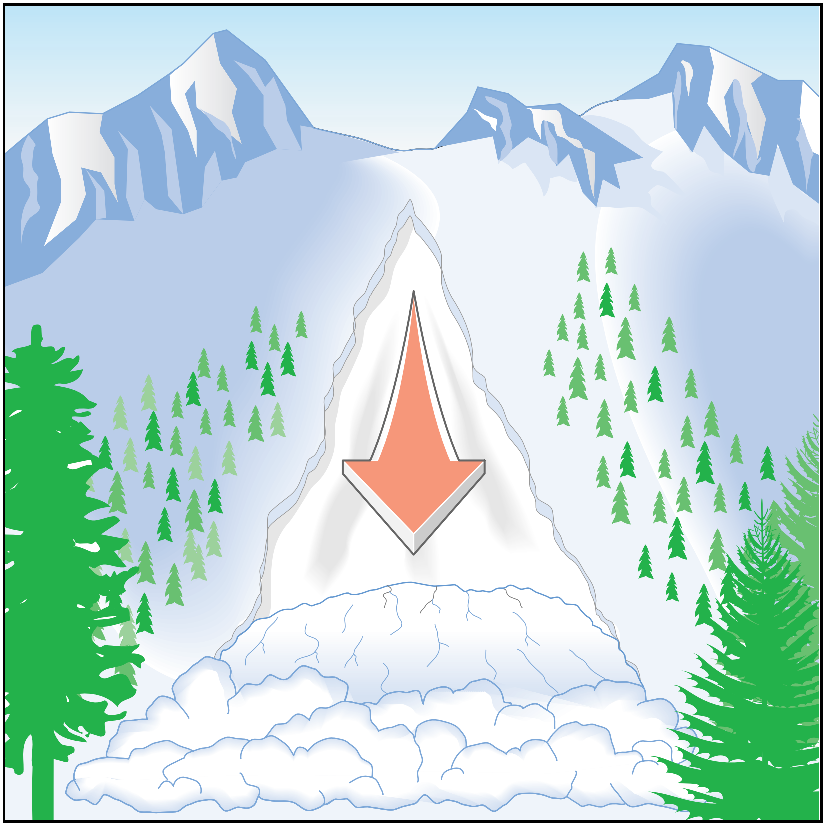
the bonds between them are not very strong, and they merely lie upon each other. A loose-snow avalanche usually begins at a single point on a slope when a small portion of snow slips and begins to slide, knocking into other crystals on the surface. As the avalanche runs downward, picking up more snow, it fans out in the shape of an inverted V.

An avalanche in the Karakoram Mountains in Pakistan. ©GALEN ROWELL/ CORBIS.

If the snow on the slope is dry and powdery, the loose-snow avalanche can travel at speeds up to 100 miles (160 kilometers) per hour. Conversely, if the snow involved is melting and wet, the avalanche may move at speeds of only 5 to 10 miles (8 to 16 kilometers) per hour. Some loose-snow avalanches travel only 10 to 30 feet (16 to 48 meters) before stopping.

Unstable snow is the most significant factor in the creation of a loose-snow avalanche, as it is in a slab avalanche. Where snow is loosely packed on a slope, any disturbance of the delicate balance existing near the slope's surface will result in a slide. The added weight of new snow dropped by a fierce storm is a leading cause. Additional snow can also be deposited on a slope by winds, which usually blow up one side of a hill or mountain (called the windward side) and down the other (called the leeward side). As winds blow up the windward side, they scrape loose snow from the slope and drop it on the leeward side after passing over the summit. This accumulation of snow stresses the existing snowpack, causing it to slide. Another strain on a snowpack can be brought about by the warmth of the Sun, which melts snow at the surface, making it denser and heavier.

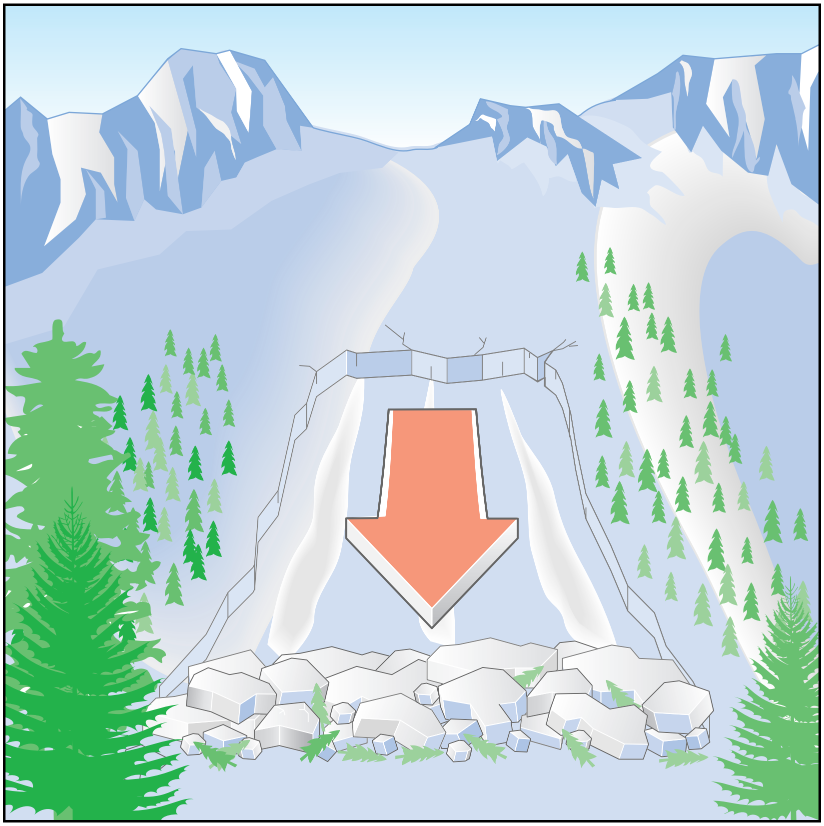
Slab avalanches A slab avalanche begins when fracture lines develop in the snowpack and a large surface plate breaks away and then crumbles into blocks as it falls down a slope. As with a loose-snow avalanche, many factors combine to produce a slab avalanche—including the condition of the snowpack, temperature, weather, and wind direction. Unlike a loose-snow avalanche, a slab avalanche brings down large amounts of snow all at once, making it much more powerful and dangerous. A slab may be more



Loose-snow avalanche.

than 100,000 square feet (9,290 square meters) in area (equal to three 100-unit apartment buildings) and more than 30 feet (9 meters) thick. As it tumbles down the slope at speeds approaching 100 miles (160 kilometers) per hour or greater, it picks up more snow and may grow to one hundred times its original size.

Again, unstable snow is the main trigger behind a slab avalanche. Throughout a winter season, numerous layers of snow build up on a slope. As layers of snow are deposited during storms, the snow crystals making up the existing layers are compacted by the weight of new snow. The older crystals become rounded, generally forming stronger bonds between themselves and making the snow layer more stable. Under optimum conditions, the weather and temperature during and between storms remain the same. Consistently cold temperatures and light snows allow each new layer to bond readily and tightly to the layer just beneath the surface.



Slab avalanche.

Weather and temperature on a mountain slope, however, hardly ever remain the same, even within a single day. Clear, warm spells often abruptly change to stormy ones. These large variations in temperature and snowfall create unstable snow layers. If cold nights follow warm days, then the crystals within a snowpack melt and refreeze, weakening the bonds between them. If warm days follow a snowfall, then the crystals in the upper layer may melt and form a slick surface to which subsequent snowfalls do not easily bond. Rain also creates slick surfaces, not only on the top layer but throughout the lower layers in a snowpack.

Snowfall and wind direction can also contribute to the creation of a slab avalanche. The added weight of a single snowfall measuring 12 inches (30 centimeters) or more can quickly produce an extremely destructive avalanche. Winds blowing up the windward side of a mountain deposit snow unevenly on the leeward side to create unstable conditions.

Earthquakes and even minor earth tremors can also set off a slab avalanche. As the ground beneath a slope moves, fractures may develop in an unstable snowpack and a large section may break loose.

Both slab and loose-snow avalanches can occur on any slope, but they most often take place on slopes that have angles measuring between 30° and 45°. Snow on slopes with angles less than 30° is generally more stable and not affected as much by the pull of gravity. Snow on slopes with angles more than 45° generally does not have a chance to accumulate because it sloughs (pronounced SLUFFS) off in frequent little avalanches.

Aftermath: The effects of avalanches

Loose-snow avalanches are usually not dangerous, but there are exceptions. Large loose-snow avalanches can carry humans and animals over the edge of a cliff or bury them in deep snow. They can also destroy buildings and whole sections of forest. Even worse, on a very unstable slope, a fast-moving loose-snow avalanche can trigger a larger slab avalanche.

Slab avalanches, because of their great size, are almost always dangerous. A large slab avalanche will usually mow down and carry away anything in its path: trees, boulders, animals, humans, and buildings. Slab avalanches composed of powdery snow have an additional destructive aspect—avalanche wind. As an avalanche sweeps down a slope, wind rushes ahead of the sliding snow mass. This wind, a mixture of snow particles and air around the avalanche, is like a dust cloud or a heavy gas and is difficult to breathe. When the avalanche comes to a sudden stop, the wind around it rushes out violently in all directions. The force of this wind is especially destructive if the sliding snow or ice mass has fallen almost vertically to a valley floor. Like a bomb blast, the wind can actually blow down nearby houses and other structures.

Avalanche paths The course an avalanche takes down a slope is called the avalanche path. Large avalanches traveling repeatedly down the same path leave a lasting scar on Earth's surface. Such scars appear as bare lines on a mountainside otherwise covered with trees and vegetation.

Paths can run through narrow gullies or across open slopes. Although they differ in shape and length, avalanche paths all have three main parts: the starting zone, the track, and the runout zone. The starting zone is where the avalanche begins, typically high up on a slope. At the starting zone, snow collects unevenly; loose surface snow begins to slough, or fracture lines cut slabs from the snowpack. The track is the trail or channel the avalanche takes

Eyewitness report: The Wellington disaster

The worst avalanche disaster in the United States occurred at Wellington, Washington, in 1910. Wellington was a small railroad town consisting of a railroad depot, a few railroad sheds and bunkhouses, and a hotel. It was located at the western end of the Cascade Tunnel, which runs almost 8 miles (13 kilometers) through the Cascade Mountain Range.

Two trains, a mail train and a passenger train of seven cars, came to a halt on the westbound tracks at Wellington in the late evening of February 24, 1910. Heavy snow had been falling for days, and portions of the track ahead of the trains lay buried under snowdrifts and small avalanches. Looming above the trains was the broad, snow-covered slope of Windy Mountain.

For days after, the trains were motionless as railroad workers tried to clear the tracks with rotary plows. Progress was slow. While the plows were clearing packed snow in one area, snow would pile up in another area. One plow soon broke down and another, out of fuel, was stranded between snow piles.

Railroad workers, discovering that the telegraph lines were down, decided to hike 4 miles (6 kilometers) through the snow to the depot of Scenic to send for more plows and men. Shortly thereafter, six male passengers and a few more railroad men joined them. The remaining passengers and railroad laborers remained with the trains, waiting for the weather to change.

During the evening of February 28, the falling snow turned to rain, and a lightning storm followed. At 1:30 AM on March 1, a snow mass about 1,350 feet (411 meters) wide slipped loose from the slope of Windy Mountain and dropped 500 feet (152 meters) to the tracks below. The avalanche carried the passenger train, the mail train, a plow, some boxcars and electric engines, and more than 100 people over a ledge and into a canyon 150 feet (46 meters) below.

Railroad workers who had not been on the trains quickly descended into the canyon and began digging for survivors. The digging, slow and by hand, continued for eight days. When it was complete, only 22 of the 118 passengers and workers who had been buried by the avalanche had been found alive.

as it races downward. This middle section of the track is where the rushing snow or ice mass reaches its greatest speed. The runout zone is where the snow and debris finally come to a halt. It may be a level area at the base of a mountain where the avalanche gradually slows down, or a deep gully or ravine where the avalanche stops abruptly. The runout zone, where snow and debris pile the highest, is where victims are most often buried.

Avalanches and the paths they create do have certain benefits. Since trees and other large plants have been cleared from these paths, meadows are able to develop in spring and summer. Filled with grasses, wildflowers, and small shrubs, these areas provide necessary food for mountain-dwelling animals such as bear, deer, elk, and moose.

Avalanches have little, if any, benefits for humans. Any interaction between avalanches and humans typically ends in destruction, injury, and death. Roads and towns built near avalanche paths are either partially or completely buried. Each year, thousands of people around the world are killed or injured in avalanches.

The human factor

For thousands of years, humans have settled in valleys at the base of mountains where snow runs down and forms clear streams, and the fertile soil produces abundant vegetation. The natural beauty of such settings is often astounding. As long as humans have inhabited these areas, however, they have had to face the peril of avalanches. For centuries, villages in the Swiss Alps have been buried by avalanches, only to be rebuilt and buried again.

Forests surrounding these valley communities have provided protection against the force of certain avalanches: trees in mature or well-developed forests can slow or stop the rush of a small avalanche. But over time, as these villages grew in size, the inhabitants began to cut down the surrounding trees for fuel and housing. In the process, they destroyed their only protective barrier. In modern times, remaining forest regions in the Alps have withered away because of the effects of acid rain (rain that is made more acidic by sulfuric and/or nitric acid in the air, due to the burning of fossil fuels). In the western United States, the risk of avalanche damage has increased because of the clear-cutting of forests (logging practice of harvesting all trees from vast forest tracts).

Avalanche fatalities have also recently increased because of an upsurge in mountain recreation activities. In the United States and other countries, thousands of people are drawn each year to mountain areas to ski, hike, and take part in other winter sports. To accommodate these recreationists, roads, buildings, and towns have been built in avalanche-prone areas, increasing the risk of avalanche-related deaths.

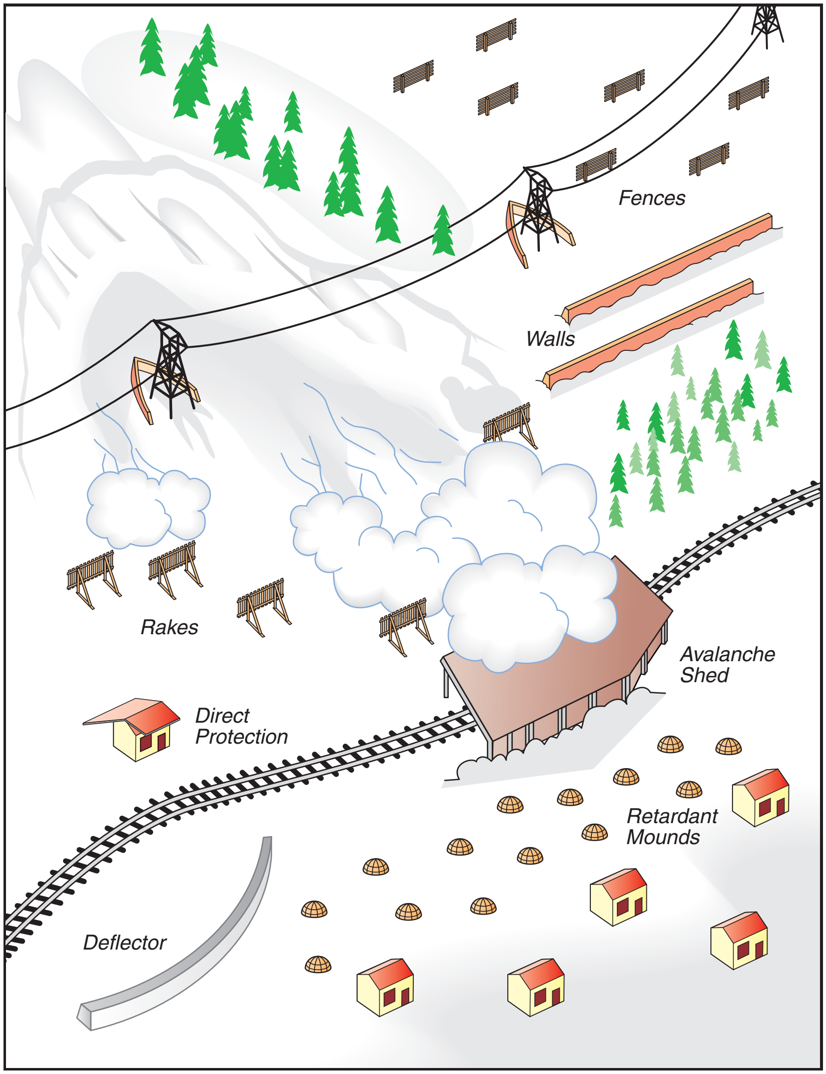
With increasing numbers of people entering hazardous mountain terrain, more and more avalanches are being triggered. Larger avalanches are usually set off by natural events and do not involve people unless they happen to be in the area. Small- and medium-sized avalanches are responsible for more human deaths overall because humans often set them off. In the United States, snowmobilers, climbers, and backcountry skiers are the parties most responsible for starting avalanches. The simple weight of these people on unstable snow is enough to begin an avalanche that, most times,

Two avalanches simultaneously make their way through a ski resort in the Swiss Alps. ©FABRICE COFFRINI/EPA/CORBIS.

kills them. Experts predict that as the sport of snowboarding increases in popularity, snowboarders will join the list of victims.

A matter of survival: Living through avalanches Nearly all avalanche fatalities can be avoided. Two ways to accomplish that are to stop building communities in avalanche-prone mountain valleys and to prohibit recreation on mountain slopes. Both solutions, however, are impractical.

In areas where avalanches frequently threaten communities, numerous steps can be taken to lessen their impact. On the slopes above roads or buildings, structures may be erected to either prevent avalanches from starting or to divert the path of an avalanche. Planting trees close together, for instance, can help prevent the formation of avalanches and stop the approach of ones that do develop. In starting zones, areas higher up on slopes where trees will usually not grow, large fences can be erected to



Examples of various structures built to lessen the impact of avalanches.

keep the snow from sliding down. Large, slotted barriers called snow rakes can also be used to decrease the amount and speed of the falling snow mass.

Farther down the avalanche path, where roads or railroad tracks pass through, avalanche sheds can be built. A shed, constructed like an overpass with one end built into the slope, diverts the snow over the road or tracks to fall on the other side. Near buildings or other structures, heavy stone or concrete walls can be built to deflect the snow. In the lower reaches of an avalanche path, earth or rock mounds can also be constructed to break up the snow mass and slow its speed.

An interesting design that provides direct protection to buildings is a wedge-shaped wall built in front of the structure with its point facing the slope. Sometimes, the building's wall that faces the slope is itself constructed in the shape of a wedge. Much like a ship's bow that cuts through water, the wedge-shaped wall cuts into the oncoming snow mass, forcing it to travel around the sides of the building.

In areas where roads and railroad tracks follow mountainous terrain for miles, the cost of these protective measures is prohibitive. In such situations, avalanche experts periodically use explosives—shot by cannon or gun, dropped from helicopters, or placed by hand—to dislodge the snow. This creates small avalanches and thus prevents the accumulation of heavier, and possibly more destructive, snowpacks.

Avalanche barriers on Mannlichen Mountain, Switzerland. ©NICK HAWKES; ECOSCENE/CORBIS.

A Dutch youth shows a drawing of how he survived being buried in an avalanche in northern Norway. ©EPA/CORBIS.

Personal safety For those venturing onto mountains, there are a few steps to avoid becoming a victim of an avalanche. The most critical step is to gather as much information in advance about snowpack conditions and upcoming weather from forest service, national park, or ski patrol personnel. Before going on a mountain, it is also wise to have proper safety equipment, including an avalanche transceiver or beacon (a device that emits a signal indicating one's position) and a portable shovel. In addition, when on a mountainside, it is important to be alert to the surrounding conditions, such as the slope angle, tender or weak spots in the snow, fracture lines and other disruptions on the surface, and wind direction. When traveling on a snowy mountain, it is also safest to be part of a group. If buried by an avalanche, an individual will most likely need the help of others to get out alive.

People caught in an avalanche die in one of two ways: they either suffer a fatal injury when they hit a boulder or tree during the slide, or they suffocate to death shortly after the slide comes to a halt. If caught in an avalanche, one's chances of survival are increased if certain techniques are followed. When the avalanche begins to slide, try to get out of its path or even move to its sides, where the snow will be moving more slowly. Remove any packs, skis, snowshoes, ski poles, or any other baggage that might weigh one down. If possible, grab a tree, large boulder, or something solid before the avalanche picks up speed. During the slide, try to stay near the snow's surface by "swimming" through the snow mass. When the slide begins to

Eyewitness report: The Iceman appears

On September 19, 1991, a German tourist set out walking across a glacier in the Alps between Austria and Italy. That summer and previous winter had both been warm. Warm winds had also been plentiful in the region. As a result, glaciers in the area had been melting; as they did, they revealed bodies of victims of climbing accidents from years past. Already that year Italian authorities had extracted eight bodies from the glaciers.

It wasn't a total surprise, then, when the tourist came upon the head and shoulders of a man frozen in the ice. Seeing a hole in the back of the man's head, the tourist suspected he had been the victim of a murder and so notified the police. When the dead man's body was removed from the ice, however, it was evident that he had been dead for an extremely long time. While the bodies of most victims trapped in a glacier are white and waxy, the body of this victim was brown and dried out.

Scientists were called in to determine the age of the dead man. After performing radiocarbon dating tests (a method of measuring the amount of carbon 14 left in organic matter), the scientists concluded the man in the ice was at least 5,200 years old. Dubbed the Iceman, he was the oldest human being ever discovered whose body was virtually intact.

Scientists speculated that the Iceman had been a shepherd who was caught in a storm and froze to death. Either icy winds or foehns dried out his body before it was covered by heavy snowfall or, more likely, an avalanche. Over time, the heavy snow compacted into ice and the Iceman's body was preserved by the cold temperature (about 21°F [–6°C]). The Iceman remained hidden for fifty-three centuries before the warm seasons and the dry winds uncovered him.

The Iceman, nicknamed "Otzi," was found with several of his belongings, including a backpack, axe, dagger, and bow and arrows. ©CORBIS/CORBIS SYGMA.

slow down, move around as much as possible. It is important to create a large breathing space rapidly, for within seconds after the snow stops moving it will harden.

Once trapped, a person may not know in what direction the surface lies. An easy way to find out is to spit or drool. The surface will be the opposite direction that the saliva flows. If a person is near the surface, he or she may be able to dig through the snow and stick a hand out to be visible to rescuers. If this is not possible, a person should remain calm—it is very important not to waste energy or remaining air by struggling. If one's avalanche beacon is in the transmit mode—and it should have been from the time he or she stepped onto the mountain—then searchers will have a better chance for a successful rescue.

Reports from the past: Avalanche casualties in World War I

World War I (1914–18) is known as the Great War because it was the largest war up to that time. In addition to the men killed by weapons, many died from natural occurrences such as disease and avalanches. It is believed that between forty thousand and eighty thousand men were victims of avalanches during the conflict.

Experts estimate that in the Dolomites, a section of the Alps in northern Italy, more men died in avalanches than from bullets, shells, and other weapons of war. During the early winter of 1916, the region received more snow than it had in fifty years. A warm period in December thawed the snow, and on December 13, more than one hundred avalanches plunged down the valleys in the Dolomites. Almost ten thousand Austrian and Italian troops were killed on that single day. Their bodies were still being recovered over thirty-five years later.

Finding survivors or victims Survivors of avalanches are most often found within the first thirty minutes after an avalanche comes to a stop. Group members who have not been buried are the ones who make the most rescues. They do so by honing in on the buried person's beacon signal with their own transceiver; by finding a glove, hat, or other sign that the person might be near the surface; by using metal probes; or by remembering where that person was last seen and then checking downhill from there.

The longer it takes to find a buried person, the less chance that person will survive. By the time most rescue teams arrive, the chance of finding any survivors is very slim.

Professional rescuers use a combination of equipment (such as sonar, radar, and infrared detectors) and trained dogs to find buried people. An avalanche dog, relying on its keen sense of smell, can search an area of more than 1,000 square feet (93 square meters) in less than thirty minutes. A team of twenty people searching the same area would need four hours. By then, anyone who was buried would almost certainly be dead.

Technology connection: Measuring and predicting avalanches

Unfortunately, scientists cannot accurately predict exactly when and where an avalanche will take place. They can determine, however, when conditions exist that are favorable for an avalanche to occur.

Avalanche experts first look at the layers within a snowpack to decide if the snow in that area might slide. They start by digging what is called a snow pit. Dug deep into a snowpack, the snow pit reveals the composition of the layers of that snowpack. After digging, the avalanche testers use shovels to probe the various layers and determine if they differ in hardness. The crystals in the layers are examined to see if a layer of powdery, loosely packed snow is lying underneath a layer of wet, denser snow. The depth of the snowpack and the angle of the slope on which it lies is also checked.

Having gathered this information, avalanche professionals monitor the weather forecast. Is a low-pressure system moving into the area, bringing with it colder temperatures and snowstorms? Or is a warm front forecasted, which may cause surface melting? Finally, they check previous data to see if a particular area is prone to avalanches and if so, what time of year they typically happen. (Most avalanche fatalities in the United States occur in February.)

Around the world, many avalanche-prone regions have prediction services. The Swiss Federal Snow Institute for Snow and Avalanche Research, founded in 1936 in Switzerland, has about seventy observation stations located in the Alps at altitudes of 3,280 to 5,905 feet (1,000 to 1,800 meters). Observers in these stations record information about snow conditions, then transmit it to the institute. There the information is processed and, if necessary, avalanche warnings are issued to newspapers and radio and television stations. In the United States avalanche danger is monitored mainly by the U.S. Forest Service, since most ski areas are located within national forests. In addition, various western states prone to avalanches hire avalanche professionals to provide prediction services.

[*See Also* **Earthquake; Landslide**]

For More Information

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Blizzard

A blizzard is a severe winter storm characterized by strong winds and blowing snow. The National Weather Service defines a blizzard as a large amount of falling or blowing snow with winds greater than 35 miles (56 kilometers) per hour and visibility reduced to 0.25 mile (0.4 kilometer) for at least three hours. A severe blizzard is defined as having wind speeds in excess of 45 miles (72 kilometers) per hour with temperatures of 10°F (–12°C) or lower.

Most blizzards are accompanied by heavy snowfalls and temperatures of 20°F (–6°C) or lower. The falling and blowing of fine, powdery snow during a blizzard sometimes reduces visibility to less than a few yards (meters).

Blizzards create conditions that are dangerous for motorists and pedestrians. Commerce and transportation systems typically grind to a halt and roofs may collapse under the weight of the snow. Many lives are lost in blizzards due to hypothermia, a drastic drop in body temperature; frostbite, a freezing of the skin; or overexertion while shoveling snow.

Blizzards occur mainly in Canada, the United States, Russia, and the former Soviet Republics, central and northern Europe, and central and northern Asia. The United States usually experiences one to seven blizzards per year, although some winters have recorded as many as thirty-five. Blizzards occur in the United States primarily during the months of December through March.

The blizzard of 1888

From March 10 through 14, 1888, a blizzard besieged the East Coast of the United States and set snowfall records from Virginia to Maine. The Blizzard of '88—with its combination of heavy snowfall, whipping winds, and frigid temperatures—was the most devastating weather event in the history of the northeastern United States. Throughout southern New England and southeastern New York, snowfalls averaged

WORDS TO KNOW

air mass: a large quantity of air—measuring thousands of square miles (the size of several states) across—where temperature and moisture content are fairly constant throughout.

blizzard: the most severe type of winter storm, characterized by winds of 35 miles (56 kilometers) per hour or greater, large quantities of falling or blowing snow, and low temperatures.

frostbite: the freezing of the skin.

ground blizzard: the drifting and blowing of snow that occurs after a snowfall has ended.

heavy snow: snowfall that reduces visibility to 0.31 mile (0.5 kilometer) and yields, on average, 4 inches (10 centimeters) or more in a twelve-hour period or 6 inches (15 centimeters) or more in a twenty-four-hour period.

hollow column: a snowflake in the shape of a long, six-sided column.

hypothermia: a condition characterized by a drop in core body temperature from the normal 98.6°F (37°C) to 95°F (35°C) or lower.

nor'easter: a strong, northeasterly wind that brings cold air, often accompanied by heavy rain, snow, or sleet, to the coastal areas of New England and the mid-Atlantic states. Also called northeaster.

sector plate: a star-shaped snowflake.

severe blizzard: a blizzard in which wind speeds exceed 45 miles (72 kilometers) per hour, snowfall is heavy, and the temperature is 10°F (–12°C) or lower.

stratus: gloomy, gray, featureless sheets of clouds that cover the entire sky, at low levels of the atmosphere.

whiteout: a condition in which falling, drifting, and blowing snow reduces visibility to almost zero.

windchill factor: the cooling effect on the body due to a combination of wind and temperature.

40 inches (100 centimeters) or more and winds were recorded at 50 to 80 miles (80 to 128 kilometers) per hour. Temperatures hovered near 0°F (–18°C).

New York City, Washington, D.C., Philadelphia, and Boston—the nation's economic and political centers—were all paralyzed by the storm. Two hundred ships in coastal waters were run aground, and many of them were destroyed by winds of 60 to 75 miles (97 to 121 kilometers) per hour. Four hundred people on city streets, in the countryside, and aboard ships perished in the blizzard because of exposure to strong winds and low temperatures. Half of the fatalities were in New York City. Thousands of people were stricken with frostbite and exhaustion.

Snow piled in front of a New York store in 1888. ©BETTMANN/CORBIS.

Blizzard caused by convergence of storms The intensity of the blizzard was the result of the convergence of two low-pressure systems: one, a warm, moist air mass from the south, and the other a storm system from the west. A low-pressure system is a region of low air pressure measuring thousands of square miles in area, the size of several states, that brings clouds and sometimes stormy conditions.

The southern air mass originated on March 9 over the northern Gulf of Mexico. During the next couple of days it traveled to the northeast, through Georgia and North Carolina, to New England. On March 11 and 12, the air mass held a steady position over the coast of southern New England. At the same time, a cold northeasterly wind, called a nor'easter, blew cold air into the region.

The western low-pressure system developed on March 8 over Salt Lake City, Utah. Over the next two days it moved across Colorado and the Missouri River Valley and on to the Great Lakes region. The western system ran into the southern system over Cape Hatteras, North Carolina, and formed a monstrous storm system. The storm then headed up the coast toward New York City at 80 miles (129 kilometers) per hour.

New York City gets 22 inches of snow By daybreak on March 12, snowdrifts several feet high made the streets impassable. Visibility was reduced to a few hundred feet. By that afternoon, no trains were entering or leaving New York City. The winds were strong enough to knock people off their feet and tip streetcars off their tracks. The pedestrian bridges into Manhattan were also closed. Several hundred determined people, however, walked between Manhattan and Long Island across a pack of ice that had floated up the East River and became trapped between the two shores.

On the morning of Tuesday, March 13, the temperature was –1°F (–18°C), and the snow was still falling. Several small fires broke out as the result of faulty heating stoves. Fortunately, firefighters were able to extinguish the blazes before they developed into major fires.

By the time the snow quit early on March 14, snowfall in New York City measured 22 inches (56 centimeters), Brooklyn was socked with 26 inches (66 centimeters), and White Plains had 32 inches (81 centimeters) on the ground. The wind continued blowing even after the snow stopped, whipping up enormous drifts.

The damage in New York City The snowfall in New York City brought power lines to the ground and disabled the city's new telephone and electrical systems. Four workers with the New York and Harlem Railroad were killed when they tried to crash their train through a huge snowdrift. Many horses perished, buried in snowdrifts. March 12 went down in the history books as being the first weekday the New York Stock Exchange closed since its opening in 1790.

The blizzard paralyzes the region The blizzard socked New Jersey, eastern New York, Connecticut, Vermont, New Hampshire, and other parts of New England, as well as the cities of Boston and Philadelphia. Railroad service was cut off. In parts of upstate New York, Connecticut, and western Massachusetts, 40 to 50 inches (102 to 127 centimeters) of snow fell, and drifts measured 30 to 40 feet (9 to 12 meters). In Middletown, New York, where the snow reached the second stories of buildings, residents dug tunnels across streets. In Pittsfield, Massachusetts, some houses on the main thoroughfare were entirely buried by 20 feet (6 meters) of snow.

Albany and Troy, in northeastern New York state, each received more than 4 feet of snow in just a few hours—as did Middleton, Connecticut. The site of the largest snowfall was Saratoga Springs, New York, with 58 inches (147 centimeters). Gravesend, New York, had a snowdrift of 52 feet (15.6 meters), only topped by New Haven, Connecticut's 53-foot (16-meter) snowdrift.

In Camden, New Jersey, residents were trapped in their homes by mountains of snow. Ferry service to Philadelphia was hampered by severe winds, which blew the water right out of the Delaware River. The water level was driven so low in parts of the river that loaded ferries scraped bottom. One boat full of passengers struck ground and became stranded midway across the channel.

Poles fall down after the blizzard of 1888. © CORBIS-BETTMANN.

Recent events: Catastrophic blizzards

In recent years the northeastern United States has been hit hard by winter storms. The years between 2000 and 2005 saw three record-breaking storms that were both damaging and deadly.

In 2003 the northeastern United States saw an historic blizzard. The Blizzard of 2003, which is also called the President's Day Blizzard, caused then-record snowfalls across the region. The storm caused over 40 inches of snow to fall in Garrett County, Maryland, and almost as much in parts of West Virginia.

The President's Day Blizzard of 2003 exacted a greater human toll than some major storms in the following years. The 2003 storm caused at least forty-four deaths. The effort to clean up and repair damages caused by the storm cost tens of millions of dollars.

January 2005 brought another powerful winter storm to the northeastern United States. The 2005 blizzard was one of the worst storms on record to hit the region. Heavy snows covered the eastern seaboard from Mississippi to New England. At the height of the storm, as much as three feet of snow blanketed parts of Massachusetts, which saw some of the worst of the storm.

The National Weather Service ranked the Blizzard of 2005 in the top five storms in the past 100 years. The service compared the blizzard to the catastrophic Blizzard of 1978, which caused $1 billion in damage. The

Snowplows clear snow during a blizzard in Rhode Island. AP IMAGES.

temperature in Boston during the storm came within one degree of the record set by the historic Blizzard of 1888. Temperatures during that storm were logged at –2°F (–18°C).

Despite the severity of the storm, the Blizzard of 2005 did not cause the type of casualties and havoc wrought by earlier storms, like the Blizzard of 1978. This is partly due to advances in technology and forecasting, which allowed preparations for the storm to be made.

In 2006, just more than a year after the Blizzard of 2005, another powerful storm hit the northeastern and mid-Atlantic regions of the United States. The storm caused record amounts of snow accumulation. This severe storm lasted from February 11 though 13. The 2006 blizzard dumped at least a foot of snow on mid-Atlantic and northeastern U.S. cities. However, despite record amounts of snow, the storm caused relatively few casualties.

Snow accumulations for the 2006 blizzard broke records. Snowfall in Central Park in New York City was recorded at 26.9 inches, an all-time record for the city. By contrast, the destructive and famous Blizzard of 1888 caused only 22 inches of snow in the city. The 2006 blizzard caused well more than 25 inches of snow throughout Connecticut and New Jersey. The storm's low-pressure system deepened as it moved up the eastern seaboard, causing power outages in tens of thousands of homes.

Dangerous science: How blizzards happen

Blizzards form in winter when two or more air masses of different temperatures and different air pressures collide. One of the air masses must contain warm, moist air, and the other cold, arctic air. For blizzards that occur in the United States, the warm air mass comes from the southern states or the Gulf of Mexico, and the cold air mass comes from Canada.

When a cold air mass advances upon a warm air mass, the approaching cold air is called a cold front. When this happens, the cold air, being denser and heavier than the warm air, wedges underneath the warm air and forces it sharply upward. The infusion of cold air causes the temperature on the ground to drop sharply. The collision of air masses also produces strong winds because of the difference in air pressures between the two masses.

The warm air cools as it rises, and water vapor within it condenses and forms clouds. Those clouds may take the form of a low-lying layer, called stratus, or they may develop steeply upward into thunderstorm clouds.

If the temperature in the clouds drops below freezing, ice crystals form. Ice crystals can then grow into snowflakes by several methods. When the snowflakes become too heavy to remain suspended in the cloud, they fall to the ground. The combination of sudden cold temperatures, high winds, and snow results in a blizzard.

Consequences of blizzards

When a blizzard strikes, it spells danger for motorists, pedestrians, public transportation systems, communication systems, and buildings. Blizzards frequently cause auto accidents, force traffic to a standstill, strand motorists, knock out power, freeze pipes, and shut down entire cities. Airports and railroads close because travel becomes too dangerous. A blizzard's whipping winds can create snowdrifts tall enough to bury cars or even buildings. A blizzard's heavy snows can make roofs collapse. Blizzards can cause agricultural losses by killing livestock and destroying crops.

Blizzards can also claim human lives. Seven out of ten people who die in blizzards are trapped in their cars and succumb to hypothermia, which is a drastic reduction of body temperature. Others die in traffic accidents on snowy, low-visibility roads. Some motorists trapped in blizzards become unconscious or die because of dangerous fumes that enter their running car when the car's tailpipe becomes clogged with snow.

When falling, drifting, and blowing snow reduces visibility to almost zero, the condition is called a whiteout. Everything appears white, making the ground and sky indistinguishable. In such conditions, a stranded person may become disoriented and lose their way. People in whiteouts

A key reference to: The structure of snowflakes

While snowflakes come in a variety of shapes, they all have the same basic hexagonal (six-sided) configuration. The structure of ice crystals, the smallest units of snowflakes, is also hexagonal. This basic shape can be traced back to water molecules. Because of the electrical attraction between water molecules, they form a hexagon when they freeze.

A snowflake begins its existence as an ice crystal within a cold cloud, where ice crystals coexist with water droplets that are supercooled—meaning they remain in the liquid state below the freezing point. As an ice crystal is bounced between the bottom and top of the cloud by the wind and by currents within the cloud caused by differences in temperature, the crystal grows. This can be the result of coalescence, in which the crystal hits and sticks to supercooled water drops, or by deposition, in which water vapor molecules in the cloud freeze and stick directly onto the ice crystal. As the ice crystal grows, it bonds with other ice crystals and takes on the shape of a snowflake. When the snowflake becomes heavy enough, it falls to the ground.

Snowflakes can exist in the following forms: flat, hexagonal plates; long, six-sided columns; needles that are two hundred times longer than they are wide, or starry shapes called sector plates. When a sector plate accumulates moisture it may develop feathery branches on its arms, thus becoming a dendrite—the most distinctive and most common type of snowflake. As dendrites bounce around through a cloud they may combine with other dendrites, forming a variety of complex patterns.

The shape of a snowflake depends upon the air temperature in which it is formed. Hollow columns, for instance, form when the temperature is either below –8°F (–22°C) or between 14 and 21°F (–10 and –6°C). Sector plates form at temperatures between –8 and 3°F (–22 and –16°C) and between 10 and 14°F (–12 and –10°C). When the temperature is between 3 and 10°F (–16 and –12°C), dendrites are formed. Between 21 and 25°F (–6 and –4°C) you get needles, and over 25°F (–4°C) you get thin, hexagonal plates.

The size of a snowflake depends upon the temperature of the air as the snowflake descends. If the temperature is above freezing, the snowflake melts around the edges. This process produces a

have frozen to death just steps from their door. People have even choked to death on the blowing fine, powdery snow. Other causes of death during blizzards are frostbite and heart attacks.

Cold weather is hard on humans Low air temperatures combine with high winds during blizzards to produce the wind chill factor: the *apparent* temperature, or how cold it feels. For instance, when it is 0°F (–18°C) outside and the wind is blowing at 20 miles (32 kilometers) per hour, it feels like –40°F (–40°C). In low wind chills, humans are susceptible to hypothermia, which is the drop in the internal body temperature from film of water, which acts like glue. Snowflakes that strike each other stick together, producing large, soggy snowflakes, 2 to 4 inches (5 to 10 centimeters) or greater in diameter. These snowflakes stick to surfaces and are heavy to shovel.

Snowflakes that descend into cold, dry air, in contrast, do not readily combine with one another. Those flakes produce dry, powdery snow on the ground that is ideal for skiing.

Electron microscopy shows many different snowflake shapes. ©ELIZABETH SAUER/ZEFA/CORBIS.

the normal 98.6°F (37°C) down to 95°F (35°C) or lower, as well as to frostbite, which is the freezing of the skin.

The human body has little natural protection against the cold. Without the proper clothing in cold weather, a person rapidly loses body heat. Even at 68°F (20°C), an unclothed person will begin to shiver. Children and older people are the least able to withstand cold weather since their bodies regulate temperature with less efficiency than people of other age groups.

Once hypothermia sets in, a person will shiver violently and experience a gradual loss of physical and mental functions. As the body

A doctor treats the frostbitten hand of a mountain climber. ©JASON BURKE; EYE UBIQUITOUS/CORBIS.

temperature continues to drop, however, the shivering will decrease, and the victim may actually feel warm. Advanced hypothermia can lead to unconsciousness and even death.

Another hazard of cold weather is frostbite: the freezing of the skin, which causes damage to tissues. There is a risk of exposed skin freezing when the wind chill is below –22°F (–30°C), and it only takes a minute or so for skin to freeze when the wind chill is below –58°F (–50°C). The parts of the body most susceptible to frostbite are the ears, nose, hands, and feet. In the mildest cases of frostbite, while complete recovery is possible, the affected area may feel numb for several months. Serious cases of frostbite can produce a long-term sensitivity to the cold. In the most severe cases, when the tissue freezes to the point that it dies, the affected limb turns black. In such cases the affected area has to be amputated.

The earliest warning sign of impending frostbite is pain in the fingers, toes, or nose. If the pain is followed by numbness, then frostbite is setting in, and it is necessary to get out of the cold immediately. If you can, run the affected area under warm water, from 105°F to 110°F (41°C to 43°C). If the area hurts as it gets warmer, this is a good sign. It means that the tissues are still alive.

Low temperatures are also hard on humans in other ways. Greater stress is placed on the heart as the outer parts of the body become cool. The heart compensates for this by working harder to pump blood to those

Extreme weather: The New England blizzard of 1978

On February 6–7, 1978, southeastern New England suffered its most disruptive snowstorm of the century. The snow was produced by a low-pressure system that remained stationary for more than twenty-four hours just off the eastern tip of Long Island. At the same time, a strong, northeasterly wind known as a nor'easter blew in from southern Canada. The snowstorm, which came just seventeen days after a previous blizzard, claimed at least fifty lives. Most of the deaths were due to overexertion while shoveling snow.

Over a thirty-hour period, heavy snow fell on the upper Chesapeake Bay area, Long Island, parts of eastern Massachusetts, central Rhode Island, eastern Connecticut, Vermont, and New Hampshire. Both Boston and Providence received more than 3 feet (0.9 meter) of snow. Some parts of Rhode Island reported 4 feet (1.2 meters) of snow. The storm also brought significant snowfall to New York City, New Jersey, and eastern Pennsylvania.

The weather paralyzed traffic, caused power outages, and forced businesses to close in Rhode Island, Connecticut, and Massachusetts for the better part of a week. President Jimmy Carter declared emergencies in those three states. In many parts of New England driving in nonemergency cases was banned, and violators were slapped with hefty fines.

Gale-force winds shook much of the region during the storm. A gust measuring 79 miles (127 kilometers) per hour was reported at Boston's Logan Airport, with a two-day wind-speed average at the airport of 30 miles (48 kilometers) per hour. Hurricane-force winds greater than 74 miles (119 kilometers) per hour blasted Massachusetts' eastern shore. Those winds combined with high tides to produce colossal waves that smashed into coastal communities. More damage was caused by coastal flooding during that storm than from any hurricane affecting New England to that date.

More than one thousand army troops from the Midwest and the South were flown to New England to assist in the cleanup from the storm. Over 140 military aircraft, carrying nearly 7 million pounds (3.2 million kilograms) of snow-clearing equipment, landed at airports in Boston, Providence, and Hartford, Connecticut, for use in the effort.

areas. Strenuous activity, such as shoveling snow, can bring on heart attacks—especially in older people or people with histories of heart trouble.

Are humans causing blizzards?

The Blizzard of January 1996, which produced record-breaking snowfalls on the East Coast and caused more than one hundred deaths, made some scientists wonder if global warming was bringing on strong blizzards and other types of extreme weather. Many scientists agree that global average

Vehicles are abandoned along a Massachusetts road in the deep snow left by the blizzard of 1978. AP IMAGES.

temperatures have begun to rise and will continue to rise, because of an increase of certain gases in Earth's atmosphere. According to the U.S. Environmental Protection Agency (EPA), global average temperatures have increased by 1°F (0.5°C) in the last century. Much of this global climate change, especially during the last fifty years, may be due to human activity.

Human activities have caused the build-up of greenhouse gases in Earth's atmosphere. These gases are called greenhouse gases because they let sunlight come in but don't let heat go back out into space—as if Earth were covered with a big glass greenhouse that keeps everything warm. The most plentiful greenhouse gases are water vapor and carbon dioxide. Other greenhouse gases include methane and nitrous oxide.

The increase of carbon dioxide in the atmosphere is believed to be the main reason for global warming. Carbon dioxide is produced by burning fossil fuels, such as coal, fuel oil, gasoline, and natural gas, and is emitted into the air by homes, factories, and motorized vehicles. During the last century, the amount of carbon dioxide in the atmosphere has increased by 30 percent. During that same period, the planet has become, on average, slightly more than 1°F (0.5°C) warmer.

There doesn't seem to be much doubt that humans have affected global warming by burning fossil fuels and other activities, but is that activity making blizzards more frequent and more intense?

A man in Brooklyn, New York, shovels snow after a blizzard in 2006. AP IMAGES.

Some say yes; others no Some scientists say global warming causes more water to evaporate from the oceans into the atmosphere. When this warmer, moister air collides with colder air, it can produce more ice crystals and stronger winds, which can result in stronger blizzards. They also say that because this evaporation process is going on all the time, it also produces a steady supply of moist air, which can result in more frequent blizzards.

Other scientists point out that global warming should also warm the colder regions and therefore produce less cold air to collide with the warm, moist air. This should produce fewer blizzards, they claim. They also note that in many areas, no real increase in the amount of moisture in the air has occurred. These scientists claim that although global warming is real, it has not resulted in more frequent or more intense blizzards.

Technology connection

There are many ways to predict, prepare for, and respond to blizzards. Today's weather forecasters use satellite images, radar, data from weather stations on the ground, and computer models to determine where and when blizzards are forming.

In blizzard-prone regions, residents attempt to lessen the impact of the storms by erecting snow fences, which reduce drifts on roads. They also maintain fleets of snowplows for snow removal, stock salt for melting

A Chicago expressway after a snowstorm paralyzed the area in 1967.

ice, and stock sand for providing traction on slippery roads. When a blizzard starts, snowplows and salt and sand spreaders are dispatched to keep roads open—at least for use by emergency vehicles.

Weather satellites Weather satellites, circling the globe in space, provide meteorologists with pictures and other information about blizzards and other storms. The first weather satellite, called TIROS 1 (Television Infrared Observation Satellite), was launched in April 1960. Today, several nations operate satellites that continuously monitor global weather.

For most people, the words "weather satellite" conjure up images of swirling clouds that are seen on television newscasts. While weather satellites do produce those photos, they also perform other functions. Weather satellites determine the temperature throughout the atmosphere, from the cloud tops down to the land and oceans. They also measure humidity and wind speeds in the upper air and even track plumes of invisible water vapor. Weather satellites give meteorologists their first look at blizzards and other storms forming over land or sea. Once a developing storm is spotted, it is probed in greater detail using Doppler radar located on the ground.

Doppler radar Doppler radar is a sophisticated type of radar that relies on the Doppler Effect—when a wave, like a radio wave, bounces off a moving object, it changes the frequency of the wave. Scientists use this technique to determine wind speed and direction, as well as the direction in which precipitation is moving. Radar, which is an abbreviation for "radio detection and ranging," works by emitting short radio waves, called microwaves, that reflect off clouds and raindrops. This information allows forecasters to identify potential blizzards in their earliest stages.

In 1996 a network of 156 high-powered Doppler radars, called NEXRAD (Next Generation Weather Radar), was installed across the United States. Data from these radars around the nation are sent, via high-speed computers, to National Weather Service (NWS) centers and field offices

Extreme weather: The great Midwest blizzard of 1967

One of the largest blizzards on record for the Midwest came on January 26–27, 1967. The storm of snow and ice affected central and northern Illinois, central and northern Indiana, southeast Iowa, lower Michigan, Missouri, and Kansas. Kalamazoo, Michigan, received 28 inches (71 centimeters) of snow. Gary, Indiana, and Chicago, Illinois, both reported 24 inches (61 centimeters).

The blizzard was produced by a storm system that formed over the Gulf of Mexico and traveled north to the Ohio River Valley. The system had brought unseasonably warm weather to the Midwest in the five-day period prior to the blizzard. Then on January 24, just two days before the blizzard, a cold air mass arrived from the North. The combination of warm and cold air produced severe thunderstorms and tornadoes. The tornadoes tore through Missouri, Illinois, and Iowa. They killed several people and damaged or destroyed 200 houses.

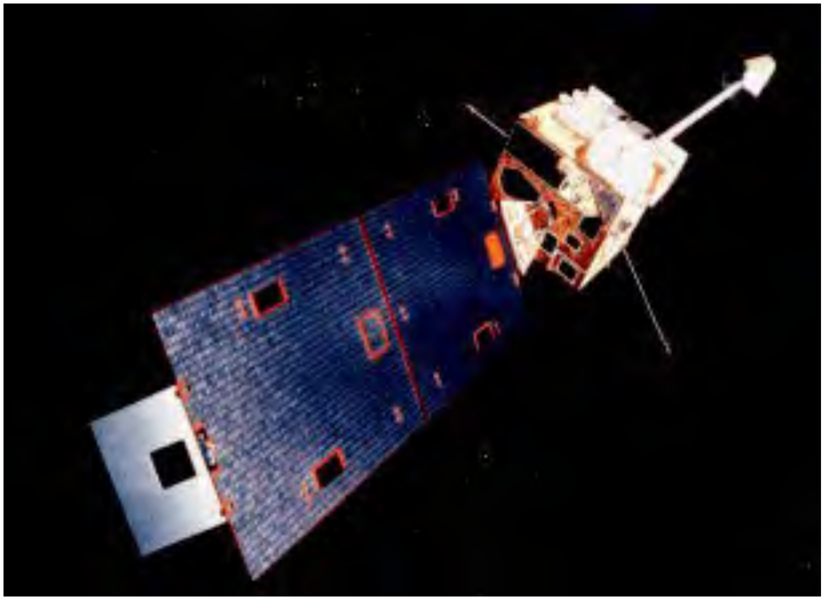
On January 26 the weather changed sharply in Chicago. While lightning still flickered in the sky, the temperature dropped and the wind picked up. Snow began falling and a blizzard was soon underway. A record-setting 24 inches (61 centimeters) of snow fell in a little more than twenty-nine hours. Winds clocked at 50 miles (80 kilometers) per hour, and gusting to 60 miles (97 kilometers) per hour, piled up snowdrifts 20 feet (6.6 meters) high. There were seventy-six deaths due to the storm, most of them in Chicago.

Chicago remained at a stand-still for several days under 24 million tons (22 metric tons) of snow. The city was a tangled mass of stranded cars, taxicabs, and trucks. More than three hundred city buses and even some snowplows were among the stalled vehicles. The city's expressways looked like huge parking lots. Long-distance and commuter train service was suspended. Chicago's O'Hare Field (now O'Hare International Airport), one of the busiest airports in the world, was closed for a record three days.

In central Illinois, central Indiana, Missouri, and Kansas the snow, plus sleet and freezing rain, brought down power lines and put much of the region in a blackout. National Guardsmen were called out to help with snow removal in Indiana.

around the country. At the NWS' Storm Prediction Center in Norman, Oklahoma, meteorologists analyze weather data from Doppler radars and other systems twenty-four hours a day. When they detect conditions that could give rise to winter storms, they notify the weather center in that area. The local weather center may then issue a winter storm alert.

Computer-based prediction Computer-based prediction relies on a sophisticated computer program called a numerical prediction model. The model incorporates mathematical equations that mimic processes in nature. When data from weather instruments is entered into a computer,



The Geostationary Operational Environmental Satellite (GOES) system. ©CORBIS.

the program projects how the weather will change over the next twelve hours, twenty-four hours, forty-eight hours, and several days into the future.

Due to improved computer forecasting models in recent years, the amount of time between when a blizzard warning is issued and when the storm strikes has greatly increased. In fact, major storms can now be predicted by computer even before their associated conditions are detected by weather stations.

Snow fences Snow fences are devices that slow winds and reduce the blowing and drifting of snow. They are erected along highways to reduce the amount of snow that ends up on the road. As the wind whips across a clearing, it picks up snow. When the snow-laden wind hits a snow fence, it slows down. The wind then deposits its snow, forming a gradual drift on the other (downwind) side of the snow fence.

A snow fence must be placed far enough from the road to allow room for the snowdrift to form, without reaching the road. The rule of thumb is that snow will accumulate downwind of the fence for a distance approximately ten times the height of the fence. Therefore, if a fence is 10 feet (3 meters) high, it should be placed at least 100 feet (30 meters) from the road.

A snow fence near a highway in Wyoming. ©TED SPIEGEL/CORBIS.

Salting icy roads Salt is applied to snowy, icy roads because it melts ice and prevents the water from refreezing. Salt is also relatively cheap and easy to apply, making it the de-icing agent of choice since the 1960s.

Sodium chloride (NaCl), the type of salt used on roads, melts ice through an equilibrium change. Ice on the ground is in a state of dynamic equilibrium between the liquid and the solid states. When sodium chloride comes into contact with the ice, it is dissolved. When dissolved, sodium chloride breaks down into one positively charged sodium ion (Na+) and a negatively charged chloride ion (Cl–). At the same time it causes the water molecules making up the ice to disassociate into one hydroxide ion, OH–, and one hydronium ion, H+. The positively charged hydrogen atoms are drawn to the negatively charged chloride atoms, and negatively charged oxygen atoms are drawn to the sodium atoms.

Experiment: Freezing salty water

Normally, water freezes at 32°F (0°C). However, salt can be used to lower the freezing point of water. This is why some communities throw salt on roadways during winter storms. To demonstrate how this works, take two cups of water of the same size. The water should be the same temperature. Place a tablespoon or so of salt in one of the cups and place both cups in the freezer. Then check each cup every ten minutes or so. You'll see that the cup of plain water freezes before the cup of salty water. This is because a chemical reaction between the salt and the water lowers the water's freezing point. You can vary this experiment by doing more trials in which you add more or less salt. The more salt you add, the colder the water will have to become before it freezes.

The sodium and chloride ions bond with the hydronium and hydroxide ions so that hydronium and hydroxide are not free to recombine into water. The sodium and chloride ions also draw water molecules away from one another. Salt, in this way, both prevents liquid water molecules from forming ice crystals and breaks up existing ice crystals. The speed of melting is increased, while the speed of freezing is not changed. Sodium chloride is only effective at melting ice at temperatures down to 20°F (–7°C).

Whereas salt provides an efficient means of melting snow and ice on roads and has greatly contributed to highway safety, it also has a downside. Salt is bad for the environment. It kills vegetation along the side of the road and can seep down into wells, making the water undrinkable. Salt also causes vehicles to rust and bridges to corrode. For these reasons, salt is applied only in the minimum quantities necessary to get the job done.

A matter of survival

The National Weather Service issues blizzard warnings whenever blizzard conditions are expected. If forecasters predict a winter storm that is less severe than a blizzard, but still serious enough to create dangerous travel conditions, they will issue another type of winter storm alert. Four classes of winter storm alerts, based on the seriousness of the storm, are defined as follows:

- **A winter weather advisory** states that snow, sleet, freezing rain, or high winds may be on the way. It advises people to exercise caution when traveling.
- **A winter storm watch** states that at least 6 inches of snow and an ice storm may be on the way. It advises people to limit their travels and to exercise great caution if they must venture onto the roads.
- **A winter storm warning** states that a storm, including heavy snow and possibly ice, has already begun or will soon begin. It advises people not to travel, except in an emergency.
- **A blizzard warning** states that a blizzard—including blowing or falling snow, low temperatures, and winds of at least 35 miles

Reports from the past: Tragedy at Donner Pass

One of the most famous blizzard-related tragedies in history occurred during the winter of 1846–47 in the Sierra Nevada Mountains of California. A group of eighty-seven pioneers, including men, women, and children, left Illinois for California in April 1846. The group, led by George and Jacob Donner, was known as the Donner Party.

On October 31, the Donner Party began their ascent into the mountains in northeastern California. When they reached a pass (today called Donner Pass) at an altitude of 7,085 feet (2,160 meters), the snow and wind forced them to a halt. A few members of the party pressed on to seek help, while the others erected shelters and prepared to wait for better weather.

The snow and wind relentlessly blasted the pioneers in the mountain pass. Some drifts reached 60 feet high. "We cannot see twenty feet looking against the wind," Donner Party member J. F. Reed wrote in his diary, "I dread the coming night."

Before long the group's food supplies ran out. The oxen they had planned to kill and eat had become lost in the snowstorms. For a time the pioneers lived on mice and twigs; then the winter became so severe that people dared not venture outside. Forty people died of disease or starvation in the following months. In time, the survivors became so desperate and addled by starvation that members of the party resorted to eating their own dead. Food supplies were finally brought to the trapped group in February 1847 after the men who had gone for help finally reached the Sacramento Valley and organized a rescue party.

Today a major highway and railroad tracks connecting San Francisco with Reno, Nevada, run through the Donner Pass. The Donner Memorial State Park was erected near the pass to commemorate the pioneers who lived and died through that terrible winter.

Drawing of the Donner Party's winter settlement in Salt Lake, California. ©BETTMANN/CORBIS.

Forest service employees measuring snow depth.

(56 kilometers) per hour—is on the way. The combination of moving snow and low clouds make it appear that the ground and sky are a continuous white sheet (called a whiteout), making travel nearly impossible. It advises people to remain indoors.

Preparing for blizzards If you live in an area affected by winter storms, it is wise to take the following precautions at the start of the season:

- Store extra blankets and warm clothing and boots for every member of the family.
- Put together a supplies kit for your home containing first aid materials, a battery-powered flashlight, a battery-powered radio, extra batteries, nonperishable food, a nonelectric can opener, and bottled water.
- Store a similar supplies kit in the trunk of your car, plus a shovel, a bag of sand, tire chains, jumper cables, and a piece of brightly colored cloth to tie to your antenna.
- Keep your car's gas tank full to prevent the fuel line from freezing.

Tips for outdoor survival If you must go outside during a winter storm, follow these rules:

- Be aware of the current temperature and wind chill. When dangerous conditions are present, only venture out for short periods.

- Wear several layers of lightweight clothing, mittens, a warm hat with ear flaps, a scarf covering your face and neck, warm socks, and waterproof boots. Wear wool clothing closest to your skin. (Wool will trap your body heat even if it gets wet.) Wear a brightly colored coat.
- Don't venture out alone.
- Walk carefully over icy ground.
- When shoveling snow, take frequent breaks to avoid overexertion.
- If you must drive, inform someone of your route, destination, and expected time of arrival.
- Stay away from downed wires—they can cause burns or electrocution. Report downed wires to the power company.
- If you're trapped outdoors in a blizzard, dig a large hole in the snow and climb in. This "snow cave," as it is called, will protect you from the wind and decrease the rate at which your body loses heat.

Surviving a blizzard in your car If you get stranded in your car during a blizzard, follow these rules:

- Stay with your car. Tie the brightly colored cloth to your antenna so rescuers can spot you. Don't attempt to walk away! It's easy to become disoriented and lose your way in a snowstorm.
- Only start the car and turn on the heater for ten minutes out of every hour. When the car is running, leave on the inside light so you can be spotted. When the car is not running, periodically check the tailpipe and clear it of snow, if necessary. If your tailpipe is blocked, dangerous exhaust fumes can back up into the car.
- Move your arms and legs continuously to stay warm and maintain your blood circulation.
- Let in fresh air by slightly opening the window that's opposite the direction of the blowing wind.

[*See Also* **Forecasting; Precipitation; Weather: An Introduction**]

For More Information

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Drought

A drought (pronounced DROWT) is an extended period where the amount of rain or snow that falls on an area is much lower than usual. A drought usually lasts at least one season and sometimes continues for years. It may affect an area the size of several states or greater. During a drought, the amount of water used by plants, animals, and people is much greater than the precipitation, which is the amount of water that falls to the ground in the form of rain or snow. Rivers and lakes may dry up. Droughts happen almost everywhere in the world, although some areas experience drought more frequently than others.

There is no universal definition of drought based on rainfall amounts, since what is considered usual varies from region to region and climate to climate. In Australia, which is a dry climate, a drought is defined as a year in which precipitation is less than 10 percent of average. In the United States—most of which has a temperate, humid climate—drought is defined as a period at least twenty-one days long during which rainfall over an extensive area is less than 30 percent of average. In places with distinct wet and dry seasons, such as India, a drought is defined as a year in which precipitation is less than 75 percent of average. The severity of a drought is determined by the amount of rainfall, the water levels in rivers and lakes, the duration of the dry spell, and the size of the area affected.

Droughts lead to crop losses, soil erosion, death of livestock, and even famine (long-term shortages of food that can lead to hunger, malnutrition, and death). Human beings sometimes make drought conditions worse by stripping the land of vegetation and placing heavy demands on the water supply.

The African Sahel: Devastated by drought

The longest-lasting and most devastating drought in recent times occurred in the Sahel region of Africa in the last half of the twentieth

WORDS TO KNOW

air mass: a large quantity of air throughout which temperature and moisture content is fairly constant.

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

aquifer: an underground layer of spongy rock, gravel, or sand in which water collects.

arid: describes a climate in which almost no rain or snow falls.

blocking system: a whirling air mass containing either a high-pressure system (a blocking high) or a low-pressure system (a blocking low), that gets cut off from the main flow of upper-air westerlies.

climate: the weather experienced by a given location, averaged over several decades.

desert climate: the world's driest climate type, with less than 10 inches of rainfall annually.

desertification: the process by which semiarid lands turn into desert (also called land degradation). It is caused by prolonged drought, during which time the top layers of soil dry out and blow away.

drought: an extended period where the amount of rain or snow that falls on an area is much lower than usual.

ecosystem: a community of plants and animals, including humans, and their physical surroundings.

El Niño: means "the Christ child" in Spanish. A period of unusual warming of the Pacific Ocean waters off the coast of Peru and Ecuador. It usually starts around Christmas, which is how it got its name.

erosion: the wearing away of a surface by the action of wind, water, or ice.

global water budget: the balance of the volume of water coming and going between the oceans, atmosphere, and continental landmasses.

heat cramps: muscle cramps or spasms, usually afflicting the abdomen or legs, that may occur during exercise in hot weather.

Heat exhaustion: a form of mild shock that results when fluid and salt are lost through heavy perspiration.

heat stroke: a life-threatening condition that sets in when heat exhaustion is left untreated and the body has exhausted its efforts to cool itself. Also called sunstroke.

heat wave: an extended period of high heat and humidity.

La Niña: Spanish for "little girl," a period of unusual cooling of the Pacific Ocean waters off the coast of Peru and Ecuador. It often follows an El Niño.

semiarid: a climate in which very little rain or snow falls.

transpiration: the process by which plants emit water through tiny pores in the underside of their leaves.

upper-air westerlies: global-scale, upper-air winds that flow in waves heading west to east (but also shifting north and south) through the middle latitudes of the Northern Hemisphere.

century. The Sahel (Arabic for "margin" or "shore") is a strip of semiarid land in northern Africa, sandwiched between the Sahara to the north and the wetter grasslands to the south. It extends from the continent's west

A man walks on drought-cracked soil in the African country of Mali. ©KAREN KASMAUSKI/CORBIS.

coast almost to its east coast. The Sahel ranges in width from 200 to 700 miles (320 to 1130 kilometers) and covers more than 2.5 million square miles (5.1 million square kilometers). It runs through the countries of Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, and Sudan. A similar semiarid belt exists in Ethiopia and Somalia. The Sahel region constitutes about 20 percent of the landmass of Africa, and the nations within this region are among the poorest in the world.

The ecosystem of the Sahel is the most fragile in all of Africa. The primary vegetation includes low-growing grass, thorny shrubs, and a few varieties of trees.

During the last thirty years of the twentieth century, the Sahel suffered from desertification—the process of turning the land into desert. In the beginning of desertification, the soil slowly loses its ability to grow plants. Next comes a period of rapid soil breakdown. In the final stage of desertification, the soil becomes unable to hold nutrients or retain enough water to support plant life. Desertification is a long process and is difficult to reverse.

The major cause of desertification in the Sahel has been a series of droughts that lasted for years. Human activity, such as intensive farming and grazing large numbers of livestock, has also contributed to desertification.

Drought is common Throughout history the Sahel has experienced frequent droughts. The region receives an average of just 4 to 20 inches

Refugees at a camp in Sudan wait for food distribution during the Sahel drought. ©CHRIS RAINIER/CORBIS.

(10 to 50 centimeters) of rain per year, mostly in the southern areas during the months of June, July, and August. Because the area is also hot during this period, about 90 percent of the water that falls to the ground returns to the atmosphere through evaporation and transpiration. With the water balance so unsteady in normal times, even a small decrease in rainfall over a season may result in water shortages and crop failures.

After a relatively rainy period in the 1950s and early-to-mid 1960s, a drought started in 1968 and lasted until 1973. During that period, crops died throughout the region, and a famine took the lives of some 250,000 people and 3.5 million grazing animals. Many more people would have died if not for a massive amount of help from other countries.

After a few years of normal rainfall, relatively dry conditions prevailed from 1976 through 1981. Then drought struck the region again from 1983 through 1985 and in the early 1990s. Throughout the dry years, desertification continued its march southward from the Sahara. Overall, between the years 1935 and 1985, a portion of the Sahel, roughly equal in size to the combined size of France and Austria, turned into desert.

By the end of the 1990s, however, normal precipitation levels had returned to the Sahel. While desertification was continuing in some places, much of the Sahel had recovered to the point that local food production needs were being met.

The influence of the people Although the problem of desertification in the Sahel started because of the long periods of drought, population growth and bad use of the land intensified the problem. Because of the lack of rainfall and high temperatures in the region, the soil is thin, sandy, and fragile. Most of the land is covered with grass and is best used by people who move from one area to another with small herds of animals, or by small-scale farmers.

In years past, Sahel-dwellers grew crops only on a particular piece of land one season at a time. They would then leave that piece of land undisturbed for several years so that the soil could regain its nutrients. During that time, cattle would graze on the crop stubble and fertilize the soil with their wastes.

In the latter half of the 1900s, however, the population of the Sahel increased greatly. Increasingly more land was used for growing crops, which thinned the soil and reduced its fertility. As a result, farmers could not let part of the land sit undisturbed for several years; instead, they had to plant every available piece of land every year in order to produce enough food to survive.

A series of unusually rainy years in the 1950s and 1960s also encouraged more farming in the Sahel. Shortsighted government officials, not anticipating that a drought might return, urged farmers to cultivate greater areas of land. Land previously undisturbed or used for grazing was cleared. The trees and brush were taken for firewood, and the soil was plowed for crops.

Changes in methods of grazing livestock also contributed to desertification. The traditional practice of moving livestock from one area to another to eat the grass changed as small towns were built up around water wells. Thus, the livestock would eat grass only in one area and the land in the surrounding area was stripped bare of grass and other plants. As a result, it became hard and barren within just a few years.

Dry lands that have been stripped of vegetation take a long time to recover. Even when rains do fall, very little water penetrates the earth. Most of the rain runs off the ground, washing away the topsoil and leaving a wasteland. Moreover, the wind causes more erosion when there are no plants and their roots to hold the soil in place.

Millions of people forced to move During the periods of drought from the late 1960s through the mid 1980s, more than ten million farmers and shepherds from the Sahel moved to cities and towns. They built shanties on the outskirts of already overpopulated urban areas and tried to earn a living. For example, in Mauritania, one of the countries hit hardest by the drought, refugees increased the population of the town of Nuakchott from 20,000 in 1960 to 350,000 in 1987.

The migration of people from country to city has done more than create population pressures on cities; it has disrupted centuries-old ways of life and tribal bonds. Omar Mahmoud, a former herdsman who moved to an urban shantytown in the early 1970s, was trying to live by raising vegetables on a small, dusty plot of land. He told a *National Geographic* reporter, "I don't know much about this work. My life is being with my animals, but now they are all gone. Forty head of cattle, forty sheep. Sixty goats."

Foreign aid has mixed results Foreign governments and international relief agencies began providing emergency aid to the Sahel in the late 1960s. While this assistance prevented mass starvation in many areas, and a few projects helped slow the pace of desertification, many of the projects were costly and poorly managed; they also did not have much effect on the problems.

Many relief-agency projects involved the planting of trees or grasses in an effort to stabilize the soil and prevent further erosion. In some cases planners planted too few trees, which did not provide enough stability for the soil. In other cases, the planting of trees was not coupled with instructions about the importance of the trees to the people's survival. As a result, many people cut down the trees for firewood. Some agencies made the mistake of providing seeds for crops such as eggplant that were unfamiliar and distasteful to the people living in the region.

In one notable success story, however, the relief agency CARE began a project in the Majja Valley in Niger. They planted a double row of trees along a 230-mile-long (370-kilometer-long) stretch of land. The trees, which have been maintained by local villagers, stop the wind from eroding the soil during dry times and protect crops from the wind during the rainy season.

What can be done in the Sahel? Scientists have different opinions about what can be done to save the Sahel from drought in the future. Some feel the people must be moved out of the area and the farmlands replaced with forests to prevent future problems. Others feel the people themselves can solve the problems without being moved by exchanging ideas, building water supplies, and planting trees. Everyone seems to agree that a big part of the solution is to develop a society in the Sahel where there are fewer people dependent on the land for their survival and more people doing other jobs.

Food delivery to Niger, Africa, during the Sahel drought, 1973. ©FARRELL GREHAN/ CORBIS.

Recent events: Major droughts since 2000

Between 1999 and 2002, the United States experienced a drought that was among the worst of the past 40 years. During these years of drought, parts of the United States experienced the driest conditions in more than 100 years of record keeping. The year 2001 was the second-hottest on record in the United States, second only to 1998, which saw record temperatures due to El Niño (an extraordinarily strong episode of the annual warming of the Pacific waters off the coast of Peru and Equador).

The consequences of the 1999 to 2002 drought were significant and far reaching. Heat and water restrictions hampered U.S. crop production. Rivers lost water, and fish died by the thousands. People, especially elderly people living in cities, died in their homes from the heat. Wildfires raged and caused millions of dollars worth of damage.

Drought is defined as an extended period of unusually dry conditions. However, drought conditions can and do exist even in years not officially termed "drought" years. In August 2006, for example, the National Weather Service published drought statements for thirty American cities from Talahassee, Florida, to Denver, Colorado, to Duluth, Minnesota.

Even in the absence of an official drought, hot and dry conditions create the risk of wildfires, crop destruction and river evaporation. Many cities throughout the United States experience water shortages during the summer months. City governments sometimes respond by imposing bans on water use for irrigation purposes in order to conserve precious water supplies.

What causes a drought?

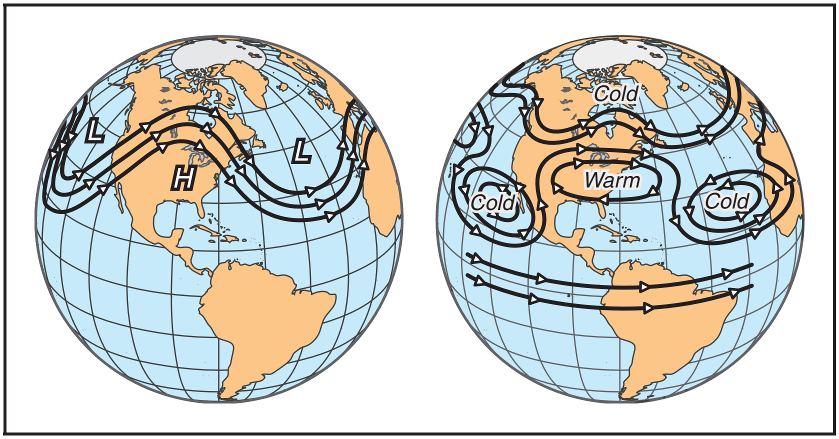
Droughts occur when rain-producing clouds fail to form, and there is little, if any, rainfall. Several factors can bring on those conditions. In

Drought conditions in Sebago Lake, Maine, in 2002. AP MAGES.

temperate regions, including much of the United States, the primary cause of drought is the prolonged presence of a high-pressure system called a blocking high. In many parts of the world, the weather condition known as El Niño (and its sister, La Niña), which occurs about every five to seven years, also influences rainfall amounts. The removal of vegetation can also contribute to drought in some regions.

Blocking highs The main cause of drought in the United States is the prolonged presence of a high-pressure system over a given area. High-pressure systems generally produce clear skies and little rain. As air descends beneath a high-pressure system, the moisture within it evaporates. Low-pressure systems, in contrast, are associated with cloudiness. The air beneath them rises, and the moisture within the air condenses and forms clouds.

Systems of high and low pressure typically alternate over a given location as they are pushed along by upper-air winds. Those winds circle the globe along a wavy, west-to-east path. Sometimes, however, an air mass (a large quantity of air throughout which pressure, temperature, and moisture content is fairly constant) gets cut off from the main flow of upper-air winds. If that air mass has high pressure, it is called a blocking high; if it has low pressure, it is called a blocking low. The presence of a blocking system typically brings about an extended period of one type of weather.



The formation of blocking high (H) and blocking low (L) systems.

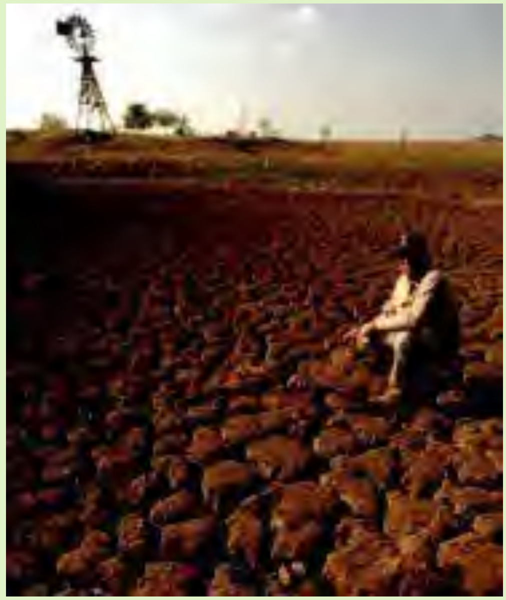
A blocking high may remain stationary for several weeks. In addition to producing dry conditions, the blocking high may produce exceedingly hot weather. The surface air heats up because the upper-air circulation, which moderates temperatures by alternating warm and cold air masses, passes around the area.

El Niño and La Niña In some parts of the world, drought is driven by El Niño (pronounced el NEE-nyo). El Niño is a current of warm water in the tropical Pacific Ocean. Every few years, the water that flows from the western Pacific and settles off the coast of Peru and Ecuador is unusually warm and remains for an extended period of time.

Air pressure across the Pacific Ocean is linked to El Niño. In normal conditions, air pressure is higher over the eastern Pacific, near South America, and lower over the western Pacific, near Australia. (High pressure is typically associated with clear skies, while low pressure is typically associated with cloudy skies and rain.) The difference in pressure between the two areas makes the winds blow from east to west, and toward the equator. The winds carry warmth, moisture, and rainmaking clouds toward Australia and Indonesia.

During an El Niño year, the air pressure in the western Pacific rises while the air pressure in the eastern Pacific lowers. As the warm water in the eastern Pacific evaporates into the air and forms clouds, the normally dry coastal South American nations get more-than-average rainfall, causing flooding and erosion. At the same time, Australia, Indonesia, the

Question: Is global warming causing droughts?



Farmer surveying the parched soil on his Texas farm. ©JIM SUGAR/CORBIS.

As Earth's climate changes, drought becomes a more regular part of human existence. Many U.S. states now experience drought conditions regularly, and the U.S. experienced its worst drought in almost half a century between 1999 and 2002. Scientists believe that global temperatures are on the rise, but could this be contributing to the increase in drought conditions?

Recent scientific data indicates that the global average temperature increased by about 1°F in the last century. Scientists refer to this process as global warming, which is partly caused by increase of certain gases, called greenhouse gases, in Earth's atmosphere. Many scientists think that temperatures will rise even more in the decades to come, and some are worried that increased temperature will cause more frequent, severe, and prolonged droughts.

There are many factors that cause drought, and droughts have plagued humanity for centuries. Certainly global warming is not the only factor that contributes to drought. However, warmer temperatures increase the evaporation of water from Earth's surface, which contributes to and worsens drought conditions.

Philippines, and other lands of the western Pacific experience less-than-average rainfall and sometimes drought.

Often in the wake of El Niño comes La Niña—a period of unusual cooling of the ocean water off the coast of Peru and Ecuador. La Niña's effects on rainfall patterns are practically the opposite of El Niño's. One consequence of La Niña is that drier than usual conditions prevail in many parts of the United States. La Niña also means drought for the South American coast and flooding for the western Pacific region.

The water cycle

The water cycle (also called the hydrologic cycle) is the continuous movement of water between the atmosphere and the Earth's surface (oceans and landmasses). On one side of the equation is precipitation—rain and snow—and on the other side is evaporation—the process by which liquid water at the surface converts to a gas and enters the atmosphere.

From 85 to 90 percent of the moisture that evaporates into the atmosphere comes from the oceans. The rest evaporates from the soil, lakes, and rivers that make up the continental land-masses. Even plants emit water through tiny pores in the underside of their leaves in a process called transpiration.

Some of the moist air above oceans is carried over land by the wind. Clouds form and drop rain and snow on the ground. When precipitation hits the ground, it either sinks in or runs off, depending on the surface composition. On soft ground, most of the water sinks into the soil to be absorbed by plant roots or to seep down into underground aquifers. Some of it runs off into streams and rivers. If the water strikes a hard surface, like rock or pavement, most of it runs directly into streams or artificial drains. Eventually this water also flows into rivers.

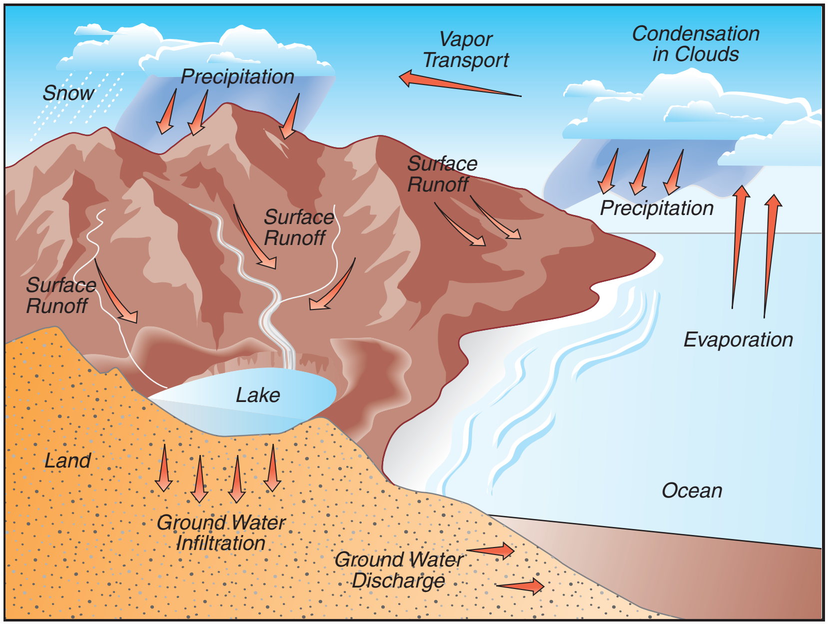
The oceans lose water in this portion of the cycle—more water evaporates from them than returns as precipitation. The oceans get this water back when the rivers empty their water back into the oceans. Thus the global water budget—the volume of water coming and going from the oceans, atmosphere, and continental land-masses—is kept in balance.

If the water cycle is kept in balance, that means that global precipitation levels remain fairly constant. So why do droughts occur? The answer is that rain and snow do not consistently fall in equal amounts in any given place. Moisture may evaporate from one place, travel through the atmosphere, and fall to the ground as rain in another. It is possible, then, for a given location to get lots of rainfall one year and almost no rainfall the next.

Aftermath: The effects of drought

While drought does not produce the sensational pictures of destruction seen in other natural disasters, its economic impact is often greater and longer lasting. According to the Nebraska-based National Drought Mitigation Center, the average yearly economic damage done by droughts in the United States is greater than the economic damage done by floods and hurricanes combined. Droughts cost the United States between $6 billion and $8 billion per year, while the annual cost of floods and hurricanes are $2.4 billion and $1.2 billion, respectively.

The impact of droughts varies widely, depending on the severity and length of the drought and its location. Among the consequences of drought



The water cycle.

are shortages of water, livestock and wildlife death, crop loss, soil erosion, wildfires, and dust storms. Famine is the most drastic consequence of drought and is most likely to occur in poor nations where food supplies are already scarce and governments have little money for importing food or drilling wells.

Reduction in water levels One direct consequence of drought is a shortage of water. Wells run dry, and water levels drop in lakes and rivers. The first water supply to be affected is aquifers, which are underground water reservoirs made of porous rock, gravel, or sand. Aquifers feed lakes and rivers; the top of an aquifer is higher than the bed of the lake or river it feeds. When water is plentiful and an aquifer is full, water runs over into a surface body of water. During drought, however, the level of the aquifer falls below the floor of the lake or river, and the aquifer ceases to replenish the surface body of water. In severe drought, aquifers go dry, and lake and river levels become very low. Wells (holes drilled into aquifers that provide people with water) also may run dry, in which case it becomes necessary to continue drilling to tap sources of water deeper underground.

Experiment: How rainfall affects soil

During a drought, rainfall is extremely scarce. To understand some of rain's effects, try this experiment. Get two large disposable aluminum baking pans. Fill one with some dirt from a garden or yard. Use a pair of scissors or an awl to poke six or eight small holes in one end of the pan that is full of dirt. Put the empty pan under the side of the dirt-filled pan that has holes in it. Lift up the opposite end of the pan (you can use books to hold it up), and then use a watering can to pour water onto the dirt at the elevated end of the pan. Notice what happens to the dirt when the water comes into contact with it, and pay attention to the color of the water as it runs into the second pan.

The lowering of water levels in lakes and rivers has several consequences. For one, fish and other forms of aquatic life may die. If bodies of water become too shallow for boats to operate, the water recreation industry suffers economic harm. If barges and ships cannot carry goods down waterways, the increased cost of shipping materials over land gets passed on to consumers. In addition, the amount of electricity produced by hydroelectric power stations (facilities at which the energy of the moving water is converted into electricity) decreases when rivers flow less forcefully.

The reduction in water levels that results from a drought are felt long after the rains resume. First, enough rain has to fall to recharge dried-out aquifers. This process typically takes a year or more. Only when the aquifers are full will the water begin its slow journey to rivers and lakes.

Migration and famine When drought is serious enough to affect food and water supplies, people in the affected region are forced to move to another area or subsist on donated food. In Africa, Asia, and Australia—regions where there have been droughts lasting several years—the loss of crops and cattle has caused widespread human suffering. A severe drought in northern China in 1876, for instance, caused crop failures that led to the deaths of millions of people. As many as five million people died in Russia as a result of a drought along the Volga River basin in 1921.

Secondary impacts Droughts also have indirect impacts, such as increased prices for food, energy, lumber, and other products; unemployment (in the agricultural, forestry, and fishing industries); and the closing of businesses in the affected area. The loss of crops that results from drought does not just

Cattle in a field in New South Wales, Australia, during the 1983 drought. ©PENNY TWEEDIE/CORBIS.

affect the pocketbooks of farmers. It also means a reduction in revenues for merchants who provide goods and services to farmers.

The human factor

While drought on Earth is older than human existence, human activity in recent years has contributed to the frequency and severity of droughts. The primary way in which people bring about drought is by stripping the land of vegetation. Denuded land not only suffers more than covered land during times of drought, but the lack of vegetation also contributes to the occurrence of drought. The major ways in which people encourage drought are through farming intensively, overgrazing cattle, and cutting down trees for timber or fuel.

The concept of surviving a drought has different meanings depending on the location and severity of the drought. For some people, especially those in poor nations, surviving a drought means subsisting on donated food or migrating to wetter regions. In wealthier nations, where food is more abundant, people learn to change their behaviors to adapt to chronic drought rather than aiming merely to survive it. Coping with drought may entail conserving water and keeping cool in hot weather.

Desertification Desertification, also called land degradation, is the process of turning an area into desert. Approximately 25,000 square miles

A family struggles through a drought in Ethiopia's Tigre region in 2000. ©JOUANNEAU THOMAS/CORBIS SYGMA.

(64,750 square kilometers) of Earth's surface is turned into desert each year. Reversing desertification is a lengthy and difficult process.

While drought is the primary cause of desertification, humans can make the problem worse by removing a land's natural vegetation. Exposed soil is susceptible to erosion by wind and rain. In the absence of roots to bind the soil together and trees and shrubs to slow the wind, heavy rains create deep ravines and gullies in the land, and the wind blows away the topsoil.

The enforcement of travel restrictions across political boundaries in Africa and Asia in the twentieth century has been one of the leading causes of human-induced land degradation in those areas. Prior to the restriction of travel across national borders, nomads roamed with their herds in search of vegetation. New policies forced herdsmen to settle in particular areas, and wells were drilled to meet their water needs. As a result, the settled areas have been overgrazed and stripped of vegetation, and the water levels of the reservoirs feeding those wells have greatly decreased.

Vegetation loss and the cycle of drought The clearing of vegetation also acts as a deterrent against cloud formation and rain—in essence creating a cycle of drought. When water evaporates from leaves, that water condenses to form clouds, which can cause precipitation. In the absence of plants, the air is dry and does not form clouds. When it does rain, the lack of vegetation also means the surface is less able to retain the water. The water runs off and erodes the soil, which means even fewer plants can grow—making the cycle repeat and grow worse.

Overuse of groundwater Another practice that creates many problems during droughts is the overuse of groundwater. Groundwater is water from rain or melted snow that seeps into underground aquifers. Pumps are used to tap groundwater for community needs. If the rate of groundwater usage is not reduced during dry periods, aquifers can become depleted, thus contributing to the lowering of lake and river levels.

When aquifers become depleted they may collapse, causing the ground around them to sink—thus forming sinkholes. A sinkhole is a large depression in the Earth's surface; often shaped like a funnel, it is typically 50 feet (15.3 meters) in diameter and up to 100 feet (30.5 meters) deep.

Conserving water In the United States, water conservation measures are typically required in times of drought; nonessential uses of water, such as car-washing and lawn-watering, are banned. Some communities have programs in place to recycle wastewater (from sources such as bathtubs and dishwashers) for use on small farms and domestic gardens.

There are many ways people can reduce water consumption. For example, people can take showers instead of baths. A bath typically uses 30 gallons (114 liters) of water, whereas a five-minute shower, at a flow of 5 gallons (19 liters) per minute, uses 25 gallons (95 liters) of water. An economy showerhead reduces the flow to 2.5 gallons (9.5 liters) per minute and would use only 12.5 gallons (47.5 liters) for a five-minute shower. If each person in a family of four takes a bath every day for a week, the family uses 840 gallons (3,180 liters) of water. If the family installs an economy showerhead, and each person takes a five-minute shower each day instead of a bath, however, they will use just 280 gallons (1,060 liters) of water. This would save 560 gallons (2,120 liters) of water a week.

Another water-saving device is a low-flow toilet. This type of toilet uses less than 2 gallons (7.6 liters) per flush, as compared to the 5 gallons (19 liters) per flush used by a conventional toilet. Some states in drier regions of the United States have laws requiring the installation of reduced-flow showerheads and toilets in new construction.

Some people conserve water by collecting rainwater and using it for watering the garden. When rainfall is minimal, bath water can be used on the garden. Another method of saving water is installing plumbing that routes

Drought in Australia

Australia experienced a serious drought in the early twenty-first century. The drought, the worst in two decades, began in March 2002. Like the U.S. drought of the same year, the Australian drought produced record-breaking low amounts of rainfall.

The consequences of the Australian drought have been dire. Livestock and crops were particularly hard hit. Because the country had less to export, its trade deficit soared to its highest point in years. Bush fires caused damage and destruction throughout the country.

Animal skeletons during a drought in New South Wales, Australia, in 1982. ©PENNY TWEEDIE/CORBIS.

bath water or water that has been used for washing dishes to the toilet, for flushing.

Community water-saving initiatives have been shown to work. In Tucson, Arizona, where conservation is mandated, residents use an average of 160 gallons (606 liters) of water per day. In Phoenix, by comparison, where water-conservation measures are not required, residents use an average of 260 gallons (984 liters) per day.

The heat factor Heat waves (extended periods of high heat), which are frequently associated with drought and actually worsen the effects of drought, are among the leading causes of death during droughts. Under drought conditions there are few, if any, clouds to block the incoming solar energy. The sunlight heats the land and robs it of existing moisture by causing rapid evaporation. The loss of moisture, in turn, makes the air even hotter. When the

How to survive a heat wave

The following suggestions can help you stay healthy during hot weather:

- Avoid overexertion, especially during the hottest part of the day. The coolest part of day, and the safest time for strenuous activity, is between 4 AM and 7 AM.
- Wear loose, lightweight, light-colored clothing. This type of clothing allows air to circulate while protecting the skin from the Sun's heat and damaging rays. The light color reflects, rather than absorbs, sunlight.
- Remain indoors as much as possible. If you don't have air conditioning, stay on the first floor, out of the sunshine, and keep the air circulating with electric fans. Each day that the air is very hot, try to spend some time in an air-conditioned environment.
- Drink plenty of fluids, even if you don't feel thirsty. Water is best. Avoid drinks with caffeine or alcohol, since they actually draw fluids out of the body, which may lead to dehydration.
- Eat frequent, small meals. Avoid foods high in protein since the digestion of protein increases your body's temperature.
- Avoid overexposure to the Sun. When skin is sunburned, its ability to dissipate heat is hampered.
- If you are taking medication that affects your blood circulation, ask your doctor how that medication affects your ability to tolerate heat.
- Groups of people most susceptible to heat-related illness include elderly people, small children, people with chronic illnesses, overweight people, and people with alcohol dependency. People in those groups should be especially cautious during a heat wave.

ground is dry, all incoming solar energy heats the land (as opposed to being absorbed in the process of evaporation) and is transferred directly into the air.

Hot weather adversely affects human health by raising the body's temperature. High body temperature can lead to dehydration, heat exhaustion (a form of mild shock that results when fluids and salt are lost through heavy perspiration), and heat stroke (a life-threatening condition that sets in when heat exhaustion is left untreated, and the body has used up its efforts to cool itself). People engaged in physical activity in hot conditions, particularly if they don't drink enough water, may fall victim to one or more heat-related illnesses.

Heat also places added stresses on the body's circulatory system. For elderly people or people with serious illnesses, that added stress can prove fatal. The most common causes of death in hot weather are cardiac arrest, stroke, and respiratory distress.

Heat waves take more lives than any other type of weather calamity. They kill approximately one thousand people per year, on average, in the United States, and a far greater number in other less-developed countries. In contrast, winter storms or cold kill approximately 130 to 200 people per year, on average, in the United States; floods kill 100 to 160; tornadoes kill 80 to 130; and hurricanes kill 40 to 60 people.

Satellite view of the Tambopata River in southeast Peru. ©KEVIN SCHAFER/CORBIS.

The technology connection

Several technological innovations are used to monitor and respond to droughts. Earth survey satellites provide data about water levels in surface bodies of water and the moisture content of the soil. Irrigation systems, dams, drought-resistant crops, and soil management techniques are all used to make the effects of drought less severe.

Drought prediction, however, remains something of a mystery. Droughts are hard to foresee because they are produced by the *absence* of events in the atmosphere; notably, the absence of rain clouds and precipitation. Other weather phenomena, such as hurricanes, thunderstorms, and blizzards, all have recognizable patterns of clouds and precipitation and show up on weather sensing instruments.

At the end of the twentieth century, researchers were looking at data on the cycles of El Niño and La Niña, as well as trends shown in satellite images, for possible keys to predicting future droughts.

Earth survey satellites Starting with the launch of Landsat 1 in 1972, a series of Landsat Earth survey satellites have continually monitored drought conditions by providing information on moisture levels in the soil, as well as the depths of lakes and rivers. Two Landsats continue to transmit information: Landsat 5, launched in 1984, and Landsat 7, launched in April 1999. The satellites orbit Earth about fifteen times every day at an altitude of 438 miles (705 kilometers). Each satellite is capable of observing almost every continental surface on the globe in an eighteen-day period. It can determine moisture content in areas as small as ten football fields.

Moisture content in the soil and evaporation rates (both measured by satellites) are reliable indicators of drought. Researchers combine this information with data on precipitation, temperature, and other factors to predict the length and intensity of a drought.

The images returned by Landsat satellites are also used for monitoring deforestation, receding glaciers, and crop growth. They are used to locate mineral deposits and to observe patterns of strip mining, logging, and damage due to insect infestations and fire.

Agricultural practices One way that farmers protect the soil from the impact of drought is by planting rows of trees or shrubs, called windbreaks, at intervals throughout their fields. Windbreaks, which run crossways to the direction that the wind usually blows, slow the wind and keep it from blowing away the soil.

In some regions with low levels of rainfall, farmers find success through fallow farming, which is the practice of letting one-half of the land lie fallow, or idle, every other year, while planting the other half. During the growing season, the farmer plows the fallow land to unearth weeds. Plowing also creates spaces in the soil that can trap water and raise the moisture content of the soil. When the previously fallow land is planted the following year, seeds are more likely to germinate rapidly, and crops will have an early growth spurt.

Another way that farmers guard against the effects of drought is by planting drought-resistant crops (plants that thrive even in dry conditions). These crops are relatively small and quick to grow. One crop that is drought-resistant is sorghum (pronounced SOAR-gum). During dry periods, sorghum stops growing and reduces transpiration (the loss of water through its leaves); it resumes growing when rain comes. Another example of a crop that does well in dry conditions is alfalfa, the roots of which extend down 6 feet (1.8 meters) or more and tap into groundwater.

Irrigation Irrigation is the transportation of water from reservoirs or wells to areas where crops are growing. Since the beginning of civilization, farmers have practiced irrigation as a means of improving their ability to grow crops. Irrigated farmland, in general, is twice as productive as nonirrigated farmland. In 2000, more than 900 million square miles

Soil and water in rows.

(6 billion square kilometers) of farmland around the world were irrigated. About one-third of the world's food supply comes from irrigated land.

Irrigation, however, has its drawbacks. For one thing, it is expensive; the drilling of wells and purchase of irrigation equipment and fuel, and in some cases the water, is costly. Many farmers relying on irrigation have found themselves buried in debt. Irrigation is also wasteful. In hot, dry weather, up to one-third of water sprayed out of crop sprinklers evaporates before reaching the ground. Irrigation that relies on groundwater also presents the danger of depleting aquifers. This is particularly hazardous in coastal land, because if the water table falls below sea level, seawater will seep into the aquifer and cause the groundwater to become salty, which destroys the soil.

Dams The construction of river dams is a common method of storing water and lessening the impact of drought (as well as preventing flooding). A dam is a barrier that blocks a river and controls the flow of water. When a river is dammed, the water backs up in the area behind the dam, creating an artificial lake or reservoir (pronounced REH-zer-vwar). Pipes carry the water from the reservoir to factories, homes, and farms. This ready supply of water is especially useful during times of drought. As the 1990s came to a close, there were more than 60,000 dams in use worldwide.

Large dams—defined as those that are more than 492 feet (150 meters) high, or holding back more than 19.6 million cubic yards (15 million cubic meters) of water—have a significant impact on the surrounding community and environment. When a dam is constructed in a valley, it floods the area upstream, putting homes, farmland, and even whole villages underwater. In the process, it displaces the people who inhabit the area. Dams also disrupt a river's natural cycle of flooding. When a river floods a valley, it deposits a layer of silt that enriches the soil. After the river is dammed, the fertile soil is lost. (The soil upstream is buried beneath the reservoir, and the soil downstream remains exposed but becomes less fertile over time.) Dams also disrupt the balance of the river ecosystem, destroying the habitat of birds, fish, and other animals, as well as many species of plants.

[*See Also* **Climate; Human Influences on Weather and Climate**]

For More Information

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Dust Storm

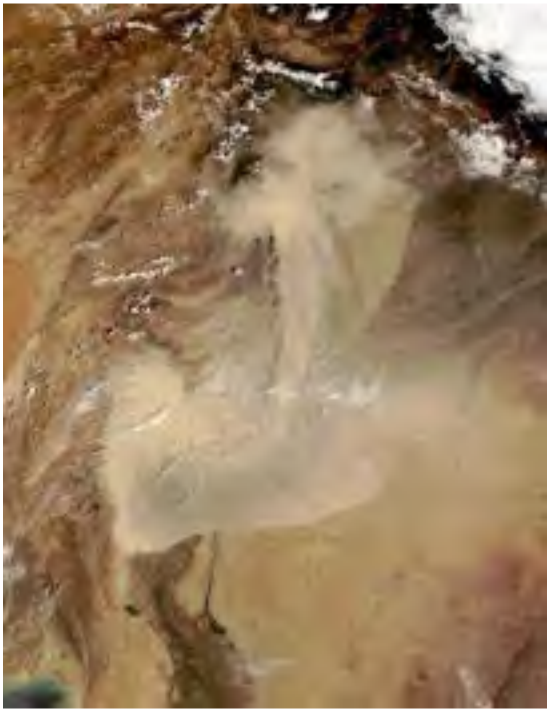
A dust storm is a large cloud of dust blown by a strong wind. The dust is primarily composed of tiny mineral particles that are lifted high into the atmosphere. The cloud of dust is so dense that it obscures the Sun and may reduce visibility to zero over an area as large as hundreds of thousands of square miles.

Dust storms primarily affect arid (desert) or semiarid (semi-dry) lands where the ground is made of loose soil and sand. They tend not to occur in the driest areas, since the ground is generally hard and flat, with rocks and gravel. Semiarid grassland that has been stripped of vegetation through plowing or overgrazing is particularly susceptible to erosion. Dust storms occur in semiarid land during times of drought, when there is no moisture to bind the soil together.

The areas of the world most prone to dust storms are northern Africa, the Middle East, and central Asia. In many places throughout these regions, dust storms take place from thirty to sixty days per year. Dust storms also occur, although with less frequency, in the arid and semiarid regions of the United States—especially in western Texas and the deserts of southern California, as well as the Great Plains states in the center of the country.

Dust storms can carry material for thousands of miles. Dust from the Sahara Desert settles as far away as Florida and other parts of the U.S. East Coast. Dust storms originating in central Asia have been spotted over the northwest Pacific Ocean, even reaching the West Coast of the United States. In the 1930s, dust from Kansas was deposited throughout the Midwest and the East Coast, and even in the Atlantic Ocean. Texas dust has been identified, through chemical analysis, in every eastern state as well as in portions of Europe.

Dust storms differ from sand storms in that sand storms are composed of sand particles, which are significantly larger than dust particles. Sand storms last a shorter time than dust storms, in general, because the



Satellite view of a dust storm swirling south across the Indus Valley in Pakistan, 2006.
©NASA/CORBIS.

heavier sand particles quickly settle to the ground when the wind weakens.

The Dust Bowl

The Dust Bowl is the popular name for the approximately 150,000 square-mile-area (400,000-square-kilometer-area) in the southern portion of the Great Plains region of the United States. This region includes the northern parts of Oklahoma and Texas, southeastern Colorado, western Kansas, and northeastern New Mexico. It is characterized by low annual rainfall, a shallow layer of topsoil, and high winds. The Dust Bowl became well known during the 1930s, when a prolonged drought resulted in violent dust storms.

Pioneers who settled in the Dust Bowl in the 1910s through the 1930s made the mistake of plowing large areas of grassland and planting wheat. As it turned out, the thin, fragile layer of topsoil in the region had been anchored only by the grasses' intricate system of roots. When that root system was destroyed, the drought and wind joined forces to cause disastrous soil erosion.

The blowing soil covered roads and created drifts that, in some places, were high enough to bury houses. Dust clouds, more than 1 mile (1.6 kilometer) high and as wide as the eye could see, blew across the land and were frequently dense enough to block out the Sun. Around 300 million tons (270 million metric tons) of topsoil blew away in a single dust storm in May 1934.

As the drought continued year after year, many people were forced to give up their dreams of farming in the area. In all, one-fourth of the people who lived in the Dust Bowl left the region. Many of them were lured to California by promises of fertile fields and plentiful work.

During and after the Dust Bowl tragedy, the federal government implemented a program to restore the land. Among the techniques used were replacing grasslands and planting trees, as well as introducing agricultural methods appropriate to the area. Those efforts were successful and, by the early 1940s, it was again possible to farm the land.

WORDS TO KNOW

air mass: a large quantity of air throughout which temperature and moisture content is fairly constant.

cold front: the line behind which a cold air mass is advancing, and in front of which a warm air mass is retreating.

conservation tillage: the practice of leaving vegetation on fields during idle periods to protect the soil from erosion and trap moisture.

convection: the upward motion of an air mass or air parcel (a small volume of air that has a consistent temperature throughout, and experiences minimal mixing with the surrounding air) that has been heated.

cumulonimbus: tall, dark, ominous-looking clouds that produce thunderstorms. Also called thunderstorm clouds.

desert climate: the world's driest climate type, with less than 10 inches (25.4 centimeters) of rainfall annually.

desert pavement: hard, flat, dry ground and gravel that remains after all sand and dust has been eroded from a surface.

downdraft: a downward blast of air from a thunderstorm cloud, felt at the surface as a cool gust.

Dust Bowl: the popular name for the approximately 150,000 square-mile-area (400,000-square-kilometer-area) in the southern portion of the Great Plains region of the United States. It is characterized by low annual rainfall, a shallow layer of topsoil, and high winds.

dust devil: a spinning vortex of sand and dust that is usually harmless but may grow quite large. Also called a whirlwind.

dust storm: a large cloud of dust blown by a strong wind.

erosion: the wearing away of a surface by the action of wind, water, or ice.

Great Depression: the worst economic collapse in the history of the modern world. It began with the stock market crash of 1929 and lasted through the late 1930s.

haboob: a tumbling black wall of sand that has been stirred up by cold downdrafts along the leading edge of a thunderstorm or cold front. It occurs in north-central Africa and the southwestern United States.

harmattan: a mild, dry, and dusty wind that originates in the Sahara Desert.

khamsin: a hot, dry, southerly wind that originates on the Sahara and produces large sand and dust storms.

saltation: the wind-driven movement of particles along the ground and through the air.

shamal: a hot, dry, dusty wind that blows for one to five days at a time, producing great dust storms throughout the Persian Gulf.

simoom: a hot, dry, blustery, dust-laden wind that blows across the Sahara and the deserts of Israel, Syria, and the Arabian peninsula.

windbreak: row of trees or shrubs placed in a farm field to slow the wind and keep it from blowing away the soil.

A cloud of parched top soil picked up by winds and moving down a road near Boise City, Oklahoma, 1935. AP IMAGES.

The destruction of the prairie In the early part of the twentieth century, farmers were encouraged to settle the Great Plains to grow wheat and other cereal crops. Land speculators claimed that the region was so fertile and the climate so dependable that "the rain would follow the plow." In the early years, plentiful rains produced bountiful crops.

With wheat in high demand, farmers plowed and planted acreages as large as their tractors could cover. As the amount of wheat being produced increased, the prices decreased. When farmers received less money for their grain, they tried to make up for the loss by increasing the size of their fields the following year. Thus increasingly more land was plowed and planted.

Certain agricultural practices added to the problem. Most farmers came to the plains from the Northeast and the Midwest, bringing with them farming techniques that had worked well in their former locations. One such method was to plant fields only every other season, allowing the fields to lie fallow—that is, without planting any crops—in between. During the fallow period, farmers frequently plowed the soil to uproot weeds, clean the surface of crop residues, and open the ground in the hopes of trapping moisture.

While that method may have worked well in the heartier soils in other parts of the country, it was a disaster in the Great Plains. The loosened, unprotected soil was made especially vulnerable to erosion by the high winds that came each year during the months of February, March, and April. The wind removed the finer silt and clay particles from the soil, leaving behind coarser particles of sand. With the fine particles went the soil's nutrients and organic matter, as well as its water storage capacity. The sandy soil that remained was of poor quality for growing crops.

Rain storms replaced by dust storms A severe drought began in the eastern United States in 1930, and by the following year it had worked its way westward. As the drought progressed, dust storms, also called "black blizzards," grew more frequent and removed increasing amounts of topsoil. The storms made the sky turn dark in the middle of the day, stranded motorists, and stalled trains. Houses quickly filled with dust, and many people died from what doctors called "dust pneumonia (pronounced NEW-moan-ya)" when the dirt clogged their lungs. The number of major dust storms increased each year from 1932 to 1935.

The year 1934 saw the worst drought in the history of the United States. Seventy-five percent of the country suffered water shortages and twenty-seven states were severely affected. By the end of the year, some 35 million acres (14 million hectares) of farmland had been rendered useless for crop production. Soil erosion continued and in 1935 alone, an estimated 850 million tons (765 million metric tons) of topsoil blew off the southern plains. Yet even as crops refused to grow, farmers continued to plow and plant—hopeful that the rains would return. Instead, it only made things worse.

Black Sunday On April 14, 1935, a day known as Black Sunday, the Dust Bowl experienced its worst dust storm of the era. Black Sunday

An Arkansas farmer and his sons in the Dust Bowl in 1936. COURTESY FDR LIBRARY.

came at the end of weeks of dust storms, including a storm just two weeks earlier that had ruined 5 million acres (2 million hectares) of wheat. In the storm of April 14, visibility was reduced to zero, and people who were trapped outdoors suffocated. Thousands of livestock died in the fields. Robert Geiger, a reporter from the Associated Press, was on assignment in Guymon, Oklahoma, on that date. In his report filed April 15, Geiger coined the term "Dust Bowl"—and the term stuck. "Three little words achingly familiar on a Western farmer's tongue," wrote Geiger, "rule life in the dust bowl of the continent—'if it rains.'"

Black Sunday, which also happened to be Palm Sunday, the Sunday before Easter Sunday, began as a clear, sunny morning. Dust Bowl residents were grateful for the crisp blue skies, having grown weary of the hazy, dusty horizon. People flocked to country churches that morning, and after services families climbed into automobiles for Sunday drives.

By noon, the temperature had reached its high for the day—90°F (32°C). Shortly thereafter, the air began to cool rapidly. By mid-afternoon the temperature had dropped to just half of the noontime level. A huge, dark cloud appeared menacingly on the horizon.

To many people who saw the cloud approaching, it appeared as if the end of the world was upon them. The cloud extended from the ground to

Dust storm moving toward two houses during the Great Depression.

a height of more than 7,000 feet (2,135 meters), and as it moved across the land, it rolled over people, homes, and fields. Nothing escaped.

"The impact is like a shovelful of fine sand flung against the face," reported Avis D. Carlson in the *New Republic* following Black Sunday. "People caught in their own yards grope for the doorstep. Cars come to a standstill, for no light in the world can penetrate that swirling murk."

The New Deal provides relief The economic disaster facing Dust Bowl farmers in the 1930s was made worse by the catastrophe plaguing the nation as a whole: the Great Depression. The Great Depression was the worst economic collapse in the history of the modern world. It began with the stock market crash in 1929 and lasted through the late 1930s. More than 15 million Americans, amounting to one-quarter of the workforce, found themselves unemployed. In better times, perhaps, the problems of the Dust Bowl farmers would have received more attention from the federal government. In the early 1930s, however, the farmers were just another down-and-out group.

When President Franklin Delano Roosevelt (1882–1945) took office in 1933, he began an enormous effort, known as the New Deal, to help the United States recover from the Great Depression. The New Deal

Eyewitness report: A first-hand account of the Dust Bowl

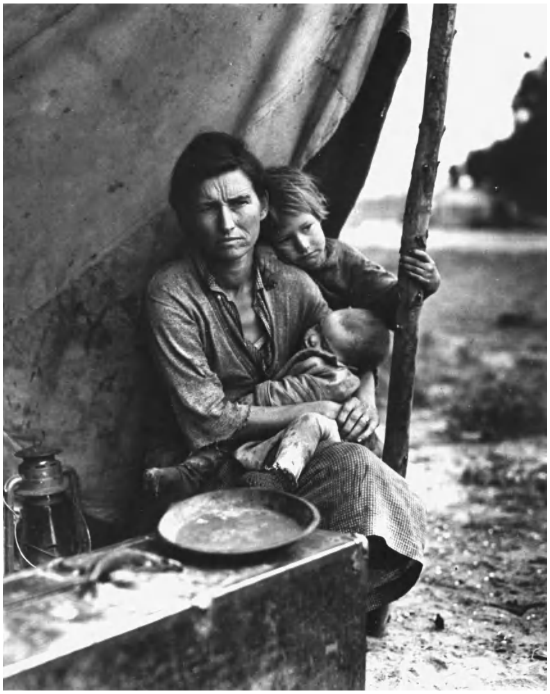
The following excerpts are from *Farming the Dust Bowl*, a memoir of the Dust Bowl years by Lawrence Svobida. Svobida was a wheat farmer in Kansas in the 1930s who had to leave his farm because of the years of drought and dust storms.

> I did not yet know that the dry era had commenced, and that the spring of 1932 would see the creation of the dreaded Dust Bowl in our section of the Great Plains.
>
> So, though my land lacked moisture, when seeding time came in September I drilled my wheat in dry ground.
>
> . . . In January a foot of snow fell, but that was all the moisture we had, and it was not enough to make a crop. Some of my wheat came up, but it was thin, sickly looking stuff, with only two or three leaves to a plant.
>
> . . . Most of my remaining wheat fell an easy prey to the first gales of February, and none of the wheat that was up in the region could long withstand the succeeding gales, which first chopped off the plants even with the ground, then proceeded to take the roots out. They did not stop there. They blew away the rich topsoil, leaving the subsoil exposed; and then kept sweeping away at the hardpan, which is almost as hard as concrete.
>
> . . . Several times each day I anxiously scanned the sky. Time after time clouds formed and united together, and my hopes would rise; but no rain came, and my hopes would fade and die. I lived in suspense, looking, hoping, wishing—expecting rain that did not come.
>
> . . . Throughout the fall and winter we had neither rain nor snow, and when the usual gales came in February they were worse in velocity and endurance than any I had previously experienced.
>
> With the gales came the dust. Sometimes it was so thick that it completely hid the sun. Visibility ranged from nothing to fifty feet, the former when the eyes were filled with dirt which could not be avoided, even with goggles. . . . During a gale the dust would sift into the houses through crevices around the doors and windows, eventually to lie an inch or more deep all over the floors, and on tables, chairs, and beds.
>
> . . . When I knew that my crop was irrevocably gone I experienced a deathly feeling which, I hope, can affect a man only once in a lifetime. My dreams and ambitions had been flouted by nature, and my shattered ideals seemed gone forever. . . . Fate had dealt me a cruel blow above which I felt utterly unable to rise. Season after season I had planted two, and sometimes three, crops. I had worked incessantly to gain a harvest, or to keep my land from blowing, and no effort of mine had proved fruitful. Words are useless to describe the sensation a human being experiences when the thin thread of faith snaps. I had reached the depths of utter despair.
>
> . . . With my financial resources at last exhausted and my health seriously, if not permanently, impaired, I am at last ready to admit defeat and leave the Dust Bowl forever. With youth and ambition ground into the very dust itself, I can only drift with the tide.

Applicants fill the waiting room of the Works Progress Administration (WPA) office in Seattle, Washington, during the Great Depression. ©SEATTLE POST-INTELLIGENCER COLLECTION; MUSEUM OF HISTORY AND INDUSTRY/ CORBIS.

consisted of hundreds of social programs, building projects, and economic initiatives to get America back on its feet. Public works programs employed large numbers of people in a variety of construction and neighborhood improvement projects. One public works program, the Works Progress Administration (WPA), employed some 8.5 million people nationwide—including many Dust Bowl farmers. The WPA built hundreds of roads, bridges, buildings, parks, campgrounds, and other public facilities across the nation.

Beginning in 1933, the federal government provided help to Dust Bowl farmers with the Emergency Farm Mortgage Act, which made two hundred million dollars in loans available to farmers to help them keep their farms. The same year also saw the birth of the Agricultural Adjustment Administration, which paid farmers to reduce their acreage under cultivation in an effort to give the land a chance to stabilize. Toward the end of 1933, the Federal Surplus Relief Corporation (FSRC) purchased pigs from farmers who were struggling to feed their livestock. The FSRC slaughtered the animals and donated the meat to relief agencies. The FSRC also provided apples, beans, flour, and other products to agencies assisting struggling farmers.



A migrant family living in California in 1936.

In 1934 Congress approved the Frazier-Lemke Farm Bankruptcy Act, which limited the ability of banks to foreclose on farmers during drought or other times of misfortune. At the same time, Congress turned 140 million acres (56 million hectares) of federally owned land in the Dust Bowl into carefully monitored grazing districts to help prevent overgrazing and to stop erosion on those lands.

Migration from the Great Plains One consequence of the long drought was that many farmers were forced off their farms. During the 1930s, one out of four farmers in the Dust Bowl loaded up his family and belongings and left the region. This amounted to the largest migration in the history of the United States.

Of the 2.5 million people who left the Dust Bowl, about 200,000 ended up in California—lured by promises of plentiful jobs. There they found conditions that were in many ways as hopeless as those they had left. The migrants' miserable experience with California began on the highway at the border, where police tried to turn them away. An account of one farmer, published in *Collier's* magazine in 1935, reported a border agent stating: "California's relief rolls are overcrowded now. No use to come farther. . . . There really is nothing for you here. . . . Nothing, really nothing." The migrant farmer replied, "So? Well, you ought to see what they got where I come from."

Once the road-weary farmers made it to the rich agricultural land of the San Joaquin, they encountered new difficulties. Owners of enormous farming operations took advantage of the large number of people desperately seeking work and lowered wages. The Dust Bowl refugees were paid about one dollar a day to pick fruit and cotton. Out of that meager wage they were charged twenty-five cents a day to live in dilapidated shacks with no electricity or running water. Some farm owners operated company stores, at which they charged exorbitant rates for basic necessities. Since the migrants were typically living far from towns and many had no transportation, they had little choice but to patronize the company stores. As a result, many workers found that not only were they unable to save money, they actually became indebted to their employers.

Soil conservation measures adopted In the early 1930s the federal government, through the Soil Erosion Service (SES), began implementing soil conservation measures on certain federal lands in the Great Plains. The SES's director, Hugh Bennett (1881–1960), came to be known as the father of soil conservation and pushed tirelessly for a greater commitment on the part of the federal government to save the land.

On April 27, 1935, Bennett was scheduled to address a Congressional committee about the need for enhanced soil conservation measures. Coincidentally, a dust storm on that day was reportedly heading eastward from northeastern New Mexico. Bennett believed that if the Washington lawmakers could experience the dust firsthand, they would be more likely to accept his proposals. Bennett stalled his presentation just long enough for the black blizzard to descend upon the capital. "This, gentlemen," stated Bennett in reference to the dust that dimmed the Sun, "is what I have been talking about." Bewildered legislators responded by declaring soil erosion "a national menace" and passing the Soil Conservation Act—legislation dedicated to the improvement of farming techniques.

Bennett lost no time putting into action a number of measures aimed at stabilizing the land. His grand plan was to put each acre to its best use—farmland, prairie, or forest—and to create specific land management plans according to the needs of every area. He first concentrated on returning seriously damaged land to grassland and planting windbreaks—lines of trees and shrubs—across windswept plains. He then focused on educating farmers about agricultural methods appropriate to the region. Farmers, reluctant to voluntarily change their practices, were paid one dollar per acre to go along with the federal conservation program.

By the end of the 1930s, conditions in the Dust Bowl were improving. As a result of conservation measures, the quantity of blowing soil had been decreased, and in the fall of 1939 the rains returned. Farming once again became possible in the Dust Bowl. Economic conditions also improved during the 1940s, driving up the price of wheat and other crops. As a result, farmers were able to make a living by cultivating smaller parcels of land. In 1943 Hugh Bennett summed up the hopeful spirit that had come over the region as follows: "If we are bold in our thinking, courageous in accepting new ideas, and willing to work with instead of against our land, we shall find in conservation farming an avenue to the greatest food production the world has ever known."

On the shelf: Dust Bowl migrants immortalized in *The Grapes of Wrath*

The anguish of the Dust Bowl years was captured by American writer John Steinbeck (1902–68) in his famous novel *The Grapes of Wrath.* This book tells the story of the Joads, a family of farmers forced to leave their land in Oklahoma. The Joads followed the promise of agricultural opportunity in California, only to face further hardships at the hands of ruthless farm owners. The novel opened the eyes of the nation to the plight of migrant farmworkers during the Great Depression.

The Grapes of Wrath won a Pulitzer Prize and a National Book Award, and was made into a movie in 1940. Steinbeck won the Nobel Prize for Literature in 1962. Following are excerpts from *The Grapes of Wrath:*

> When the truck had gone, loaded with implements, with heavy tools, with beds and springs, with every movable thing that might be sold, Tom hung around the place. . . . Behind him Ma moved about in the kitchen, washing children's clothes in a bucket; and her strong freckled arms dripped soapsuds from the elbows. . . .
>
> She said, "Tom, I hope things is all right in California."
>
> He turned and looked at her. "What makes you think they ain't?" he asked.
>
> "Well—nothing. Seems too nice, kinda. I seen the han'bills fellas pass out, an' how much work they is, an' high wages an' all; an' I seen in the paper how they want folks to come an' pick grapes an' oranges an' peaches. That'd be nice work, Tom, pickin' peaches. Even if they wouldn't let you eat none, you could maybe snitch a little ratty one sometimes. An' it'd be nice under the trees, workin' in the shade. I'm scared of stuff so nice. I ain't got faith. I'm scared somepin ain't so nice about it."
>
> . . . Highway 66 is the main migrant road. 66—the long concrete path across the country, waving gently up and down on the map, from the Mississippi to Bakersfield—over the red lands and the gray lands, twisting up into the mountains, crossing the Divide and down into the bright and terrible desert, and across the desert to the mountains again, and into the rich California valleys.
>
> 66 is the path of a people in flight, refugees from the dust and shrinking land, from the thunder of tractors and shrinking ownership, from the desert's slow northward invasion, from the twisting winds that howl up out of Texas, from the floods that bring no richness to the land and steal what little richness is there. . . .
>
> Two hundred and fifty thousand people over the road. Fifty thousand old cars—wounded, steaming. Wrecks along the road, abandoned. Well, what happened to them? What happened to the folks in that car? . . .
>
> "We ain't no bums," Tom insisted. "We're lookin' for work. We'll take any kind a work."
>
> The young man paused in fitting the brace to the valve slot. He looked in

amazement at Tom. "Lookin' for work?" he said. "So you're lookin' for work. What ya think ever'body else is lookin' for? Di'monds? . . ."

Tom said, "Back home some fellas come through with han'bills—orange ones. Says they need lots a people out here to work the crops."

The young man laughed. "They say they's three hunderd thousan' us folks here, an' I bet ever' dam' fam'ly seen them han'bills."

"Yeah, but if they don' need folks, what'd they go to the trouble puttin' them things out for?" . . .

"Look," the young man said. "S'pose you got a job a work an' there's jus' one fella wants the job. You got to pay 'im what he asts. But s'pose they's a hunderd men . . . wants that job. S'pose them men got kids, an' them kids is hungry. S'pose a lousy dime'll buy a box a mush for them kids. S'pose a nickel'll buy at leas' somepin for them kids. An' you got a hunderd men. Jus' offer 'em a nickel—why, they'll kill each other fightin' for that nickel. . . . That's why them han'bills was out. You can print a hell of a lot of han'bills with what ya save payin' fifteen cents an hour for fiel'work."

Scene from the 1940 movie, The Grapes of Wrath. © CORBIS.

Dangerous science: How dust storms happen

A dust storm begins when wind sweeps through dry areas that have loosened soils. The speed of the wind must be great enough to move larger particles, which then bump into tiny dust particles. There is a very shallow layer of calm air, extending only about 0.004 inch (0.01 centimeter) above the ground, which is unaffected by the wind. The tiny particles lay in that layer and are only stirred when they are struck by larger particles around them. For semiarid areas, such as Colorado and Arkansas, a sustained wind of 25 to 36 miles (40 to 58 kilometers) per hour is required to start a dust storm; for deserts, a sustained wind of 11 to 36 miles (18 to 58 kilometers) per hour is needed.

The strong wind sets in motion a process called saltation—the wind-driven movement of sand or soil particles along the ground. The moving particles bounce into other particles, sending them in motion. Some of the particles become airborne. When they fall back to the ground they strike other particles, knocking them upward and into the wind.

As the avalanche of particles continues its forward march, the whole surface of the soil gets blown into motion. While the larger particles remain close to the ground, the smaller particles get sent higher into the air and only make their way back down very slowly. The smallest particles get carried upward by air currents, rather than falling back to the ground, creating a cloud of dust. The dust moves along with the wind and is only deposited when the wind dies down, the particles become trapped by vegetation, or when rain begins to fall.

Haboobs One type of sand-and-dust storm that occurs frequently in the deserts of the Sudan region of north-central Africa and in the southwestern region of the United States is the haboob (pronounced huh-BOOB). This word is taken from the Arabic word *habub,* which means "blowing furiously." A haboob is a tumbling, black wall of dust and sand that has been stirred up by cold downdrafts (downward blasts of air along the leading edge of a thunderstorm or a cold front, felt at the surface as cool gusts). The downdrafts strike the hot, dusty ground and force the surface air, as well as the top layer of sand and dust, upward. They create a wall of particles that may rise a mile or more above the ground, sometimes all the way to the base of the thunderstorm cloud, reducing visibility to near zero.

Haboobs generally last for thirty minutes to an hour and encompass areas ranging from several square miles to hundreds of square miles. They travel at speeds of about 30 miles (48 kilometers) per hour across short

A sand storm, or haboob, in North Khartoum, Sudan, 1906. ©HULTON-DEUTSCH COLLECTION/CORBIS.

spans or for great distances. Dust storms caused by the downdrafts of cold fronts—because of the vigorous winds and forceful lifting of air—tend to be the most intense form of haboobs. At the leading edge of a cold air mass, dust may be thrown as high as 23,000 feet (7,000 meters or 7 kilometers) into the air and transported for thousands of miles (kilometers).

Other types of desert dust and sand storms Dust and sand storms occur frequently in deserts, due to the combination of loose soil and high winds. The windiness of deserts is primarily due to the heating of the surface. The temperature of the dry ground on a sunny day may be exceedingly hot, in some places more than 130°F (54°C). Air rises from the hot surface in a powerful convection (upward thrusting) flow, which sets surface winds blowing across the ground as cooler air rushes in from the surrounding area to take the place of the rising hot air. Wind speeds are greatest during the hottest part of the day and the hottest time of year.

As strong winds blow across a desert, they lift up and carry dust and sand. Dust and sand storms occur with the greatest frequency over western Africa, due to the harmattan (pronounced har-ma-TAHN; also spelled harmatan, harmetan, or hermitan)—a mild, dry, and dusty wind that originates in the Sahara. The harmattan is an easterly or northeasterly wind that produces dust and sand storms up to 20,000 feet (6,100 meters) high. More than 300 million tons (272 million metric tons) of reddish Saharan dust are transported westward across the continent each year, 100 million tons (91 million metric tons) of which are deposited into the Atlantic Ocean. Two or three times a year, Saharan dust travels 1,600 miles (2,574 kilometers) to Great Britain where it falls to the ground as a red precipitation that the locals call "blood rain."

Another hot, dry, southerly wind originating on the Sahara that produces large sand and dust storms is the khamsin (pronounced kahm-SENE). The khamsin forms over Libya and Egypt. When a storm is present to the west over Turkey, the khamsin blows dust over the northern tip of the Red Sea and into Saudi Arabia, Jordan, and Israel. The khamsin is a regular, annually occurring wind. Its name is the Arabic word for "fifty"; it blows for about fifty days straight, starting in mid-March. This dry wind brings air to the region that is hotter than 120°F (49°C) and has less than 10 percent relative humidity.

Great dust storms are produced each year throughout the Persian Gulf and the lower valley of the Tigris and Euphrates in Iraq by the shamal (pronounced shah-MALL). *Shamal* is the Arabic word for "left-hand" or "north." This hot, dry, and dusty wind from the northwest blows for periods lasting from one to five days at various times throughout the year. Once a year, typically in June and early July, the wind blows for forty days straight, at about 30 miles (50 kilometers) per hour, in what is known as the great shamal, or the forty-day shamal.

A dry, blustery, dust-laden wind called a simoom (pronounced si-MOOM) blows across North Africa and the Middle East, depositing its dust on Europe. The simoom, which often reaches temperatures of more than 130°F (54°C) and can cause heatstroke, is nicknamed the poison wind.

Consequences of dust storms

Dust storms can cause millions of dollars in damage to crops, roads, and buildings. Dust storms strip the land of the most fertile portion of the soil. Damage to soil results in a decline of productivity and a loss of income for farmers—often translating to higher food prices for consumers. Blowing soil can kill or damage seedlings, stunt the growth of vegetable crops, and introduce pathogens (microorganisms) that cause plant disease.

Water quality suffers during dust storms, as well. Dust settles into drainage ditches, and the tiny particles are difficult to remove entirely

Abandoned farm during the Oklahoma Dust Bowl. ©BETTMAN/CORBIS.

during the water treatment process. Dust storms also destroy wildlife habitat, causing certain populations of animals to either migrate in search of food or starve.

The sediment thrust into the air during dust storms reduces air quality and is harmful to human health. Inhalation of the particles is damaging to lungs and sinuses, and can trigger allergy attacks. During dust storms, hospitals and clinics report increased admissions for respiratory infections, cardiac disease, bronchitis, asthma, and pneumonia.

Dust storms, because of their reduction of visibility (sometimes to zero), pose a hazard to vehicles on the ground, in the air, and on the water. Dust enters and damages the inner workings of motor vehicles and other machines, as well.

Windblown dust, specifically the rubbing together of dirt particles, produces static electricity. During Dust Bowl storms, farmers saw balls of electricity traversing their barbed wire fences. The electric charge can

Dust devils

Dust devils, also called whirlwinds, are spinning columns of sand and dust. They typically arise on clear, hot, relatively calm days, over warm, dry surfaces such as deserts, plowed fields, or flat expanses of dirt. Dust devils form with less frequency along the leading, cold air/warm air boundary of a haboob (a tumbling black wall of sand that has been stirred up by cold downdrafts). Although dust devils bear a superficial resemblance to tornadoes, they are less destructive than their cloudy cousins and form by different processes.

The first step in the formation of a dust devil is when hot air rises forcefully from the surface by convection, creating a low pressure area at the surface. Next, surface winds converge (come together) to that point of low pressure. If there are horizontal layers of wind traveling at different speeds (a phenomenon called wind shear), it causes the rising air to spin about a vertical axis.

Dust devils are usually small, measuring less than 10 feet (3 meters) in diameter and less than 300 feet (91 meters) in height. They often last less than one minute. The largest dust devils reach a diameter of 100 feet (30 meters) and a height of 5,000 feet (1,524 meters) and last for twenty minutes or more. The wind speed in the largest dust devils may exceed 86 miles (138 kilometers) per hour.

A dust devil moving across the land in Kenya. JLM VISUALS.

Every year dust devils cause significant damage in the United States, including overturning mobile homes and tearing roofs off buildings. A large and long-lived dust devil can toss more than 50 tons (45 metric tons) of dust and debris up toward the sky.

cause dry material, such as withered crops and fence posts, to catch fire. It also alters the workings of electronic equipment; it can scramble radio broadcasts and short out car ignitions.

The human factor

Humans contribute to the formation of dust storms through improper agricultural practices and overgrazing cattle. This is particularly true in semiarid areas, such as the southern portion of the Great Plains. The topsoil there exists in a thin layer and is best suited for growing grass. Grass protects the soil above ground by reducing the force of the wind; underground, its roots anchor the soil in place. If the land is plowed for planting, or if cattle overgraze, the grass is removed and the soil's stabilization system is destroyed. If dry conditions then prevail (removing moisture—the remaining anchor for the soil), the soil can easily be blown away.

While erosion on the scale of the Dust Bowl has not recurred in the United States since the 1930s, erosion remains a serious problem in the Great Plains and in the western United States. The states most susceptible to this problem are Texas, Colorado, Nevada, and Montana. In 2000, almost five million acres of agricultural land in the United States experienced soil loss.

On the shelves: *Dust Bowl Diary*

Dust Bowl Diary, by Ann Marie Low, provides a first-hand account of what it was like to grow up during the Dust Bowl era of the late 1920s and early 1930s. The book is based on a diary that Low kept beginning in 1927, when she was fifteen years old and living on a farm in North Dakota. The book spans ten years and chronicles her life during the Dust Bowl and Great Depression.

"Many days this spring the air is just full of dirt coming, literally for hundreds of miles," Low writes in her April 25, 1934, entry. "It sifts into everything. After we wash the dishes and put them away, so much dirt sifts into the cupboards we must wash them again before the next meal. Clothes in the closets are covered with dust."

Through her personal account, Low offers a window into the social and economic conditions that characterized the era. *Dust Bowl Diary* also provides a rare and exciting opportunity to read about a major historical event from the perspective of a teenager.

Technology connection

Soil scientists have developed several methods for reducing the incidence and intensity of dust storms, all of which involve the anchoring of the soil to prevent it from blowing away. On nonagricultural lands, such as seacoasts, steep slopes, and deserts, people plant sturdy grasses to prevent erosion. On agricultural lands, the practices used to prevent or lessen the effects of dust storms are similar to those used against drought.

One example of an erosion-combatting agricultural practice is the planting of rows of trees or shrubs, called windbreaks, at intervals throughout farm fields. Windbreaks, which run crossways to the direction that the wind usually blows, slow the wind and keep it from blowing away the soil. According to one study, a thin row of cottonwood trees is capable of reducing wind speed by one-third, dropping the speed from 15 miles (24 kilometers) per hour to 10 miles (16 kilometers) per hour. Trees also trap snow on the ground, thereby increasing the moisture content of the soil.

Extreme weather: Dust storm accidents

Dust storms greatly reduce visibility and make for treacherous traveling. The following are a few examples of crashes caused by dust storms:

On July 10, 1997, a dust storm in southern Arizona reduced visibility to zero in the early afternoon. On Interstate 10, there were eleven accidents involving twenty-eight vehicles. About twenty-five people in those vehicles received minor injuries; some of the injured were teenagers on a tour bus that was rear-ended by a large truck.

One month later, on August 15, 1997, a dust storm descended upon Denver, Colorado, causing chain reaction crashes on Interstate 70. Eleven vehicles were involved in accidents, and ten people were hospitalized with injuries. The dust came from a prairie north of the freeway, causing a "total brownout" in the words of one motorist. Visibility was estimated at 30 feet (9 meters).

On the morning of September 25, 1999, a sudden dust storm, with wind gusts up to 50 miles (80 kilometers) per hour, developed in northern Oregon. On Interstate 84, near the city of Pendleton, traffic accidents claimed seven lives and injured twenty-seven people. Dozens of vehicles, including cars and trucks, were involved in five separate pileups as the dusty darkness overtook the region.

Another strategy, called conservation tillage, is the practice of leaving stubble from the previous season's crop, or growing a cover crop, on fields during fallow (idle) periods. The vegetation left on fields protects the soil from erosion and traps moisture. Farmers also protect the soil by digging waterways in fields. The waterways keep soil from washing away during heavy rains, as well as catch and divert rainwater.

Strip plowing, terrace farming, and crop rotation are three more ways to guard against dust storms on agricultural lands. Strip plowing is the alternating of rows of wheat with rows of fast-growing, dense plants such as sorghum (pronounced SOAR-gum) or sudan grass. Terrace farming, which also aims to trap soil and water, involves the building of earthen terraces in fields as well as mixing rows of cereal crops, like wheat, with rows of grasses, shrubs, and trees. Crop rotation is the alternating use of a given field from year to year. A three-year cycle of crop rotation may involve, for example, using a field for wheat one year, then sorghum, and then letting it lie fallow—that is, without any planting.

A matter of survival

Dust storms, though of lesser intensity and frequency than during the 1930s, remain common occurrences in the western United States. A typical dust storm today lasts fifteen to twenty minutes. It either reduces visibility, causing a brownout, or blocks out all light, causing a blackout.

If you see a dust storm coming, immediately seek shelter indoors. Seal openings around doors and windows with wet towels. If you are stuck outdoors during a dust storm, turn your face away from the wind, and cover your mouth, nose, and eyes with a cloth.

If a dust storm approaches while you are traveling in your car, pull off the road as far as possible so other cars don't run into you. If you're on a highway shoulder, turn off your lights so that other drivers do not think you're on the road and drive up behind you. If a dust storm approaches, and you are not able to pull off the road, slow down and put on your flashing hazard lights. Exit the road as quickly as possible. Don't leave your car; it's easy to become disoriented and lose your way in a dust storm.

[*See Also* **Drought**]

For More Information

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Earthquake

An earthquake is a sudden shifting of masses of rock beneath Earth's surface. This motion releases enormous amounts of energy and sends out shock waves that cause the ground to shake. Geologists believe that no spot in the world is completely safe from earthquakes. The great internal forces of the planet are constantly changing the shape of Earth's surface. In fact, Earth has been resounding with earthquakes for more than four billion years.

Thousands of earthquakes occur each day. While not all of these earthquakes are significant, some are powerful enough to wreck cities and kill thousands of people. In the twentieth century alone, deadly earthquakes have claimed more than a million lives.

The 1906 San Francisco earthquake

On April 18, 1906, as the first rays of dawn began to spread across the sky, residents of San Francisco, California, were violently awakened as an earthquake shook the ground beneath the city. Most present-day geologists believe the earthquake, which came in two stages, measured 8.3 on the Richter scale. Other geologists believe the magnitude of the earthquake was slightly less, measuring about 7.8. (The Richter scale measures the magnitude of an earthquake or size of ground waves generated at the earthquake's source; a magnitude of 7.0 produces major damage, and a magnitude of 8.0 produces almost total damage. Every increase of one number on the Richter scale means a ten-fold increase in magnitude.)

Minutes after the earthquake struck, fires from broken gas and electrical lines began raging through the city. They burned uncontrollably for three days. Initial reports listed the number of dead as 700 to 800, but present-day research has led historians to conclude that more than 3,000 deaths were caused directly or indirectly by the earthquake and fires. Out of a population of 400,000, more than 200,000 people were injured and

WORDS TO KNOW

aftershock: ground shaking that occurs after the main shock of an earthquake.

asthenosphere: region of the mantle below the lithosphere, composed of partially melted rock.

continental drift: geologic theory that all continents were part of a single, original landmass before they slowly separated and gradually drifted apart.

convection current: circular movement of a gas or liquid between hot and cold areas.

crust: outermost layer of Earth, varying in thickness from 3.5 to 50 miles (5 to 80 kilometers).

epicenter: the point on Earth's surface directly above the focus of an earthquake, where seismic waves first appear.

fault: crack in Earth's surface where two plates or sections of the crust push and slide in opposite directions against one another.

fault creep: slow, continuous movement of plates along a fault, allowing pressure to be released.

focus: the underground starting place of an earthquake, also called the hypocenter.

foreshock: ground shaking that occurs before the main shock of an earthquake.

intensity: description of the physical damage caused by an earthquake.

liquefaction: the transformation of water-saturated soil into a liquidlike mass, usually by the action of seismic waves.

lithosphere: the rigid outermost region of Earth, composed of the crust and the upper part of the mantle.

magnitude: the power of an earthquake, as recorded by a seismograph, or seismometer.

mantle: thick, dense layer of rock that lies beneath Earth's crust. The mantle is about 1,800 miles (2,900 kilometers) thick and accounts for about 84 percent of Earth's volume.

modified Mercalli scale: scale developed by Italian seismologist Giuseppe Mercalli to measure the intensity of an earthquake based on the amount of vibration felt by people and the extent of damage to buildings.

plate tectonics: geologic theory that Earth's crust is composed of rigid plates that "float" toward or away from each other, either directly or indirectly, creating the major geologic features on the planet's surface.

Richter scale: scale developed by American seismologist Charles Richter that describes the amount of energy released by an earthquake.

seismic waves: vibrations that move outward from the focus of an earthquake, causing the ground to shake.

seismograph: instrument used to detect and measure seismic waves. Also known as a seismometer.

more than 250,000 were left homeless. Some 28,000 buildings were destroyed. The estimated total property damage from the earthquake and three-day fire was placed at more than 400 million dollars (in 1906 dollars).

Troops walking down Market Street after the 1906 San Francisco earthquake. ©BETTMANN/CORBIS.

A city's history is changed in one day The area from present-day San Francisco south to Monterey Bay had been home to Native Americans for more than ten thousand years before the first Europeans arrived on the land. About forty culturally diverse native tribes (now known collectively as the Ohlone, a Miwok word meaning "western people") occupied this area when Spanish explorers and missionaries established a presidio (fortress) and a mission on the site of present-day San Francisco in 1776.

The Spanish settlement, named Yerba Buena, remained in Spanish hands until 1821, when it came under Mexican control. U.S. naval forces occupied the village in 1846 when the Mexican War (1846–48) broke out between the United States and Mexico. When the war ended in 1848, the United States gained control of the village and renamed it San Francisco.

At about the time the war ended, gold was discovered in California. The population of San Francisco was then about eight hundred. Two years later, because of the mad rush to find gold, the city's population had grown to some twenty-five thousand. California became linked to the east by the Pony Express (mail delivery system comprised of relay teams of men riding ponies between Missouri and California) in 1860, and by the first transcontinental railroad in 1869.

By the beginning of the twentieth century, San Francisco was a booming metropolis with an art museum, numerous universities, a

San Andreas Fault, California. JLM VISUALS.

large commercial and fishing port, and a population of about 400,000. In just fifty years, it had become one of the largest cities in the United States. On April 18, 1906, however, San Francisco's rapid growth was brought to a halt, and the city's landscape and history were forever changed.

Lies on a fault A fault is a crack in Earth's surface where two plates (sections of the crust) meet. At the San Andreas Fault, on which the city of San Francisco is situated, the Pacific plate and the North American plate push past each other. The Pacific plate moves slowly to the northwest, while the North American plate moves equally slowly to the southeast.

The San Andreas Fault came into being about fifteen to twenty million years ago. The entire fault system forms a continuous narrow break in Earth's crust that runs more than 800 miles (1,287 kilometers) from northwest California south to the Gulf of California. The fault extends downward at least 10 miles (16 kilometers) into the planet's crust. On the surface, the fault appears as an area of crushed and broken rock measuring a few hundred feet to 1 mile (1.6 kilometer) wide.

The plates move at an average rate of about 2 inches (5 centimeters) per year. Rather than sliding smoothly past each other like oiled blocks, the plates make sudden, jerky movements. First one plate moves, then the other. Sometimes the plates lock against each other and are unable to move. Pressure builds up between them. After many years, perhaps centuries or more, the plates overcome the built-up pressure and suddenly move with great force. When that happens, a massive earthquake occurs. Such was the case in 1906 along the fault near San Francisco.

Awakening to a nightmare Before that fateful Wednesday morning in April, the Pacific and North American plates were locked, and pressure had been building along the northernmost section of the San Andreas Fault. At 5:12 AM local time, the internal forces on the fault finally broke free. Like a compressed spring that is suddenly released, the two sides of the locked fault abruptly tore the ground apart along a 290-mile (467-kilometer) stretch from San Juan Bautista to Cape Mendocino. The ground west of the fault shifted northward as much as 21 feet (6.4 meters) in places. Tremendous amounts of energy were released, and the earth shook violently. The epicenter of the earthquake—the point on Earth's surface directly above the focus, or the place where energy is first released—was near San Francisco.

The foreshock, an earthquake tremor that occurs before the larger main shock, lasted about twenty seconds. It was strong enough to be felt throughout the San Francisco Bay area. The main shock hit the area about twenty-five seconds later and lasted for almost one minute. The strong shaking, punctuated by fierce jolts, was felt from southern Oregon to southern California and as far east as Nevada.

Numerous buildings in San Francisco collapsed during the main shock. Many poorly constructed buildings situated on land that had been filled with loose stones and dirt sustained the worst damage. The newly constructed six million dollar city hall was ruined, and the Sonoma Wine Company building collapsed, spilling 15 million gallons (57 million liters) of wine.

Shaken from their slumber, many people ran into the streets dazed and horrified. Others were killed instantly or mortally wounded when bricks from nearby buildings or chimneys crashed through the roofs onto them. San Francisco Fire Department Chief Dennis T. Sullivan was one of the victims. While he was sleeping upstairs in a fire station, bricks from the California Hotel next door crashed through the roof of the station and fell on him.

Ten Deadliest Earthquakes 856–2004

Year	Place	Estimated Deaths
1556	Shanxi, China	830,000
2004	Sumatra (Indian Ocean)	280,000
1976	Tangshan, China	255,000
1138	Aleppo, Syria	230,000
856	Damghan, Iran	200,000
1920	Kansu (now Gansu), China	200,000
1927	Tsinghai, China	200,000
893	Ardabil, Iran	150,000
1293	Japan, Kanto	143,000

Firefighters spray the ruins of homes in Loma Prieta after the San Francisco earthquake in 1989. ©ROGER RESSMEYER/ CORBIS.

What people saw as they rushed onto the streets was a cityscape turned into a wasteland. American writer Jack London (1876–1916), who had been born in San Francisco and lived nearby, came into the city soon after the earthquake to witness the damage. His account appeared two weeks later in the national magazine *Collier's.*

London described the initial scene: "The streets were humped into ridges and depressions, and piled with the debris of fallen walls. The steel rails [of the streetcar and cable car tracks] were twisted into perpendicular and horizontal angles. The telephone and telegraph systems were disrupted. The great water mains had burst. All the shrewd contrivances and safeguards of man had been thrown out of gear by thirty seconds' twitching of the earth-crust."

Consumed by fire Even those buildings left standing after the earthquake were not out of danger. Just minutes after the initial tremors waned, fires began to break out across the city. Downed electrical lines, toppled stoves, ruptured gas lines: all combined to set San Francisco ablaze.

Firefighters desperately sought ways to extinguish the raging fires. Hampered by a lack of water (most of the city's water mains had been ruptured), they decided to use dynamite to blow up damaged buildings in the paths of the fires. The idea was to create a firebreak by flattening the buildings and thus depriving the fire of fuel. The plan failed. Not only did

Most intense earthquakes in U.S. history

While the San Andreas Fault in California is well known as the source of many great earthquakes in the United States, the most intense earthquakes in the country over the past two hundred years occurred elsewhere. In the winter of 1811–12, three earthquakes centered on the New Madrid Fault in Missouri affected an area sixteen times larger than the 1906 San Francisco earthquake.

The three principal earthquakes that struck New Madrid, a city in southeastern Missouri on the banks of the Missouri River, took place on December 16, January 23, and February 7. Present-day scientists estimate that the quakes ranged in magnitude from 8.4 to 8.7 on the Richter scale. The intense ground vibrations caused by the main earthquakes and their many aftershocks bent trees until their trunks snapped, opened deep cracks in the soil, caused landslides on bluffs and low hills, created waves on the Mississippi River that overturned many boats, and changed the elevation of land in the area by as much as 20 feet (6 meters). The last, and most intense, of the three earthquakes altered the course of the Mississippi River and created a depression in the northwest Tennessee landscape that filled with river water to become Reelfoot Lake.

Fortunately, few lives were lost because the area was sparsely populated. Seismic waves and their effects, however, were felt for thousands of miles. Stone and masonry buildings as far away as 155 miles (250 kilometers) suffered severe damage. Structural damage was recorded in Pittsburgh, Washington, D.C., and coastal South Carolina. The vibrations surprised people in Chicago and Detroit and even caused church bells to ring in Boston, some 1,100 miles (1,770 kilometers) away.

the dynamited buildings fail to stop the fires, but the explosions added to the inferno.

By mid-afternoon, one huge blaze had taken over the heart of the city. It had become so large and so hot that it began to create its own wind. Jack London, looking at the burning city from a boat anchored in San Francisco Bay, described the strange, dreamlike scene: "It was dead calm. Not a flicker of wind stirred. Yet from every side wind was pouring in upon the city. East, west, north, and south, strong winds were blowing upon the doomed city. The heated air rising made an enormous suck. Thus did the fire of itself build its own colossal chimney through the atmosphere."

The aftermath The fires burned for three days. Sixty percent of the residential buildings in the city and the entire business district had burned. Almost 500 square blocks had been destroyed, and another thirty-two had partially burned. Overall, more than 2,590 acres (1,036 hectares), or about 4 square miles (10.4 square kilometers), had been ravaged by fire.

In the days following the earthquake and fires, hundreds of thousands of people fled San Francisco and the surrounding area. Most of those who remained were homeless but found shelter at makeshift camps set up around the city. Donated supplies poured in from all over the United States, staving off possible famine and more deaths.

Scientists predict that San Francisco may experience another massive earthquake midway through the twenty-first century. They base this estimate on data from the last 1,500 years indicating that major earthquakes occur along the San Andreas Fault about once every 150 years. Nonetheless, the area is prone to frequent, moderate-sized (yet damaging) earthquakes. The 1989 earthquake centered at Loma Prieta, 50 miles (80 kilometers) south of San Francisco, is one such example.

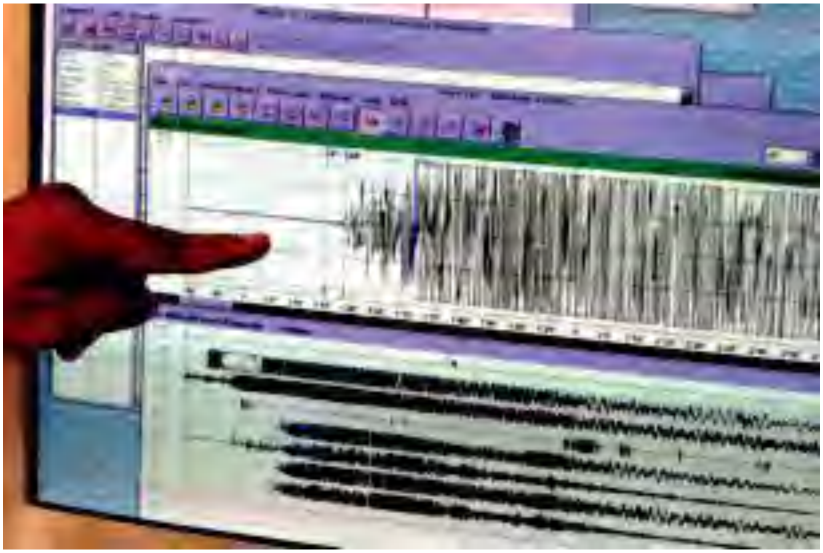
Recent events: Catastrophic earthquakes since 2000

Though many earthquakes occurred between the 2000 and 2005, the 2004 Indian Ocean earthquake and the 2005 Kashmir earthquake were especially destructive and deadly.

The Sumatra-Andaman earthquake of 2004 The Sumatra-Andaman earthquake, also known as the Indian Ocean earthquake, occurred on December 26, 2004. It was also one of the most powerful earthquakes on record. The event registered 9.0 on the Richter scale and was later upgraded to a magnitude between 9.1 and 9.3.

The Sumatra-Andaman earthquake struck off the coast of Indonesia, but its effects were far-reaching. The event is perhaps best remembered because it triggered a series of deadly tsunamis, or giant waves, which devastated countries that border the Indian Ocean. At the time of the earthquake, there was no reliable early warning system for Indian Ocean tsunamis, so the giant waves took people by surprise, battering coastal areas.

Casualties were especially high in Indonesia, Sri Lanka, India, and Thailand. When the waves hit, people were going about their business as usual. Tourists played on beaches, fisherman worked, and families went about their ordinary routines. People did not expect the giant waves that came ashore, destroying buildings and homes, and carrying debris like cars and construction materials farther inland. Well over 100,000 people



Seismograph showing the December 2004 Indian Ocean earthquake. ©MAST IRHAM/ EPA/CORBIS.

died in Indonesia alone. The damage caused by the tsunamis displaced over a million people and caused billions of dollars worth of damage.

The destructive earthquake set records. The event created the longest fault rupture on record, creating an opening in Earth's seabed almost 800 miles long. The earthquake was also the longest-lasting on record with a duration of 500 to 600 seconds (about 10 minutes). By contrast, many small earthquakes last only one second. According to scientists, the average ground movement along the fault was at least 16.5 feet (5 meters). In some places, the ground moved as much as 20 feet.

Scientists say that the Sumatra-Andaman earthquake literally shook the entire planet. Scientists were able to detect movement from the event in every place in the world that seismic activity is measured. Thanks to new technology in earthquake measuring instruments, like global broadband seismometers, scientists were able to measure the Sumatra-Andaman event with more precision than ever.

The destructiveness of the Sumatra-Andaman earthquake created widespread human suffering. This tragedy has motivated the scientific community to develop a reliable warning system for tsunamis in the Indian Ocean.

The Kashmir earthquake of 2005 Another historic and disastrous earthquake happened on October 8, 2005, in the Kashmir region of Pakistan.

This region is one of the most seismically active in the world. The 2005 earthquake had a magnitude of 7.6 on the Richter scale. It was the strongest earthquake on record in Pakistan. It was followed by a series of powerful aftershocks, measuring as much as 6.3 on the Richter scale. The epicenter of this powerful earthquake was about 60 miles north-northeast of Islamabad, Pakistan's capital.

The Kashmir earthquake was one of the most destructive of all time. In addition to causing widespread destruction, the earthquake killed almost 80,000 people. At least as many people were injured. The earthquake left three million people homeless just before the onset of the winter, which is bitterly cold and severe in the region, which includes parts of the Himalayan mountain range.

The gravest damage caused by the Kashmir earthquake was said to be in the village of Balakot, which is near the epicenter of the earthquake. Portions of the village, which is located on a hillside, literally slid down the hill. Most of the village was completely flattened by the earthquake. The residents of Balakot were among the millions displaced by the earthquake.

In addition to nearly decimating many mountain villages like Balakot, the Kashmir earthquake caused a number of landslides. These landslides cut off crucial thoroughfares across the mountains to the north of Islamabad. Because winter was coming, aid workers feared a second wave of deaths from the earthquake. They worried that people left homeless would die from exposure to the cold or from starvation. Fortunately, predictions that millions of displaced people would die turned out to be wrong. Many people were spared by a winter more mild than most. Aid agencies also found ways to transport food and supplies to isolated communities.

Still, the Kashmir quake devastated the region. Eyewitnesses reported that landslides continued well into the month of October, making mountain areas especially dangerous. Extensive farming infrastructure was destroyed, causing not only food shortages but also losses of livelihood.

Dangerous science: What causes earthquakes?

The answer to what causes earthquakes is found in both the structure of Earth's surface and the forces that rage inside the planet. The interior of Earth—from the planet's center to its surface (a distance of about 3,975

A Kashmiri man sits at a road side overlooking the devastation caused by an earthquake in the village of Kamsar, Kashmir, in 2005. ©AHMAD MASOOD/ REUTERS/CORBIS.

miles [6,395 kilometers])—is divided into layers, defined by their material composition. The core, at the center of the planet, is composed of a solid inner portion about 780 miles (1,300 kilometers) thick and a liquid outer portion about 1,380 miles (2,220 kilometers) thick. Surrounding the core with a depth of about 1,800 miles (2,900 kilometers) is the mantle. The crust, or surface layer surrounding the mantle, varies in thickness from 5 to 25 miles (8 to 40 kilometers).

The mantle is divided into two sections. The upper section, directly below the crust and about 40 miles (65 kilometers) thick, is solid. The section beneath it is soft, or partially melted. The crust and the rigid section of the mantle together compose what geologists call the lithosphere (pronounced LI-thuh-sphere). The soft section of the mantle is called the asthenosphere (pronounced ass-THEE-nuh-sphere).

Most geologists believe that convection currents (circular movements of fluid between hot and cold areas) in the asthenosphere are the driving force behind earthquakes and other movements on the surface of the planet. The heat energy at the center of Earth—where temperatures are estimated to exceed 9,900°F (5,480°C)—is carried to the surface by convection currents. As they near the crust, the currents cool and sink back toward the center to be heated once again. The pressure created by the action of these currents is released on Earth's surface through volcanoes and earthquakes.

Plate tectonics Plate tectonics is the geologic theory that Earth's crust is made up of rigid plates that float on the surface of the planet. (Tectonics comes from the Greek word meaning "builder.") The plates make up the lithosphere and float on the underlying asthenosphere. There are seven major plates and several smaller ones that are in constant contact with each other. When one plate moves, it causes other plates to move. The movement of the plates toward or away from each other either creates the major geologic features, such as mountain ranges or faults, at Earth's surface.

Plate tectonics is a relatively new scientific theory. This theory is built on the idea of continental drift, introduced in the 1920s by German geophysicist Alfred Wegener (1880–1930). Wegener believed that all continents were part of a single, original landmass—a supercontinent he called Pangaea (pronounced pan-JEE-ah)—before they gradually separated and drifted apart. His concept was based on the fact that several of the planet's continents seem to fit together like pieces in a jigsaw puzzle. This is particularly apparent when examining the eastern coast of South America and the western coast of Africa. Wegener, however, could not provide a convincing argument as to what made the continents shift around Earth's surface.

That question was answered by the theory of plate tectonics. The theory states that tectonic plates, moving about Earth's surface in response to pressure beneath them, interact with each other in one of three ways: they converge (move toward one another), diverge (move away from one another), or transform (slide past one another). The boundaries where plates meet are known as plate margins.

Reports from the past: Prehistoric earthquakes point to the future

In July 1998, two scientists published a study in the journal *Science* in which they asserted that there had been at least two giant prehistoric earthquakes near present-day Los Angeles. The scientists estimated that the earthquakes occurred within the last 15,000 years on the Sierra Madre Fault, which runs 12 miles (19 kilometers) north of the city. It was previously believed that earthquakes had not occurred on that fault.

The scientists, by measuring different layers of soil in the faulted region, determined that the ground had moved more than 16.5 feet (5 meters) on average during the ancient tremors. Based on that figure, they estimated that the earthquakes had ranged in strength from 7.2 to 7.6 on the Richter scale.

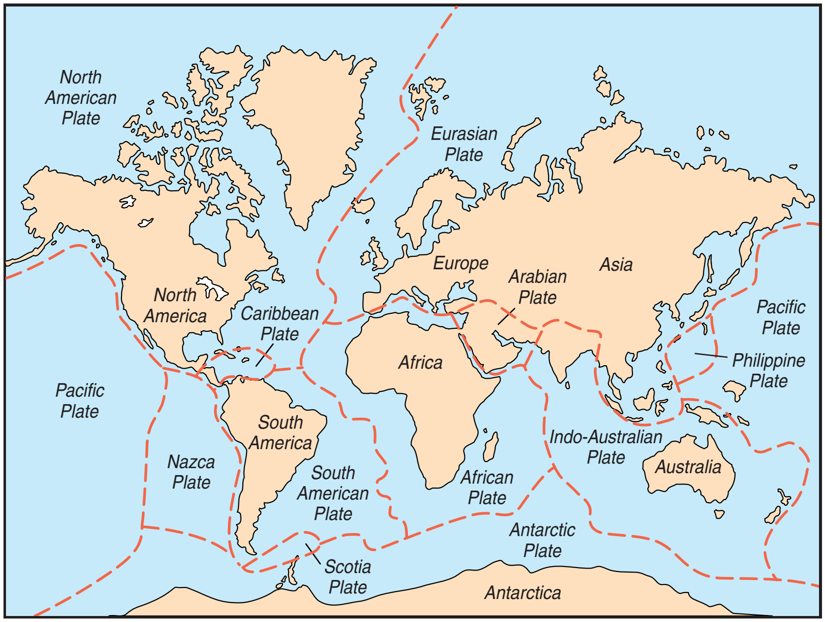
The scientists made no predictions of future earthquakes, merely pointing out that it was possible for an earthquake to eventually strike the city. If an earthquake were to occur today in the same place as the prehistoric earthquakes, the scientists reasoned, strong tremors would be sent directly into the heart of Los Angeles. Such an earthquake would cause immense destruction in the heavily populated city.

Alfred Wegener. ©BETTMANN/CORBIS.

Faults As two rock plates slide past one another, a crack or fault develops at the plate margin. Most earthquakes occur along faults (also called fault lines). The principle types of faults are normal, reverse, and strike-slip. A normal fault forms when two plates are being pulled or stretched apart. A reverse fault, in contrast, forms when two plates are being pushed together—the compression forces one plate up and over the other. A strike-slip fault, the most common type of fault, forms when the edge of one plate grinds against the edge of another as it slips sideways. The San Andreas Fault, the best known fault in the continental United States, is a strike-slip fault.

When plates along a fault move slowly and continuously, allowing pressure to be released, the movement is called fault creep. More often, however, the lower parts of the plates move slowly and continuously along the soft portion of the mantle while the upper parts of the plates, where the surface is solid rock, remain locked in position. Such a configuration causes stress to build up in the crust. When that stress becomes greater than the forces holding the surface plates in position, the crust can rupture. The stored energy is then released through ground vibrations—better known as earthquakes. There are more than one million earthquakes a year around the planet, although most are too faint to be noticed.

Earthquake zones On Earth, about 90 percent of earthquakes occur around the outer rim of the Pacific Ocean. This area is where the edges of the Pacific plate, the portion of the Earth's crust that lies beneath the Pacific Ocean, come in contact with several other plates. On its western side, the Pacific plate slides beneath the Eurasian and Indo-Australian plates. Along its northeastern side, the Pacific plate comes up against the North American plate. The north-central edge of the Pacific plate rides above the Nazca plate (located between the Pacific plate and the South American plate).



Plates composing Earth's crust.

Not only does the outer rim of the Pacific Ocean have frequent earthquakes, but it also contains three-quarters of the world's volcanoes. For this reason, this circular area is also known as the Ring of Fire (or Circle of Fire).

Seismic waves: The motion of earthquakes Vibrations transmitting the shock of an earthquake are called seismic (pronounced SIZE-mik) waves. These waves travel both underground and along Earth's surface in all directions, like ripples from a stone dropped in a pond. The underground area where energy is first released, triggering an earthquake, is called the focus (or hypocenter). The focus may be as far as 430 miles (700 kilometers) beneath Earth's surface. The point on the surface directly above the focus is called the epicenter.

When an earthquake occurs, two main classes of seismic waves are generated. The first class waves, called body waves, are generated below ground, from the source of the earthquake, and travel to the surface. Body waves consist of P (primary) waves and S (secondary) waves. The P waves travel fastest, up to 4 miles (6.4 kilometers) per second, and are the first waves to reach the surface. They stretch and compress the rock in their path and cause the ground to move vertically (upward). P waves release their energy to the atmosphere, resulting in the common thundering or rumbling sound associated with earthquakes.

S waves travel at about half the speed of P waves, or 2 miles (3.2 kilometers) per second. They move from side to side as well as upward, causing the ground to move horizontally as well as vertically. For this reason, S waves are far more destructive to buildings than are P waves.

S and P body waves combine near the epicenter to form surface waves or L (long) waves, which travel along Earth's surface. Although surface waves move slightly more slowly than body waves—less than 2 miles (3.2 kilometers) per second—they cause greater damage. Surface waves can set off avalanches, landslides, and tsunamis.

Seismic waves can travel great distances. For instance, in late 1811 and early 1812 a series of intense earthquakes hit the United States near New Madrid, Missouri. Vibrations could be felt more than 1,000 miles (1,600 kilometers) away. Although waves lose energy as they travel, they can still cause major destruction as they ripple outward.

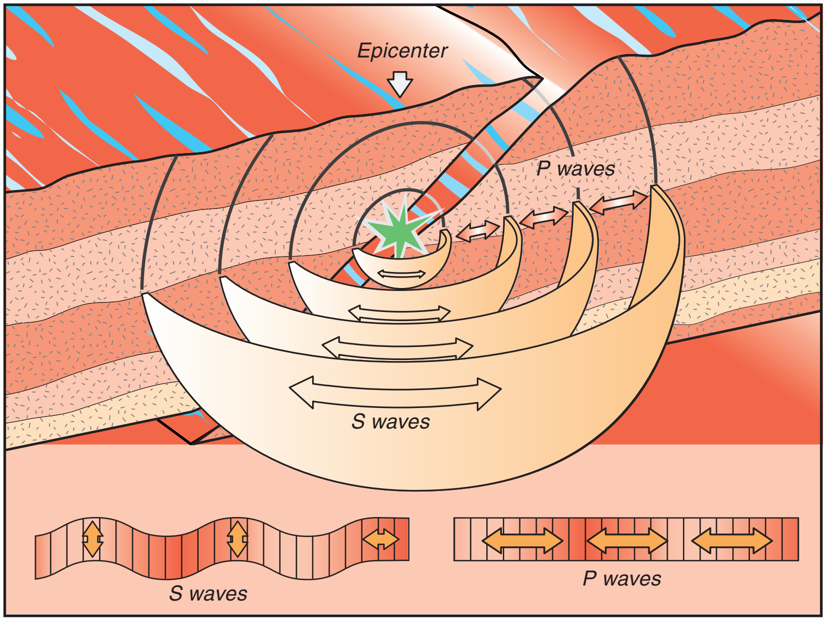
Experiment: Understanding plate tectonics

Earth's crust is made up of large tectonic plates. These plates are always moving. They move slowly, but they move with incredible force. To understand what happens when plates move into each other, try this experiment. Get a sheet of newspaper, and find a large, hard, flat surface, either a table or the floor, where you can spread the newspaper flat. Put your palms down on the newspaper about a foot apart and slowly push them together. The newspaper will crumple and fold upward in the middle. When tectonic plates fold upward, mountains are created. When they crumple together, earthquakes are the result.

Aftermath: What are the effects of earthquakes on Earth and its inhabitants?

Great earthquakes leave telltale signs in the surface of Earth, especially in the area around the epicenter. A horizontal or vertical change in the ground level can often be seen near a fault. The most dramatic change is the creation of a scarp, or cliff. Depending on the type of rock and the amount of uplift caused by the earthquake, a scarp may be up to 1 mile (1.6 kilometer) tall.

Earthquakes can also produce fissures, or long cracks, in the ground. Often the ground on one side of a fissure is uplifted several inches or even several feet. In addition to being moved vertically, the ground on one side of a fissure can also be moved horizontally. One example of vast changes in ground level occurred in southern Alaska on March 27, 1964. On that date, an earthquake measuring 8.6 on the Richter scale struck the area,



Action of seismic waves.

permanently resculpting 77,220 square miles (200,000 square kilometers) of land surface. Almost 620 miles (1,000 kilometers) of coastline from Kodiak Island to Prince William Sound was either uplifted or lowered. In some places, the vertical uplift was as much as 36 feet (11 meters); in others, the subsidence, or lowering of ground level, was as much as 7 feet (2 meters).

If a fissure occurs on a hill, it may set off a landslide. Landslides or mud slides are rapid downhill movements of soil and rock. These slides may encompass whole sections of a hill or mountain. During the landslide, the loosened soil and rock rushes down the slope, often destroying everything in its path before finally coming to rest at the bottom of the slope.

Underground structures such as springs and wells may be disturbed by earthquakes. Springs may stop flowing, either temporarily or permanently, and new springs may form. The water in wells may be muddied or its level changed. All of these effects can occur even at a great distance from the epicenter of an earthquake. An extremely intense earthquake may even force water, mud, and sand out of the ground, forming what are called earthquake fountains and sand blows.

Pre-Renaissance artwork destroyed by earthquakes

Priceless frescoes attributed to Florentine painters Giotto (c.1266–1337) and Cimabue (c.1240–c.1302) were severely damaged when two earthquakes struck central Italy within hours of each other on September 26, 1997.

The earthquakes, which measured 5.5 and 5.6 on the Richter scale, killed eleven people and caused damage to nearly 1,500 buildings. The first earthquake struck at 2:33 AM local time. Its epicenter was close to the town of Foligno in Umbria, a region dotted with historic towns. The second earthquake struck some nine hours later. Tremors from both earthquakes were felt in Rome, more than 62 miles (100 kilometers) away.

Frescoes are paintings made on damp plaster walls. When the plaster dries, the painting becomes fixed to the wall. The frescoes by Giotto and Cimabue were part of the walls and ceiling of the thirteenth-century Basilica of San Francesco in Assisi, one of early Christianity's most important shrines. A renowned tourist attraction, the basilica is famous for its twenty-eight frescoes depicting the life of Francis of Assisi (c.1182–1226), founder of the Franciscan religious order.

The first earthquake caused deep cracks in many of the precious frescoes. Just as friars and structural experts were inside inspecting this damage, the second earthquake struck, causing an even greater tragedy. Huge sections of the vaulted ceiling of the basilica collapsed, killing four people and destroying many of the frescoes.

On November 28, 1999, just over two years after the earthquakes struck, a commemorative mass was held to reopen the church. The bell tower, the vault sections, and some of the frescoes had been repaired or reattached. Restorers estimated it would take at least another two years before other damaged frescoes, including Cimabue's *St. Matthew* and Giotto's *St. Jerome*, would be reassembled.

What makes earthquakes deadly? The damage created by an earthquake is most evident in human-made structures. An earthquake is more likely to cause injuries, fatalities, and damage the closer the epicenter is to a populated area. Earthquakes occurring in crowded cities leave behind buckled and broken sidewalks and streets, downed trees and power lines, and collapsed homes and buildings.

What usually kills people in an earthquake is not the earthquake itself, but the collapse of buildings, roads, and other structures. The greatest destruction is brought about, often miles away from the epicenter of an earthquake, through the process of liquefaction (pronounced li-quh-FAC-shun). When earthquake vibrations encounter layers of loosely packed soil containing water, the vibrations cause the particles of soil to lose contact with one another. This allows the water to bubble through, transforming the ground into a watery mass resembling quicksand.

Kobe earthquake of 1995

The largest earthquake to hit Japan in the last half of the twentieth century occurred on January 17, 1995. At 5:46 AM local time, an earthquake measuring 7.2 on the Richter scale struck the region of Kobe and Osaka in south-central Japan. The region includes Kobe, Japan's sixth largest city and the world's sixth largest port, with a population of some 1.5 million. The Kobe earthquake, dubbed the Great Hanshin Earthquake by the Japanese media, killed more than 5,500 people and injured 25,000 others. More than 300,000 people were left homeless. The Kobe earthquake was the deadliest natural disaster in Japan since 1923—the year that the Great Kanto Earthquake killed about 140,000 people.

The epicenter of the Kobe earthquake was located about 20 miles (32 kilometers) south of the city of Kobe near Awaji Island. The minor strike-slip fault on which the earthquake occurred runs from Awaji Island through Kobe. The earthquake caused the ground to move 7 inches (18 centimeters) horizontally and 4 inches (10 centimeters) vertically—the greatest ground displacement ever recorded in Japan. In the twenty-four hours after the main shock, 716 aftershocks were recorded.

The Kobe earthquake damaged or destroyed one out of every five buildings in the area, totaling more than 180,000 buildings. The violent ground shaking, which lasted for about twenty seconds, caused an estimated damage of about 147 billion dollars (U.S.).

Damage occurred throughout a 62-mile (100-kilometer) radius from the epicenter. This area encompassed the cities of Kobe, Osaka, and Kyoto, with Kobe being the most severely affected. Kobe, like much of modern urban Japan trying to keep up with a growing population, was built on very soft soil and landfills. The worst damage occurred near the waterfront where severe liquefaction took place, causing industrial buildings to sink and crumble. Ninety percent of the port's 187 berths were destroyed, and most large cranes along the waterfront were either damaged or destroyed.

Major utilities were severely disrupted in Kobe and surrounding cities. At one point, almost one million households were without electrical power, another 800,000 households lacked gas, and some 250,000 telephone lines were disconnected. Severed gas lines started fires that burned for days. Approximately 150 fires broke out in Kobe and surrounding areas in the hours immediately following the earthquake. Firefighters, hampered by a lack of water because of thousands of breaks in the water line system, were ill-equipped to fight the blazes. Streets clogged

Structures and roads built on this type of soil cannot be supported by this liquid mixture and thus sink or slide from their foundations.

Another serious consequence of earthquakes is fire. Broken gas lines, downed electrical wires, and overturned stoves and heaters start many fires (as was the case in the 1906 San Francisco earthquake). Because with collapsed buildings and traffic congestion also blocked firefighters' efforts.

Houses built in the style of traditional Japanese architecture readily collapsed, killing their inhabitants. Heavy roofs composed of thick mud or tile fell as the thin walls supporting them buckled. Other structures throughout the city were also destroyed by the earthquake. Railway lines were twisted and bent, and train cars were thrown like toys. Elevated portions of the area's highway system collapsed or caved in. Impassable roads, bridges, and rails slowed the arrival of aid from nearby cities. In the period immediately after the earthquake, the only way of transporting emergency supplies was by bicycle or on foot.

The Kobe earthquake hit when most people were asleep. Had it come later in the day—when people filled trains, freeways, and sidewalks—the death toll would have been far higher.

A section of Kobe, Japan, demolished by the 1995 earthquake. ©MICHAEL S. YAMASHITA/CORBIS.

water mains and streets are damaged at the same time, the water needed to put out the fires is unavailable. In a populated region, the damage caused by fires frequently exceeds that caused by the ground shaking.

A secondary effect of an earthquake that occurs under the ocean is a tsunami (pronounced tsoo-NAH-mee), also called a tidal wave. A tsunami

Turkey's earthquakes of 1999

One of the deadliest earthquakes of the twentieth century hit northwest Turkey on August 17, 1999. At 3:02 AM local time, a violent tremor measuring 7.4 on the Richter scale shook the ground for forty-five seconds. The epicenter of the earthquake was located near the city of Izmit, 55 miles (88 kilometers) east of Istanbul. Almost half Turkish population lived in the area affected by the earthquake. When it was over, nearly 76,000 buildings had collapsed, an estimated 17,500 people were killed and more than 33,000 others injured. Almost 500,000 were left homeless. The Turkish government, which called the natural disaster one of the greatest in Turkish history.

Turkey lies atop some of the world's most unstable geology. The North Anatolian fault runs through the densely populated, industrial area of northern Turkey. This fault is a small slab of crust that marks the boundary between the Arabian plate to the south and the larger Eurasian plate to the north. Between the two plates lies the relatively small Turkish microplate, on which most of the country of Turkey is located. As the Arabian plate moves slowly northward, it pushes the Turkish microplate to the west relative to the Eurasian plate at a rate of about 1 inch (2.5 centimeters) per year. At times, the microplate sticks, then jerks free with great energy. This occurred on August 17.

The North Anatolian fault is more than 800 miles (1,287 kilometers) long and 10 miles (16 kilometers) deep. It is a perfect example of a strike-slip fault, where the ground moves side to side. After the August 17 earthquake, geologists measured the North Anatolian fault and found that in some places one side of the fault had shifted more than 12 feet (3.7 meters) relative to the other side.

Earthquakes are common in geologically unstable Turkey. According to historians, over the last 5,000 years major earthquakes have shaken northern Turkey about once every 175 years. Seven destructive earthquakes have occurred along the North Anatolian fault since 1939, the year in which an earthquake struck the eastern province of Erzincan and killed 30,000 people. Since then, the locations of the earthquakes along the fault have moved progressively westward.

The earthquake on August 17 was the most powerful to strike the area since 1939. Lives and buildings were destroyed up to 200 miles (322 kilometers) from the epicenter. Tremors from the earthquake were felt as far east as Ankara and across parts of the Balkans.

In central Istanbul, the majestic museums and historic mosques suffered no visible damage. In areas on the outskirts of the city, home to some twelve million people, newly built apartment complexes crumbled. In some places to the southeast of Istanbul, the destruction was nearly total.

is set in motion by a vertical shift in the ocean floor, which pushes the water ahead of it. The vertical shift generates waves that can travel across the ocean with speeds of 250 to 500 miles (400 to 800 kilometers) per

Rescue teams representing thirty-eight international organizations and forty-two countries arrived in the country shortly after the disaster. But many areas in desperate need of help received nothing for days, forcing the living to dig through the rubble with their bare hands in search of their family members, friends, and neighbors. Smashed sewer lines and a lack of fresh water and portable toilets raised the risk of the spread of infectious diseases among the hundreds of thousands of people left homeless by the earthquake.

On November 12, an earthquake measuring 7.2 struck the northwestern town of Duzce just after nightfall. Located in a hilly region about 115 miles (185 kilometers) east of Istanbul, Duzce was on the eastern fringe of the region hit by the August 17 earthquake. Hundreds of thousands of survivors from the first disaster were still living in tents in the rainy winter weather when the new earthquake struck. The Duzce earthquake lasted for thirty seconds, cutting communication lines and crumbling the main road leading into the town. More than 5,100 people were injured and more than 750 buildings were destroyed. The death toll exceeded 700.

Earthquake damage to a Turkish mosque, 1999. ©SERGEI CHIRIKOV/EPA/CORBIS.

hour. Tsunamis start out small and grow larger as they near land. It is typical for a large tsunami to measure 60 to 100 feet (18 to 30 meters) in height by the time it crashes onto land.

Earthquakes usher in year 2001

Within the first twenty-six days of 2001, major earthquakes struck two locations at opposite ends of Earth. The first quake shook the tiny Central American nation of El Salvador on January 13, and the second quake hit western India thirteen days later.

Measuring 7.6 on the Richter scale, El Salvador's earthquake killed some 700 people, injured more than 2,000 people, and left 65,000 families homeless. Damages totaled 1.5 billion dollars—about half of the gross earnings of all Salvadorans.

El Salvador's earthquake affected the capital city, San Salvador, and villages in the countryside alike. A large portion of the casualties occurred in Las Colinas, a suburb of San Salvador. A cluster of homes at the base of a hill there were buried under a wall of soil and mud that collapsed in an earthquake-triggered landslide. (The removal of trees from the hillside to make room for a coffee plantation and luxury homes was considered partially to blame for the landslide.) San Francisco Javier and San Augustin, both about 100 miles southeast of the capital, were representative of outlying towns in which virtually every building, most made of adobe walls and tin roofs, was reduced to rubble.

India's earthquake, a 7.9 on the Richter scale, had far greater consequences than El Salvador's. The death toll in India exceeded seventeen thousand, there were more than sixty thousand injuries, and one million people were left homeless. The earthquake, India's worst in half a century, occurred at about 9 o'clock in the morning on Republic Day (a national holiday honoring the Indian constitution).

The epicenter of the earthquake was below the heavily populated state of Gujarat, near the border with Pakistan. Buildings in cities throughout Gujarat, constructed without following earthquake-proof building codes, teetered and fell or collapsed in heaps. The hardest-hit city, Bhuj, lost 6,000 of its 150,000 residents and its hospital. Not a single building in Bhuj escaped without serious damage. In the town of Anjar, 400 children marching in a Republic Day parade were buried alive by debris from tumbling houses and high-rise buildings.

Throughout the region, the earthquake caused water supplies to become contaminated; destroyed roads, bridges, and railroad tracks; and downed telephone and power lines. The destruction not only made it hard for survivors to find food and water, but it made it difficult for relief workers with needed supplies to reach affected areas.

The human factor: How do people contribute to earthquake damage?

The most obvious way that people contribute to earthquake destruction is by building cities and towns within earthquake zones (areas situated on or near faults and other plate boundaries). Because scientists have identified these zones only within the last one hundred years, most cities were built with no knowledge of the danger. Complicating matters, wetlands and other moist lowland areas around many cities have been filled in with soil to create more living space. These filled-in areas are highly prone to liquefaction and destruction during earthquakes.

Along with ground instability and the possibility of liquefaction, the design of many buildings makes them susceptible to earthquake damage. Structures that are insufficiently braced or not tightly secured to their foundations can be damaged easily by earthquakes. The materials used to construct the buildings is another factor. For instance, wood is more flexible than brick and cement; therefore, wood-frame buildings are better equipped to withstand ground motion. Brick and cement structures often fracture and collapse during large earthquakes.

Further, some scientists said that human development and coral mining created conditions that worsened the impact of the Sumatra-Andaman earthquake. That 2004 earthquake, whose epicenter was in the Indian Ocean, triggered massive tsunamis that pulverized many countries that border that ocean. Normally, a coral reef acts as a natural barrier between the land and powerful ocean waves. When a reef is compromised or destroyed, there is no barrier to protect the land. Thus, some scientists think that the tsunami that resulted from the Sumatra-Andaman earthquake was taller and more powerful in areas where reefs had been compromised.

Artificial earthquakes? Scientists have recently begun exploring the occurrence of artificial or human-made earthquakes, such as those caused by quarry blasts or other large explosions. Another possible trigger of earthquakes is the underground detonation (for the purpose of testing) of large nuclear bombs. The tremors generated by this type of explosion are strong enough to be felt more than 100 miles away from the testing site. It is therefore plausible that such tremors could trigger the release of built-up pressure between two nearby plates, resulting in an earthquake.

The underground storage of hazardous liquid wastes is yet another problem. (Wastes deemed hazardous are those detrimental to human health or the environment because, for example, they catch fire at low temperatures, are extremely acidic, or undergo violent physical and/or chemical changes when mixed with water. Such wastes must be disposed of in accordance with strict standards developed by the Environmental Protection Agency.) Scientists believe that improper underground disposal of hazardous wastes may have caused an earthquake beneath northeastern Ohio on January 31, 1986. For the twelve years before that date, hazardous liquid wastes had been disposed of in two underground wells located almost 1.3 miles (2 kilometers) below ground. A total of about

350 million gallons (1.3 billion liters) of hazardous waste had been pumped into the wells. The pressure created by that volume may have ruptured the surrounding rock, causing cracks that reached an area where tectonic pressure had been building up. Whatever the cause, an earthquake measuring 4.9 on the Richter scale rocked this area in Ohio.

Technology connection: Measuring and predicting earthquakes

From the beginning of recorded history, people have tried to explain, predict, and measure earthquakes. Ancient people believed that the movement of various animals such as giant catfish, snakes, spiders, or turtles that lived beneath Earth's surface created earthquakes. One of the first people to attempt to explain the action of earthquakes based on natural phenomena was Greek philosopher Aristotle (384–322 BCE). He believed that winds within the planet caused shaking at the surface.

The first known earthquake-measuring device was invented by Chinese scholar and poet Zhang Heng (78–139) in the second century CE. The device, now called a seismoscope, is a huge bronze vase measuring 6 feet (1.8 meters) in diameter. Eight dragon heads are sculpted around the top. In the mouth of each dragon is a small bronze ball. Directly below each dragon head sits a bronze frog. Inside the vase, each dragon head is attached to a bar, which connects to a single pendulum (a hanging object that freely swings back and forth) in the middle of the vase. The pendulum swings from the movement of even the slightest tremor. When the pendulum swings, it pulls back one of the bars. The dragon's mouth opens, and the ball drops into the open mouth of the bronze frog directly below. The frog holding the ball indicates from which direction the tremor came.

Present-day scientists measure an earthquake's power by two standards: intensity and magnitude. While the intensity of an earthquake is determined by the amount of damage caused, magnitude is measured by using seismographs, also known as seismometers, or other devices that detect ground movement. Intensity is a measure of an effect; magnitude is a measure of released energy.

Seismology Scientists use an instrument called a seismograph, or seismometer, to measure the waves caused by an earthquake. A seismograph consists of a heavy weight or pendulum hanging over a constantly revolving drum wrapped with recording paper. Attached to the end of the pendulum, with its tip touching the paper, is a recording pen or

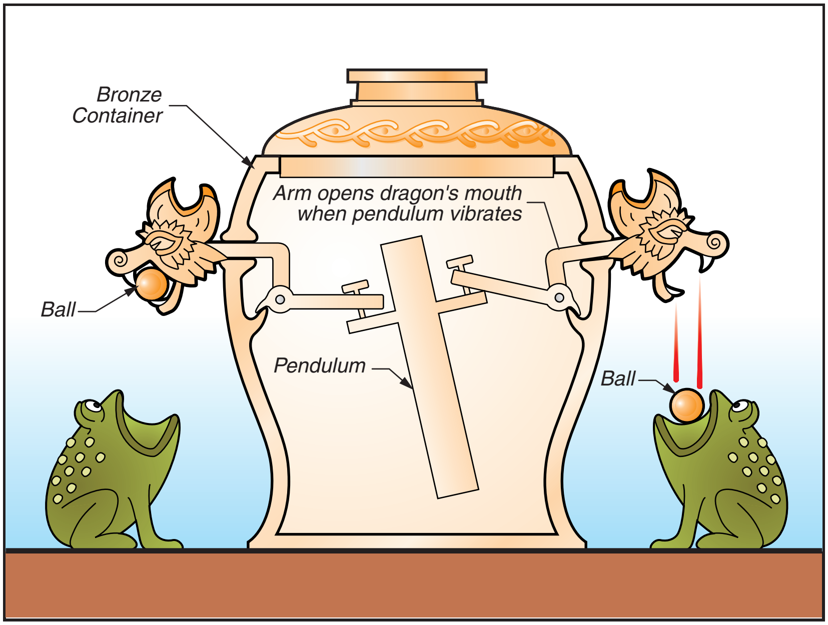


Illustration of an ancient seismoscope.

needle. When an earthquake occurs, the seismic waves cause the pendulum to swing, and the pen records that motion on the paper. The bigger the seismic wave, the larger the swing of the pendulum, and the wider the zigzag line made by the pen on the paper. Today, the motion of the pendulum can also be recorded as digital data on a computer.

Seismographs, or seismometers, are usually placed underground in deep holes away from the artificial vibrations caused by cars, airplanes, and other modern machinery. In 1931, only 350 seismographic stations existed around the world to measure earthquakes. By 2000 there were more than 4,000 stations recording data. That data is transmitted via satellite and computer to scientific institutions around the world.

The most recent seismographic technology includes the broadband seismometer, which is able to record a broad range of frequencies. These devices have allowed scientists to collect even more specific data on recent earthquakes like the 2004 Sumatra-Andaman earthquake and the 2005 Kashmir earthquake. This electronic device confines a small mass between electrical forces. When the Earth moves, the device measures how much force is required to hold the mass steady.

Mercalli scale In 1902 Italian seismologist Giuseppe Mercalli (1850–1914) developed a scale to compare the surface effects of

A scientist monitors Earth movements using a seismograph. ©REUTERS/CORBIS.

earthquakes. Mercalli's measurement of earthquake intensity was based not on scientific measurement but on the damage done to buildings. Updated in 1931 by American seismologists Harry Wood and Frank Neumann, the scale (now called the modified Mercalli scale) rates the intensity of earthquakes from levels I (detected only by seismographic instruments) through XII (destruction of all buildings).

On the modified Mercalli scale, a rating of II or III describes a weak earthquake that is felt by few people. At this strength, ground vibrations are similar to the passing of a large truck. People on upper floors of buildings would most likely feel such small tremors as a slight swaying motion. Tremors of this strength may also cause hanging objects like chandeliers to swing.

Medium-strength earthquakes with a modified Mercalli rating from IV to VI are felt by most people and usually wake those who are asleep. Earthquakes of this intensity can cause walls to crack and dishes and windows to move or break. During this type of earthquake, unstable objects may fall over or drop to the floor, heavy furniture may move across the floor, and people may feel off-balance as they walk.

Earthquakes with a VII or VIII rating on the modified Mercalli scale can cause considerable damage to poorly designed and built structures. Even well-built structures may suffer moderate damage. An earthquake of this strength can cause chimneys, factory stacks, columns, and walls to tumble, and unsecured houses to move off their foundations. The ground motion may cause wet ground to develop cracks and sand and mud to spurt up through those cracks.

Serious damage and partial-to-total collapse of buildings—even specially designed structures—is common in earthquakes rating IX or higher on the modified Mercalli scale. Underground water pipes, reservoirs, dams, and embankments break or become damaged. Railroad rails may bend, and noticeable cracks may appear in the ground. Liquefaction occurs, causing buildings and roads to sink into the ground. Landslides occur on steep slopes. At level XII of the scale, the ground ripples in waves, objects are thrown into the air, and the courses of rivers may shift.

Richter scale In 1935 American seismologist Charles Richter (1900–1985) developed a scale to measure the magnitude of earthquakes. Richter and colleague Beno Gutenberg (1889–1960) sought a standard method of measuring and comparing earthquakes. Up to that point, the Mercalli scale was the only earthquake-measurement tool. The problem

Earthquake hazard map. AP IMAGES.

Charles F. Richter, creator of the Richter scale, studying data from earthquake detection equipment in California in 1963. AP IMAGES.

with the Mercalli scale, however, was that it depended on nonscientific factors. It was greatly influenced by the soundness of building construction and the behaviors of the people living in the earthquake area. The Mercalli scale also made it difficult to rate earthquakes that occurred in rural areas where there were few buildings or people.

Richter and Gutenberg developed a way of measuring an earthquake's power, rather than its effects on humans or buildings. The Richter scale, ranging from 1 to 10, uses seismographic readings to compare the energy released by a specific earthquake to the energy released by other earthquakes. Each whole number increase in value on the scale indicates a ten-fold increase in the energy released and a thirty-fold increase in ground motion. Therefore, an earthquake with a value of 6.0 on the Richter scale is ten times more powerful than an earthquake with a value of 5.0, and so on up and down the scale.

Most earthquakes that are reported measure between 3.0 and 8.0 on the Richter scale. Those that have a rating less than 3.0 are not usually felt. Earthquakes measuring between 3.0 and 6.0 cause minor to moderate damage. Strong earthquakes, causing destruction in areas with large populations, measure between 6.0 and 6.9 on the scale. Earthquakes measuring 7.0 to 7.9 are major. (California is struck by earthquakes in this range about once every eighteen years.) Any earthquake that measures 8.0 or above on the Richter scale is considered a massive earthquake, one that causes widespread destruction. An earthquake of this magnitude generally occurs somewhere on the planet once every five to ten years.

Earthquake prediction Of the more than one million earthquakes that shake the surface of Earth each year, the vast majority measure 3.4 or below on the Richter scale and cannot be felt by people. The few earthquakes that register high on the Richter scale, however, can be disastrous. Great earthquakes have accounted for some of the most dreadful natural disasters in recorded human history. In the past eight hundred years, seventeen earthquakes have caused fifty thousand or more deaths apiece.

Earthquake rattles Washington State

At 10:54 AM on February 28, 2001, northwest Washington state was rocked by its most powerful earthquake in fifty-two years. The forty-second tremor measured 6.8 on the Richter scale. It was centered between Olympia and Tacoma, some 30 miles from Seattle, on the southern border of Puget Sound. The quake produced just one fatality (one woman died of a heart attack) and approximately 235 injuries; only a handful of the injuries were serious, and none were life-threatening.

Damage caused by the earthquake was estimated at more than two billion dollars. Examples of damage included crumbled bridges, buckled roads and sidewalks, and broken glass and fallen plaster in buildings. Some of the worst destruction occurred at the seventy-four-year-old capitol building in Olympia, about 12 miles from the earthquake's epicenter. The building's dome was cracked in several places, and engineers were unsure as to whether or when the statehouse could be used again.

Geologists noted that the damage in the region was relatively minor for a quake of that magnitude. They attributed the gentleness of the earthquake to the location of its epicenter, which was more than 30 miles beneath the surface. "We were very, very lucky," stated Washington governor Gary Lock in the *New York Times* of March 2, 2001. "There could have been utter catastrophe had it been higher, closer to the surface."

Also deserving credit for the prevention of greater damage was the strict earthquake code for building construction in the region. Those regulations are intended to protect buildings from all but catastrophic earthquakes. Almost all buildings built or upgraded to be in compliance with the code escaped without serious damage.

Seismologists in many countries constantly monitor the stresses within Earth's crust. Ultrasensitive instruments placed across faults at the surface measure the slow, almost imperceptible movement of plates. Other instruments measure phenomena that sometimes precede earthquakes, including changes in tide and groundwater levels, fluctuations in the magnetic properties of rocks, and the swelling or tilting of the ground.

For more than thirty-five years, the U.S. Geological Survey (USGS) has operated seismographic stations throughout the world. In the mid-1990s, the USGS and the Incorporated Research Institutions for Seismology (an association of more than ninety universities) developed the Global Seismographic Network (GSN). This worldwide network is composed of 128 stations in more than eighty countries on all continents. Its purpose is to make readily available high-quality data regarding earthquakes. Within minutes after data is received and recorded, scientists can analyze the information to determine the location and magnitude of any large seismic event that has occurred anywhere on the planet.

Earthquake braces installed at Diablo Canyon nuclear power plant in California. ©ROGER RESSMEYER/CORBIS.

Even with this state-of-the-art equipment, scientists cannot predict the exact time and place an earthquake will occur. Earthquake researchers continue to sharpen their ability to correctly interpret the significance of seismic activity. At present, scientists rely primarily on information about past earthquakes in order to determine the likelihood of future earthquakes.

Some people look to peculiar animal behaviors as a sign of impending earthquakes. Certain animals have heightened sensitivities to electricity, magnetic fields, odors, and vibrations. In China it is said that prior to earthquakes snails come out of the ground, rats leave houses, birds fly from their nests, and dogs bark constantly. In Japan, there are reports of goldfish swimming frantically just before earthquakes. From a scientific standpoint, however, the connection between animal behavior and earthquakes has not been proven.

A matter of survival: How can we live through earthquakes?

Earthquakes can neither be stopped nor controlled, but humans can minimize the destruction earthquakes cause. A seemingly simple solution is for people to avoid living in earthquake-prone areas. This solution is not very practical, however, since many cities—some with large and growing populations—already stand in these areas.

A more realistic solution is to design structures resistant to earthquake damage. In many earthquake zones, strict building codes for new structures have been adopted. For existing buildings, internal and external braces have been added to strengthen them. Buildings have also been anchored to their foundations to keep them from slipping off during an earthquake.

Builders in earthquake zones now use metal straps or braces to help strengthen a building's (especially a tall building's) resistance to earthquakes. They use materials and designs that can absorb or withstand ground vibrations. They also put layers of rubber and steel underneath new buildings to lessen the effect of an earthquake on the building itself.

Bridges can also be constructed to withstand earthquakes. San Francisco's Golden Gate Bridge, for instance, has a flexible structure that allows it to sway but not break during most earthquakes. Cantilever bridges (type of bridge made of two sections that extend outward from banks or piers and join together in the middle), like the San Francisco-Oakland Bay Bridge, in contrast, are less flexible and more prone to collapse during earthquakes.

Personal safety An earthquake is unpredictable and terrifying, but people caught in one can follow a few steps to help reduce personal injury. Safety experts recommend the following:

- First and foremost, do not panic. The shaking of the ground is not harmful; falling objects are.
- If you are indoors when an earthquake hits, stay there. Crawl beneath and hang onto a heavy desk or table. If that is not possible, move into a hallway or crouch against an inside wall. Stay away from windows, fireplaces, and heavy standing objects. Get out of the kitchen—stoves and heavy appliances make it a dangerous place. Do not run downstairs or rush outside while the house or building is shaking.
- If you are outside when an earthquake hits, move quickly into an open area away from buildings, power lines, walls, or other structures that might fall.
- If you are driving when an earthquake hits, move the car out of traffic as quickly and carefully as possible and stop. Do not park on or under a bridge or overpass, or under trees, light posts, power lines, signs, or anything else that might fall. Stay inside the car until the tremors stop.

- If in a mountainous area, move into a clearing or open area. Be mindful of landslides, falling rocks, or other loose debris that could come rolling down a slope.

After the tremors of an earthquake subside, remember to do the following:

- Check the utilities. If the smell of gas is present in the air, turn off the main gas valve and open the windows, if possible. Do not light matches or lighters. Do not turn on electrical equipment or appliances. A spark from any of these may cause an explosion and fire. Leave the house or building and report the gas leak.
- Use the telephone only to report an emergency. If there is an emergency and the telephone lines are down, send someone for help.
- Stay out of damaged buildings. Aftershocks (tremors that occur after the main shock of an earthquake) can topple already weakened structures.
- Advance preparation for an earthquake, like for any disaster, can greatly reduce the chances of injury or death. Develop an earthquake plan at home or at school that explains the safest course of action should an earthquake strike. Keep on hand an emergency kit that includes a flashlight, a battery-powered radio, extra batteries, first-aid materials, a fire extinguisher, canned or packaged food (with a manual can opener), plastic containers filled with drinking water (allow at least one gallon or three liters per person per day), warm clothes, matches, candles, and a camp stove or barbecue with extra fuel (stored carefully).

[*See Also* **Tsunami**]

For More Information

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El Niño

In the late 1990s, the weather news was dominated by a phenomenon called El Niño (pronounced el-NEE-nyo). El Niño is a disruption of the ocean-atmosphere system in the tropical Pacific characterized by elevated water temperatures off the coast of Peru. Water temperatures may rise by 5 to 11°F (3 to 6°C). During an El Niño event, the Pacific coast of South America may experience floods, while Australia may suffer drought conditions. The event may also trigger unusual weather disturbances all over the Western Hemisphere. While El Niño is not new—indeed, its occurrence has been recorded for centuries—only in the past few decades have scientists begun to understand the mechanics and scope of this climate-altering event.

The term "el niño" is Spanish for "the child." When it is capitalized as "El Niño," it means "the Christ child." The name was given by sailors in the late 1800s to a weak warm current that appeared off the coast of Ecuador and Peru each year around Christmastime. The term "El Niño" first appeared in print in a Peruvian scientific journal in 1892.

There is evidence that strong El Niños have occurred periodically for thousands of years. In the late 1990s an unusually strong El Niño was blamed for floods, droughts, wildfires, storms, and unseasonable temperatures around the world.

Defining El Niño

El Niño has traditionally been defined as the annual warming of the waters off the coast of Peru. A massive pool of warm water—containing twenty to thirty times as much water as all the Great Lakes combined—arrives from the western Pacific equatorial region, replacing the cold water that typically resides on the South American coast. Most years the warm water only persists for a month or so before the cold water returns.

The water off the coast of Peru is typically about 68°F (20°C). During El Niño years, the water warms—sometimes just slightly and other times by several degrees. During El Niño conditions in December 1997, for example, the water temperature off the coast of Peru was 77°F (25°C).

A telltale sign that El Niño has arrived is the dwindling of fish populations (anchovies, in particular). Large numbers of fish die off or migrate to less-affected areas because the warm water is unable to sustain the tiny animals that fish eat. In scientific terms, the warm water is nutrient poor. The cold water, which is considered nutrient rich, does support tiny marine organisms. As the warm water moves in and these microorganisms die, it becomes nutrient poor.

In recent times the term "El Niño" has come to mean only extraordinarily strong El Niño episodes. Such episodes generally occur every three to seven years, but sometimes happen as often as every two years or as infrequently as every ten years. During these events, coastal waters become significantly warmer than usual—up to 10°F (5.6°C) higher than normal. In addition, the warm waters last longer than a few months (the longest recorded El Niño lasted four years, from 1991–1995) and occupy much of the eastern Pacific Ocean.

Commonly accepted standards for what constitutes a major El Niño event (that from hereon will simply be called an "El Niño") were developed by the Japanese Meteorological Agency (JMA). Those criteria, or conditions that must be met, are as follows: 1. Pacific Ocean temperatures, along the equator from Papua New Guinea in the west to the Galápagos Islands in the east, must be an average of 1°F (0.5°C) above normal; 2. The warm waters must persist for more than six months.

The 1997 to 1998 El Niño

In April 1997 the strongest El Niño in recorded history got underway. It produced heavy rain and flooding on the Pacific coast of South America, in California, along the U.S. Gulf Coast, in Eastern Europe, and in East Africa. Drought and wildfires spread in Australia, Southeast Asia, Mexico, Central America, Texas, Florida, and northeastern Brazil. A series of hurricanes swept through the eastern and western Pacific.

More acres of tropical rain forest burned during the El Niño of 1997–98 than at any other time in recorded history. By the time the episode ended in May 1998, the worldwide death toll due to El Niño–-related weather was approximately 23,000, and property damage totaled at least thirty-three billion dollars.

WORDS TO KNOW

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

ecosystem: a community of plants and animals, including humans, and their physical surroundings.

El Niño: means "the Christ child" in Spanish. A period of unusual warming of the Pacific Ocean waters off the coast of Peru and Ecuador. It usually starts around Christmas, which is how it got its name.

ENSO: stands for El Niño/Southern Oscillation. It describes the simultaneous warming of the waters in the eastern Pacific Ocean and the shifting pattern of air pressure between the eastern and western edges of the Pacific.

food chain: transfer of food energy from one organism to another. It begins with a plant species, which is eaten by an animal species; it continues with a second animal species, which eats the first, and so on.

jet stream: the world's fastest upper-air winds. Jet streams travel in a west-to-east direction, at speeds of 80 to 190 miles (130 to 300 kilometers) per hour, around 30,000 feet (9,150 meters) above the ground. Jet streams occur where the largest differences in air temperature and air pressure exist. In North America, jet streams are typically found over southern Canada and the northern United States, as well as over the southern United States and Mexico. The northern jet stream is called the polar jet stream, and the southern jet stream is called the subtropical jet stream.

La Niña: Spanish for "little girl," a period of unusual cooling of the Pacific Ocean waters off the coast of Peru and Ecuador. It often follows an El Niño.

monsoon: a name for seasonal winds that result in a rainy season occurring in the summer on tropical continents, when the land becomes warmer than the sea beside it.

numerical prediction model: a computer program that mathematically duplicates conditions in nature. It is often used to predict the weather.

trade winds: dominant surface winds near the equator, generally blowing from east to west and toward the equator.

upwelling: the rising up of cold waters from the depths of the ocean, replacing the warm surface water that has moved away horizontally.

Droughts and wildfires Southeast Asia, plagued by drought (prolonged periods of unusually dry conditions) and wildfires, was the hardest hit area of the 1997–98 El Niño. Indonesia was hit with its worst drought in fifty years. Fires claimed more than twelve million acres of Indonesian and Malaysian rain forest in 1997, and 7.5 million acres in early 1998. (The fires predominantly burned on the islands of Sumatra and Borneo. Sumatra is part of Indonesia and Borneo is divided between the countries of Indonesia and Malaysia.) Relief, in the form of rain, came in May 1998.

The fires were set by farmers who burn the land to clear it for planting. Most years, any lingering flames are put out by the September monsoon. In 1997, however, the monsoon rains were delayed until December. The fires spread rapidly through the parched trees, propelled by hot winds. This method of clearing land for planting, called slash-and-burn agriculture, was outlawed after the 1997 fires. (The law, however, is proving hard to enforce, especially in remote regions).

The smoke from the fires was so thick that the Sun was blocked for days and drivers turned on their headlights at noon. Schools and businesses were shut down, and birds fell from the sky. People were advised to wear face masks outdoors in Indonesia, Malaysia, Singapore, the Philippines, and Thailand. Hundreds of people died of respiratory ailments, and tens of thousands were sickened.

In Sumatra, poor visibility in September 1997 was responsible for the crash of an airplane that killed 234 people. The smoke traveled thousands of miles to the west, affecting air quality and visibility on the Maldives, an island group in the Indian Ocean. Crop losses plagued much of the region. In Indonesia and Malaysia millions of people suffered shortages of food and drinking water. The fires carried a price tag of at least 1.3 billion dollars; the damages due to the haze alone tallied another one billion dollars.

Australia was hit by a severe drought in 1997. Cattle ranchers were forced, due to the lack of water and food, to slaughter their herds. In neighboring Papua New Guinea, drought resulted in widespread hunger. By the end of 1997 several hundred people had died as a result of famine and famine-related diseases, and half a million people were in urgent need of food and water.

In the spring of 1998, drought in the United States struck the Southwest and the Southeast. Texas's rainy winter of 1997–98 gave way to its third driest spring on record, in 1998. Accompanying Texas's drought was one of its worst heat waves of the century, claiming thirty lives.

In March, April, and May 1998, drought and wildfires came to Mexico, Central America, and northeast Brazil. Mexico lost more than 1.25 million wooded acres to fire. Smoke from those fires reduced visibility throughout much of Texas and spread haze and soot as far away as Wisconsin, Florida, and Oklahoma.

Due to drought conditions in the spring of 1998, the Rio Grande River in Texas fell to its lowest levels in years. AP IMAGES.

The source of Mexico's fires, like those of Southeast Asia, was a combination of slash-and-burn agriculture and exceedingly dry conditions. Fires also burned out of control in Guatemala, Honduras, El Salvador, Nicaragua, and Costa Rica, leading each of those countries to be declared disaster areas. The fires in Mexico and Central America were finally extinguished in May and June, when El Niño faded and the rains fell.

Floods Rain and snow fell heavily in South America in 1997 and 1998. Ten times the normal amount of rain for the period had fallen in central Chile by mid-August 1997. Floods and mud slides damaged crops, buildings, roads, and bridges. In Chile's Atacama Desert, one of the driest places in the world, heavy rains washed out roads. Rain that drenched the central Andes caused serious flooding in Chile's capital city, Santiago. Paraguay, Uruguay, northeastern Argentina, and southern Brazil also endured heavy rain and sustained damages to buildings and crops.

From November 1997 through May 1998, storms, floods, and mud slides in Peru and neighboring Ecuador claimed 450 lives and did more than three billion dollars in damage to crops, roads, and buildings. Along the coast of Peru storms washed away some 300,000 homes, downed power lines, and destroyed roads and bridges. Waterborne diseases such as cholera and hepatitis, and mosquito-borne diseases such as malaria and dengue fever spread rapidly in coastal Peru.

Peruvian president Alberto Fujimori (pointing, on raft) observes flood damage near Ica, Peru, in 1998. AP IMAGES.

The town of Chato Chico, Peru, was washed away completely. In the Peruvian coastal town of Mampuesto, where floodwaters caused erosion in a cemetery, caskets and skeletons floated down the streets. A similarly macabre event occurred in Peru's third-largest city, Trujillo, where flooding in a cemetery emptied 123 graves and washed the corpses through the town. In the Peruvian Andes severe snowstorms caused the deaths of 2,500 alpacas, a cold-adapted, llama-like species.

In Peru's coastal Sechura Desert, normally so dry that the ground is hard and cracked, floodwaters formed a lake 90 miles (145 kilometers) long, 20 miles (32 kilometers) wide, and 10 feet (3 meters) deep. To ease food shortages, government officials stocked the temporary lake with fish.

California had its seventh-wettest winter of the century. Between December 1997 and March 1998, the state received between two and four times its normal rainfall. The Sierra Nevada mountain range in eastern California had nearly 200 inches (500 centimeters) of snow; in some spots the snowpack in March measured 20 feet (6 meters).

An early December storm caused street flooding in southern California, dumping 6.81 inches (17.30 centimeters) of rain in a 24-hour period. In February 1998 a storm packing 90 mile-per-hour (145 kilometer-per-hour) wind gusts invaded southern and central California. It downed trees

Heavy rains in Southern California damaged the Ventura Pier during El Niño–driven storms in 1997 and 1998. AP IMAGES.

and power lines and produced flooding and mud slides. Waves up to 35 feet (10.7 meters) high pounded the coast. Just south of San Francisco, mud slides on the cliffs of Pacifica washed homes into the bay.

Also due to heavy rains in California, some two thousand cattle were stuck in knee-deep mud and died. The flooding also led to crop losses of strawberries, tomatoes, and lettuce. Agricultural losses were estimated at 200 million dollars.

Seventeen people lost their lives in storms and flooding during the California winter. Total El Niño–related property damages (including agricultural losses) throughout the state ran approximately one billion dollars.

The damage toll would have been far greater had Californians not been preparing for the onslaught of El Niño. Since early 1997, residents had been building dikes to keep back ocean water, clearing flood-control channels, and repairing roofs. In Redondo Beach, for example, high waves washed away the sand barriers built to protect the beach but left the beach intact.

East Africa, which usually suffers from drought during El Niños, was inundated with rain. The rain, which fell from October 1997 through January 1998, drowned crops and led to famine throughout the region. Relief agencies set up soup kitchens in Sudan, Somalia, and Kenya, all hard hit by flooding. In Somalia floods claimed the lives of more than 2,300

Sudanese women sit outside their homes in Khartoum following heavy rains in 1999. AP IMAGES.

people, left 250,000 people homeless, and submerged entire villages. Some 100 people were killed in Kenya due to flooding in January 1998.

People and farm animals in Kenya and Somalia also suffered from mosquito-borne diseases that spread as a result of El Niño's rains. Many farmers lost up to 90 percent of their camels, cows, sheep, and goats to an illness, characterized by severe bleeding, called Rift Valley fever. There was also an outbreak of Rift Valley fever among humans—some eighty-nine thousand people were infected. Although the illness is not usually fatal to humans, it exacted a death toll of two hundred people that season.

A strengthened jet stream (the world's fastest upper-air winds) brought abundant rainfall to much of Europe in May and June of 1997. Southwestern Poland, the Czech Republic, eastern Germany, northeastern Hungary, Romania, and northern Slovakia experienced some of their worst floods of the century. Floods claimed the lives of fifty-five people in Poland and sixty people in the Czech Republic. There was more than two billion dollars in damage in the region. Some 300,000 cattle were lost in the Czech Republic and around one million chickens died when Polish farms were flooded.

Hurricanes and typhoons As predicted for an El Niño year, Atlantic hurricane activity in 1997 was greatly reduced (the hurricane season for the Northern Hemisphere runs from June through December). The only Atlantic hurricane to make landfall in the United States was Hurricane Danny. Danny struck the Gulf Coast in July, bringing high winds and flooding to Louisiana and Alabama. Danny caused four deaths and 100 million dollars in damage.

In contrast, in 1997 there were seven major hurricanes in the Pacific Ocean (those that occur in the western North Pacific are called typhoons). A major hurricane is defined as one that is at least a Category 3 on the Saffir-Simpson scale of hurricane intensity. A category 3 storm does extensive damage and has winds between 111 and 130 miles per hour (179 and 209 kilometers per hour). In an average year the Pacific spawns five major hurricanes.

Hurricane Linda, which lashed Mexico's west coast in mid-September 1997, packed 185 mile-per-hour (298 kilometer-per-hour) winds. By way of comparison, Hurricane Andrew, which did extensive damage to Florida in 1992, had winds of 130 miles (209 kilometers) per hour. Linda—one of the strongest hurricanes ever recorded in the eastern Pacific—was so severe that meteorologists proposed adding a new category, Category 6, to the Saffir-Simpson Scale (the scale presently goes up to 5).

In late September 1997, Hurricane Nora made landfall on Mexico's Baja California peninsula. It then headed north, bringing heavy rains and flooding to Los Angeles and Arizona. Three people were killed in traffic accidents in Los Angeles and San Diego during the storm, and 1,000 people had to evacuate their homes in Arizona.

The following month Mexico's west coast was devastated by Hurricane Pauline. Heavy rains, floods, and mud slides killed as many as 230 people in Acapulco and surrounding areas, and destroyed thousands of homes. Tourists and residents faced shortages of food and drinking water for several days before rescue crews could reach them.

Weather report: El Niño is hardest on the poor

Around the world, poor people bear the brunt of El Niño. One reason for this reality is that it is more difficult for poor people to escape affected areas. Poor people are therefore more likely to suffer, and die, from drought-related famine or flooding-related illness. Poor people often live in flimsy or substandard housing that is vulnerable to floods; slums sustain the greatest damage due to mud slides and coastal flooding. For people who have little or no financial safety net, a loss of one's home or farm means financial ruin. Another factor is that governments often tend first to the needs of their most powerful constituencies—wealthy and middle-class people—while the needs of the poor are overlooked.

During the 1998 El Niño, when northeast Brazil suffered from drought and famine, poor people in that nation fought back against a neglectful government. Hungry crowds, angered at the failure of the government to distribute relief supplies, looted supermarkets and food trucks. Many of the nation's Catholic priests supported the rebellion, claiming that looting is justified when survival is at stake.

Weather report: United States has typical El Niño winter in 1997–98

In general, the winter of 1997–98 in the United States was typical of an El Niño winter. The polar jet stream, which runs over central Canada, ran farther north than usual, through central Canada, keeping cold, polar air out of the northern United States and southern Canada. From Bismarck, North Dakota, to Buffalo, New York, temperatures were between 5 and 10°F (3 and 6°C) higher than normal. One way to gauge the severity of a winter is by looking at heating bills; northerners spent approximately 10 percent less on fuel in the winter of 1997–98 than they do on average.

Also as predicted, a strengthened subtropical jet stream brought increased precipitation and below-normal temperatures to the southern United States. Several southern cities, such as Tampa, Florida; New Orleans, Louisiana; and Charleston, South Carolina, had record rainfall during the winter of 1997–98. The state of Florida recorded its wettest winter ever. The Deep South experienced a rare snowstorm in December 1997. Four-to-eight inches of snow blanketed central Mississippi and central Alabama. Heavy snow also fell on the Southwest and the southern Plains states that month.

Typhoon Winnie whirled across the western Pacific in August 1997, striking the Philippines, Taiwan, and China. Winnie claimed nearly three hundred lives. In early November Typhoon Linda struck the southern tip of Vietnam. Nearly 100,000 homes were lost to the storm's winds and rains. Some three thousand people, most of them fishermen, died in the storm and flooding.

In December 1997, a strong hurricane formed over the El Niño–warmed waters south of Hawaii. Hurricanes rarely form in this region. Typhoon Paka, as it was named, soaked Guam in the southern Mariana Islands on December 16. Winds were measured at 108 miles per hour (174 kilometers per hour) before they destroyed instruments at a weather station on Guam.

Ice storms, tornadoes, and other unusual events In January 1998 southeastern Canada and New England experienced the region's worst ice storm in recent history. (Meteorologists are divided as to whether or not El Niño is to blame for this event.) Freezing rain fell for five days, bringing down trees, power lines, and high-voltage towers in Eastern Ontario, New Brunswick, Nova Scotia, Maine, Vermont, New Hampshire, and upstate New York. At least twenty-five people lost their lives to the storm. Power was lost for more than four million people—including more than half the population of Maine—most of them for over a week. There was more than one billion dollars in damage to homes, businesses, and power systems throughout the region. More than 18 million acres of forestland were damaged in Maine, New Hampshire, Vermont, and upstate New York. The damage cost was estimated at between 650 million and 1.4 billion dollars.

During the unusually warm spring, which was blamed on El Niño, the ice melted and caused flooding through much of central Canada. Around 5,000 people were forced to evacuate their homes as channels overflowed their banks, turning streets into rivers, in Quebec and Ontario provinces.

A pedestrian walks around downed branches and power lines following a severe ice storm in Watertown, New York, in 1998. AP IMAGES.

The southeastern United States experienced a spate of deadly tornadoes in the spring of 1998. On the night of February 22, forty-one people were killed, many as they slept, as tornadoes tore through central Florida. The tornadoes destroyed more than 800 homes and damaged more than 3,500 more, at a cost of more than 500 million dollars. A tornado that struck northeast Georgia on March 20 took twelve lives. On April 8 and 9, a string of tornadoes in Georgia and Alabama left thirty-four people dead and some five thousand acres of forests destroyed.

Dangerous science: What causes an El Niño?

While scientists have made great strides in recent years toward understanding and predicting El Niño, the origins of El Niño remain a mystery. At present, there are three primary theories as to what triggers an El Niño event: undersea volcanic eruptions, sunspots (magnetic storms on the Sun's surface), and the previous El Niño.

The first theory rests on the assumption that eruptions and lava leaks from volcanoes that dot the floor of the eastern Pacific Ocean provide enough heat to put an El Niño in motion. This theory is supported by the large number of earthquakes that have occurred on the ocean floor, west of South America, during recent El Niños. There is a strong link between the occurrence of undersea earthquakes and volcanic eruptions.

The second theory suggests that the ocean warming at the start of an El Niño is connected to the cycle of sunspots. Sunspots are areas of magnetic disturbance on the surface of the Sun, sometimes referred to as storms. When these storms reach maturity they eject plasma—an extremely hot substance made of charged particles—into space. A link has been established between increased sunspot activity and warmer temperatures on Earth. Scientists are attempting to determine whether the amount of warming during increased sunspot activity is sufficient to trigger an El Niño.

The third theory is that El Niños occur in cycles, with each successive El Niño being set in motion by the one before it. The theory goes like this: as an El Niño weakens, it generates long ocean waves, called Rossby waves, that travel westward across the Pacific. The Rossby waves carry with them the warm surface waters. As the warm layer thins in the eastern Pacific, cold water upwells to take its place.

The mass of warm water, driven by westward-blowing trade winds, then piles up in the western Pacific. When the pile of water in the west becomes so steep (up to five feet above mean sea level) that the trade winds can stack it no higher, the water is drawn down by gravity and flows back to the east. The shifting position of the warm waters creates a change in the air pressure gradient, and the trade winds weaken or reverse direction. The next El Niño is underway.

The influence of oceans on global weather As scientists have recently discovered, El Niño is second only to the changing seasons as the strongest factor influencing world weather patterns. The reason for El Niño's strength has to do with the role of oceans in regulating weather, and with the enormous amount of energy contained in El Niño's warm waters.

Oceans cover more than 70 percent of the Earth's surface and are responsible for about one-third of total heat distribution around the planet. It is estimated that the top ten feet (three meters) of the ocean water contains as much heat as the total atmosphere.

The heat that is stored in oceans rises into the air above. The warm, moist air ascends and forms clouds. The water vapor within the clouds condenses and falls to the ground as rain. Therefore, it stands to reason that the world's wettest zones are the regions in which ocean temperatures are highest.

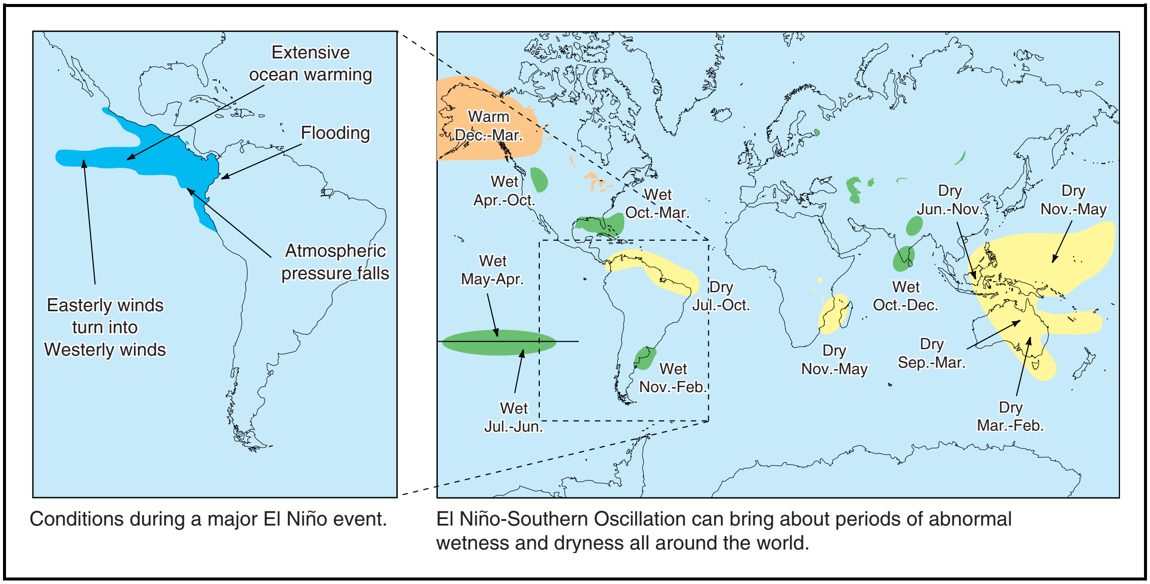
The central Pacific Ocean (near the equator), the world's longest continuous open body of water, is a tremendous storehouse of solar energy. Most of the time, the warmest water is concentrated in a deep layer in the western central Pacific, near eastern Australia and Indonesia. Accordingly, that region has a rainy climate. The waters in the eastern Pacific, off the coast of Peru and Ecuador, are much cooler. With less heat to rise into the air, comparatively little rain falls in that region.

During El Niño, the pool of warm water moves eastward across the Central Pacific. The South American coast receives the heavy rains that typically fall in the western Pacific.

The thermocline Meteorologists (scientists who study weather and climate) explain El Niño as a shift in the thermocline. The thermocline is an imaginary dividing line between warm surface water and the cooler water below in the ocean. Under normal conditions, the thermocline is around 500 feet (150 meters) below the surface in the western Pacific and around 165 feet (50 meters) below the surface in the eastern Pacific. In other words, the warm water extends to a depth of 500 feet in the west and 165 feet in the east. Directly off the coast of Peru, cold water churns up from below and cools the surface water—bringing the thermocline nearly to the surface.

Under El Niño conditions, when the warm surface water heads eastward, the thermocline nearly levels out (it remains slightly lower in the western Pacific than in the eastern Pacific). The layer of warm water off the Peruvian coast is so deep that even water churned up from below is warm.

The trade winds connection In the early 1960s Norwegian-born American meteorologist Jacob Bjerknes (1897–1975) discovered a link between the warming of waters in the eastern Pacific Ocean and a shift in the direction of the major surface winds at the equator, called the trade winds. Trade winds are a class of global winds—winds that bring warm air to cold areas and cold air to warm areas around the planet. Global winds rise and fall and move along the Earth's surface through a series of loops, or cells, on their route from the equator to the poles and back.



El Niño and the Southern Oscillation.

Trade winds originate in the Northern Hemisphere at approximately 30° north (this runs through the southern tip of Florida) and in the Southern Hemisphere at approximately 30° south (this runs through the Amazonian region of South America). At those latitudes air sinks to the surface, warming as it descends, and blows toward the equator. In the Northern Hemisphere trade winds blow to the southwest, and in the Southern Hemisphere trade winds blow to the northwest.

Every so often the trade winds weaken or reverse direction (begin blowing toward the east) in the tropical Pacific Ocean. That change is called the Southern Oscillation (oscillation means shift, swing, or variation). The Southern Oscillation is brought about by a shifting pattern of air pressure between the eastern and western edges of the Pacific Ocean. Air pressure, also known as barometric pressure or atmospheric pressure, is the weight of the air over a given area. Wind flows from areas of high air pressure to areas of low air pressure, in an attempt to equalize conditions.

As it turns out, El Niño and the Southern Oscillation occur at the same time. Years marked by El Niño and the Southern Oscillation are called El Niño/Southern Oscillation, or ENSO, years (they are sometimes called warm-phase ENSO years).

Air pressure and water temperature in normal years and ENSO years During normal years (also called cold-phase ENSO years) air pressure is higher over the eastern Pacific, near South America, and lower over the western Pacific, near Australia. (High pressure is typically associated with clear skies while low pressure is typically associated with cloudy skies and rain.) This pressure gradient (change in air pressure across a horizontal distance) drives the trade winds from east to west, and toward the equator. The winds carry warmth and moisture toward Australia and Indonesia.

At the same time, the winds push along the surface layer of warm water, actually increasing the sea level in the western Pacific. In contrast, the sea level along the coast of tropical South America lowers, and the top layer of warm water thins. Cold water from the depths of the ocean along the South American shores rises to the surface and replaces the warm water. The water in the western Pacific is typically 14°F (8°C) warmer than the water in the eastern Pacific.

Just prior to an ENSO year, the easterly (coming from the east) trade winds weaken and sometimes reverse direction, and the warm waters in the western Pacific begin to move eastward. The warm water flows eastward in a long chain of waves called Kelvin waves. The air pressure in the eastern Pacific decreases, while the air pressure in the western Pacific rises.

The warm water, stretching for a distance of thousands of miles, piles up on the coasts of Peru and Ecuador. The layer of warm water becomes so deep along the South American coast that upwelling, or rising cold water, only brings up warm water (the cold water that normally rises to the surface on the South American coast is too far submerged). As the warm water evaporates into the air and forms clouds, the coastal South American nations experience an excess of rain, which causes flooding and

Experiment: Measuring atmospheric pressure

Changes in air pressure over the Pacific Ocean help bring about the weakened and reversed trade winds that are a hallmark of the ENSO. Scientists use an instrument called a barometer to measure air pressure. To understand how barometers work, try this experiment.

Get a balloon and a clean glass jar with a wide top (such as a mayonnaise jar or a peanut butter jar). Use scissors to cut off the neck of the balloon. Brush some rubber cement or glue around the rim of the jar, and the stretch the balloon over the jar so that you have a nearly flat piece of rubber stretched over and glued to the mouth of the jar. Tape a straw to the top of the balloon so that one end of the straw is in the middle of the mouth of the jar and the straw sits parallel to the floor.

When air pressure goes down, the air in the jar will expand, causing the balloon to swell and the straw to point down. When the air pressure goes up, outside air will expand into the jar. The balloon will get pushed down, and the straw will point up.

Who's who: Jacob Bjerknes and ENSO

Jacob Bjerknes (1897–1975), a Norwegian-born meteorologist teaching at the University of California, Los Angeles, put together the pieces of Sir Gilbert Walker's puzzle in 1969. Bjerknes had earlier gained fame as a meteorologist in Norway by describing the life cycle of storms in the middle latitudes (the regions of the world that lie between the latitudes of 30 degrees north and south, such as the United States and Europe).

Bjerknes became interested in the tropical Pacific during the strong El Niño of 1957–58. That event coincided with the International Geophysical Year (IGY), a year in which scientists the world over cooperated in a study of the earth (with an emphasis on oceans) and space.

As an IGY participant Bjerknes discovered that trade winds, or dominant surface winds near the equator, in the tropical Pacific Ocean weakened at the same time that waters warmed in the eastern Pacific. Soon thereafter he established a link between the arrival of warm waters and the following: heavy rains in South America; drought in the western Pacific; and the air pressure seesaw across the tropical Pacific (the Southern Oscillation). By 1969 Bjerknes had demonstrated conclusively that all these ocean-atmosphere interactions were intricately connected in a single, large-scale phenomenon that he called the El Niño/Southern Oscillation (ENSO).

erosion (removal of soil) while Australia, Indonesia, and the Philippines have unusually dry weather, and sometimes brush fires.

During a strong ENSO, the warm water doesn't stop once it reaches the shores of South America. Instead, it flows northward along the west coast of North America, sometimes as far north as northern Canada and Alaska. The moisture and heat rise from the ocean to the atmosphere, fueling storms that sweep eastward across North America.

Aftermath: The effects of El Niño

With the exception of the changing seasons, El Niño is the single greatest influence upon world weather patterns. El Niño's importance can be understood in terms of the role of oceans in controlling weather and the enormous amount of energy contained in El Niño's warm waters.

Oceans cover more than 70 percent of Earth's surface and are responsible for about one-third of total heat distribution around the planet. It is estimated that the top 10 feet (3 meters) of the ocean water contains as much heat as the entire atmosphere.

The heat that is stored in oceans warms the air just above the ocean's surface. This warm, moist air rises and is blown over land to form clouds. The water vapor within the clouds condenses into droplets and falls to the ground as rain. Because of this process, the world's wettest zones are the regions in which ocean temperatures are highest.

The central Pacific Ocean near the equator, the longest open body of water on Earth, is a tremendous storehouse of heat from the Sun. Most of the time, the warmest water is found in a deep

Who's who: Sir Gilbert Walker and the Southern Oscillation

In the 1920s British mathematician and physicist Sir Gilbert Walker (1868–1958) was the first to point out the connection between unusual weather events around the globe during certain years—now called El Niño years.

Walker began his research in 1903, when he was named head of the Indian Meteorological Service. Walker was charged with predicting when India's annual monsoon rains would fail (drought was a huge, reoccurring problem in India as it led to periodic famine and the starvation of large numbers of people). At that time, weather authorities believed that local factors, such as increased logging in the region's forests, were responsible for monsoon failures.

Walker sifted through local and global weather records, searching for clues that might explain a pattern of monsoon failures. After two decades of research, Walker made an important discovery. He found that in years when Asian monsoons failed, Australia and parts of Africa also experienced droughts.

Walker looked at air pressure readings for Australia (in the western Pacific) and Tahiti (in the eastern Pacific) for a period of several years. He discovered that in years when the monsoon failed, there was a shift in the pressure gradient (change in air pressure across a horizontal distance) across the ocean. Specifically he found that during dry years, pressure in the west was higher than usual and pressure in the east was lower than usual. Walker called this seesaw of the pressure gradient the Southern Oscillation.

Taking things one step further, Walker found a link between increased ocean temperatures and greater precipitation in the eastern Pacific. In reports written in the 1920s and 1930s, Walker provided evidence linking abnormal weather patterns around the world with the Southern Oscillation. He hypothesized that global weather patterns were set in motion by a combination of the Southern Oscillation and a warming of water in the eastern Pacific, but was unable to verify it. The missing ingredient in his equation was data on wind speed and direction across the Pacific. Walker's theory was proven correct in the 1960s, when Jacob Bjerknes collected the necessary information and put the pieces together.

While Walker made important strides toward understanding a global weather phenomenon, he failed in his task to predict monsoon failures in India. Even with today's sophisticated forecasting equipment, scientists are still grappling with that challenge.

layer in the western central Pacific, near Australia and Indonesia. Accordingly, that region has a rainy climate. The waters in the eastern Pacific, off the coast of Peru and Ecuador, are cooler. They put significantly less heat into the air; as a result, comparatively little rain falls in that region.

During El Niño, the pool of warm water moves eastward across the Central Pacific. The result is that the South American coast receives the heavy rains that usually fall in the western Pacific.

Weather report: Shifting air pressure patterns in the North Atlantic

In recent years more attention has been paid to the El Niño/Southern Oscillation's (ENSO) less-famous cousin, the North Atlantic Oscillation (NAO). The NAO is a balancing act between air pressure on the northern and southern reaches of the North Atlantic Ocean. Most years, the prevailing winds (winds blowing in the direction that's observed most often during a given time period) blow from a high-pressure region near the Azores (islands west of Portugal) northward to a low-pressure region near Iceland. From time to time, however, the pressure near Iceland declines. In the early years of the twenty-first century the pressure gradient appears to be weakening, which may indicate warmer summers and colder winters in Europe. However, long-term changes in the NAO indices are hard to predict and the winds weaken—this phenomenon is called an NAO event.

A normal pressure gradient has prevailed since the mid 1970s. The winter weather associated with this pattern is that Europe stays relatively warm while Canada stays relatively cold. When there is an NAO event, however, winter conditions cool down in Europe and warm up in Canada.

Through extensive research into the ENSO phenomena, scientists have determined that ENSO occurs every three to seven years. Understanding of NAO, in contrast, is still in its infancy and the phenomenon's period has yet to be discerned.

Effects of El Niño on the United States and Canada In the United States and Canada, El Niño is one factor among many that determines the weather. The effects of any given El Niño depend on the strength of the event, particularly the way in which it affects the positions of the jet streams.

El Niño's influence on the weather is always greatest in the winter. Winter is when El Niño reaches its most mature stage in the Northern Hemisphere. Winter is also when contrasts in temperatures between the north and south of North America are greatest, and when the jet streams are strongest. The following is a list of general weather trends observed during strong and weak El Niño episodes.

During a strong El Niño, the subtropical jet stream (over Mexico and the southern United States) strengthens over the southern United States, and sometimes merges with the polar jet stream. The strong subtropical jet stream can be seen on satellite photos as a band of clouds and moisture moving across Mexico and the southern United States. The jet stream brings greater-than-normal rainfall—and in some cases flash floods, mud slides, and tornadoes—to southern California, the southwestern United States, northern Mexico, and the Gulf Coast.

The jet stream sometimes dips south once it passes the Gulf Coast. If that happens the southeastern U.S. stays dry, sometimes giving way to wildfires, and has colder-than-usual winters.

If the subtropical and polar jet streams merge, the polar jet stream hovers farther south than usual. The polar jet stream acts as a barrier against cold polar air, keeping it to the north. When the jet stream shifts southward, it allows cold air to move farther south than usual. As a result, southern Canada and much of the northern United States experience cold and sometimes wet weather.

If the jet streams don't merge, the polar jet stream heads north to Alaska before heading eastward across central Canada. In that case southern Canada and the northern United States stay relatively warm and dry.

During a mild El Niño, a weaker subtropical jet stream crosses Mexico before swinging north over the southeastern United States. In that case the West Coast and Gulf states stay relatively dry—and often experience wildfires—while the Southeast gets rain and tornadoes.

The polar jet stream during a mild El Niño heads north into Canada on the western edge of the continent, then dips farther south than usual. With this arrangement the Pacific Northwest experiences dry weather, while the states in the Midwest and Northeast, as well as southern Canada, have cold, wet weather, and sometimes flooding.

The warm waters of El Niño also fuel the development of hurricanes in the equatorial eastern Pacific. Occasionally those hurricanes travel north and drench the coast of southern California, then travel eastward to Texas.

Effects of El Niño on Latin America and the Caribbean El Niño's effect is experienced most directly on the west coast of South America, particularly in Peru and Ecuador. There the warming of the water disrupts the fishing-based economy. Under normal conditions, cold water, rich in nutrients, rises up from the depths of the ocean to the surface along the shore. The cold water contains phosphates and nitrates that sustain tiny marine plants called phytoplankton (pronounced FIE-toe-plank-ton). The phytoplankton are eaten by tiny marine animals called zooplankton. The zooplankton, in turn, are food for fish. Under El Niño conditions, warm water replaces the cold water. The warm water holds few nutrients; it is inhospitable to phytoplankton and, as a result, to zooplankton and fish. When the coastal water is warm, large numbers of fish die off or migrate in search of food.

While El Niño spells misfortune for fishermen in Peru and Ecuador, it is a blessing to coastal farmers. The warm water fuels intense storms that irrigate thirsty crops. To those farmers, El Niño years are known as *años de abundancia*—years of abundance. In some years, however, El Niño brings so much rain that flash floods occur, washing away homes and destroying fields.

Farther south, through the western and central portion of the continent—in Chile, Paraguay, and Argentina—El Niño brings excess moisture to normally arid (dry) regions. That precipitation falls in the form of

Exploring: El Niño and the anchovy industry

In the 1950s Peruvian fishermen expanded their anchovy harvesting operations. They sought to exploit markets in the United States and other industrialized nations for fishmeal—ground-up anchovies that are fed to poultry. In 1971 the Peruvian fishing fleet pulled nearly 14.1 million tons (13 million metric tons) of anchovies out of coastal waters, making Peru the world's top fishing nation.

The following year El Niño struck. As warm waters traveled to coastal Peru in 1972 and stayed throughout 1973, the anchovy population was greatly reduced. While the economic effects were felt most strongly by Peruvians, the lack of fishmeal also affected the U.S. poultry industry and other markets around the world. The number of anchovies still has not returned to pre-1972 levels.

rain in the lowlands and snow in the mountains. Water runs down from the mountains and floods low-lying cities. In Chile's Atacama Desert, one of the driest places in the world (it sometimes goes twenty years without a drop of rain), El Niño can bring enough rain to make wildflowers bloom and wash out roads. El Niño also brings heavier-than-usual rainfall to Uruguay and southern Brazil.

During an El Niño, the northeastern portion of Brazil, as well as Central America, the Caribbean, and southern Mexico usually suffer drought. During some El Niños, crop yields in the region are reduced, and the local populace goes hungry. The dry weather also increases the likelihood of forest fires.

The west coast of Mexico, in contrast to the inland portion of the country, experiences storms and Pacific hurricanes fueled by El Niño's warm waters.

Effects of El Niño on Africa, Asia, Australia, and Europe El Niño brings dry conditions—and often droughts and wildfires—to Australia, Southeast Asia, India, and Africa. In recent years, the worst El Niño–induced droughts occurred in Australia, India, Papua New Guinea, southeast Asia, and southern Africa. Wildfires raged out of control in Australia, Indonesia, and Malaysia. El Niño is unpredictable in eastern Africa; it sometimes brings drought and other times flooding. Central and eastern Europe sometimes experience excessively rainy weather during El Niño.

El Niño also spurs on the development of hurricanes in the Pacific Ocean (or cyclones, as they are called in the western Pacific region) and typhoons (another regional word for hurricane) in the Indian Ocean. During El Niño years, hurricanes and tropical storms (storm systems that form in the tropics and are weaker than hurricanes) dump heavy rains throughout much of Asia.

Effects of El Niño on animal life El Niño not only disrupts weather patterns, but it spells disaster for many types of marine life and land animals. As previously explained, the warm waters of El Niño are inhospitable to plankton, which occupy the bottom rung of the food chain. Fish, which feed on plankton, either move to colder waters or starve. (In a normal year there are six to eight million tons of anchovies in Peru's waters, but in an El Niño year there are only three to four million tons).

The repercussions of the lack of fish are felt all the way up the food chain and persist for several years. Marine birds and marine mammals (such as sea lions) that feed on fish throughout the Pacific Ocean face starvation. Populations of animals that prey upon sea birds also decline. The damage to marine life is observed throughout the Pacific region.

The spread of nutrient-poor, warm water is not the only way that El Niño affects animals. Other effects of El Niño imperil animal life in the following ways: river flooding results in the introduction of sediments and contaminants into coastal waters; large ocean waves erode wildlife habitat; and forest fires in drought-plagued regions drive wildlife out of their homes.

A key reference to: How El Niño reaches Africa and India

In 1982–83 southern Africa experienced severe drought, and India's monsoon rains, which usually occur during the summer, never came. While the lack of moisture in both places was blamed on El Niño, scientists have only recently determined the way in which El Niño influences regions beyond the Pacific.

It turns out that at the same time that waters warm off the coast of Peru, a similar warming occurs in the Indian Ocean. That warming triggers a reversal of the pressure gradient (the rate at which air pressure changes with horizontal distance) in the Indian Ocean. The surface winds that typically blow to the northwest, toward the coast of Africa and India, change direction. They blow toward the southeast, bringing warmth and moisture to western Australia and leaving southern Africa and India high and dry.

Sea birds The animals most directly affected by the lack of fish are sea birds, primarily terns and gulls. In El Niño years sea birds in the western Pacific have difficulty finding enough food for themselves and their chicks. One of the biggest die-offs occurred during the 1957–58 El Niño, when some 18 million birds off the coast of Peru perished. Among the hardest-hit species were cormorants, boobies, and pelicans. Twenty-five years later, the 1982–83 El Niño drove away or killed 85 percent of Peru's sea birds. The seventeen million sea birds inhabiting Christmas Island (in the middle of the Pacific) also abandoned their homes at that time.

The 1997–98 El Niño also had a noticeable effect on sea birds. Albatrosses abandoned their nests in the Galápagos Islands in search of colder waters and more abundant fish. Peru's populations of Inca tern, guanay, and red-legged cormorant also suffered declines.

Weather report: El Niño weather around the world

Below is a summary of El Niño–inspired weather patterns around the world. This information presents general trends, not hard-and-fast rules. Weather during El Niño years is influenced by the strength of the event and a host of other factors. The weather in a given location during a particular El Niño may even be the opposite of what is listed below.

- **Increased precipitation and flooding:** Peru, Ecuador, Chile, Paraguay, Argentina, Uruguay, southern Brazil, east-central Africa, central and eastern Europe, western Australia, and eastward from California and Arizona through the southern United States.
- **Drought:** Northeastern Brazil, Central America, the Caribbean, and southern Mexico, Australia (except the west coast), India, southeast Asia, Papua New Guinea, California (during weak El Niño) and southern Africa.
- **Increased hurricane activity:** West coast of Mexico, southern California to Texas, Asia (along the coast of Indian Ocean), and Madagascar.
- **Warmer than usual winter:** Northern United States, western Canada, Alaska, northern Europe, southeast Asia, Japan, North Korea, South Korea, Mongolia, southeast Australia, and southeast Africa.
- **Colder than usual winter:** Southeastern United States.

The brown pelican population in Baja California and the Gulf of California (on Mexico's west coast) dropped to its lowest level in thirty years during the 1997–98 El Niño. In normal years there are between 10,000 and 20,000 nests in the colony. In March and April 1998, researchers found only 280 nests. Just one month later, not a single nest could be found. Biologists expected the pelicans to make a full recovery once the waters cooled and the anchovies, herrings, and sardines returned.

The decline of least terns in California during the El Niño of 1982–83 provides an interesting case study. The fish that terns typically feed on were few in number and small in size. Female terns laid their eggs later than usual, and the eggs were abnormally small. Many females abandoned their nests for lack of food, and many of the chicks that did hatch did not develop properly. Large numbers of the weakened chicks were preyed upon by small hawks called American kestrels.

The California least tern colony did not recover until 1988. The repercussions of the 1982–83 El Niño lasted so long, in part, because least terns do not breed until they are two or three years old. Thus, in 1984 and 1985 the number of breeding terns was smaller than usual.

Sea mammals Populations of sea lions, fur seals, and other sea mammals also decline during El Niño years. Those animals, which live in colonies on the South American coast, on the California coast, and on the Galápagos Islands (west of Ecuador), subsist mainly on anchovies. The scarcity of anchovies (and secondary food sources such as halibut, lantern fish, rockfish, and squid) during El Niño years has the most serious impact on young animals. Seal and sea lion pups go hungry because their mothers spend much more time than usual

Runners on a beach near Lima, Peru, pass several dead Inca terns. Scientists believe that the sea birds died due to a shortage of food. AP IMAGES.

(five to six days, instead of the usual one to two days) seeking fish rather than nursing their young. Pups either starve or grow weak. Many of those pups that survive their first season later prove incapable of finding their own food, and die.

Large numbers of adult sea mammals also starve during El Niño years. Many females are unable to sustain themselves, particularly while nursing. Males are adversely affected by their breeding behaviors. They stay on land defending their territory during breeding season, typically going without food for several weeks. Once the males return to sea, they are unable to find sufficient food to regain their strength and survive.

During the 1982–83 El Niño, 90 percent of the fur seal pups in Peru died. In the same season, more than half of the elephant seal pups in California were lost due to storms that flooded pupping beaches (beaches where seals are born).

Seals in colonies on the California cost were especially hard hit during the 1997–98 El Niño. More than six thousand pups from a colony on San Miguel Island died by the end of 1997. The mortality rate of the pups reached 70 percent; in normal years just 25 percent of the young animals die.

Sea mammals were in such distress in 1997 and 1998 that animal rescue groups set up stations on California beaches. Members of these groups fed and cared for mammals they found stranded on beaches and sandbars. When the animals were well, rescuers released them back into the ocean.

At El Niño's peak in early 1998, water temperatures off Peru's Paracas Peninsula, normally 56 to 58°F (13 to 14°C), rose to 81 to 83°F (27 to 28°C). The results of this extreme warming could be witnessed in the thousands of sea lion and seal carcasses littering South America beaches from Chile to Ecuador.

Even the sea mammals as far away as Antarctica do not escape the grip of El Niño. The icy continent's weddell seal population declines significantly during El Niño years.

The 1982–83 El Niño

The El Niño of 1982 and 1983 was the second strongest El Niño in recorded history (second only to the 1998–99 event). The Southern Oscillation (shift in air pressure across the Pacific) was so great that the trade winds not only weakened, they reversed. Storms took the lives of more than 2,000 people and caused between thirteen and fifteen billion dollars in damage worldwide. El Niño brought about devastating droughts, floods, and storms in every continent except Antarctica.

Hawaii, Mexico, northeastern Brazil, southern Africa, the Philippines, India, Australia, and Indonesia all experienced droughts—some had brush fires and dust storms. Australia was hit with its worst drought ever. A dust storm swept more than 100,000 tons of soil from farmland into coastal cities and the ocean, and 60 percent of Australian farms experienced crop loss. Bush fires killed 72 people and more than 300,000 livestock.

Meanwhile, extensive flooding plagued the southwestern United States, the Gulf states, Cuba, Ecuador, Peru, and Bolivia. Five hurricanes pounded the islands of French Polynesia, and one hurricane blew through Hawaii.

The damage toll due to El Niño in Peru, Chile, Ecuador, Bolivia, and Colombia reached six billion dollars. Peru had its greatest rainfall in recorded history; some areas received sixty times more rain than normal. There were mud slides and flooding in the north and a drought in the south. The coastal town of Chulliyachi, in northwest Peru, was wiped off the map. Twenty-foot (six-meter) waves washed away the town church (it remains submerged along the coast today) and three residential blocks, and turned roads into rivers.

Galápagos Islands iguanas and penguins Another casualty of the warm El Niño waters is green algae. Green algae, which thrives in cold water, is the main food source of the marine iguana, a 39-inch-long reptile that lives on the Galápagos Islands. When the water warms, the green algae become stunted and covered with brown algae. Brown algae are not digestible by marine iguanas. During the 1982–83 El Niño, as the green algae went into decline, much of the Galápagos marine iguana population was wiped out. In 1998, when the waters warmed by 10°F (5.6°C), marine iguanas suffered again.

The penguins that live on the Galápagos Islands also suffer during El Niño. Galápagos penguins make their homes on several of the islands, including the northernmost islands, which are north of the equator. That makes these flightless birds, which measure twenty to twenty-four inches high and weigh four to five pounds, the sole penguin species naturally occurring in the Northern Hemisphere.

The town's 1,500 residents had to be airlifted to safety.

In Ecuador, El Niño rains caused landslides and washed away roads, bridges, houses, and farm animals. The rains drowned crops and destroyed the main railroad line leading to the capital city, Quito. The flooding in coastal Ecuador and northern Peru killed 600 people, mainly those living in slums.

Damage due to storms in the United States cost more than two billion dollars. A string of violent storms traveled across the west coast of the United States, drenching California and creating mud slides and floods and washing away beaches. More than thirty houses were washed off hillsides, into the ocean. There were also storms and flooding in the Rocky Mountains and the Gulf states. The East Coast had its warmest winter in twenty-five years, at a savings of 500 million dollars in heating bills.

Costs of the 1982-83 El Niño

Droughts/Fires:	
Australia	$2.5B
Southern Africa	$1B
Mexico and Central America	$600M
Indonesia	$500M
Philippines	$450M
Southern Peru, Western Bolivia	$240M
Southern India, Sri Lanka	$150M
Flooding:	
U.S. Gulf States	$1.27B
Ecuador, Northern Peru	$650M
Bolivia	$300M
Cuba	$170M
Hurricanes:	
Hawaii	$230M
Tahiti (French Polynesia)	$50M

The staple of the penguins' diet is small fish, primarily mullet. Those fish are driven away from the islands by warm El Niño waters. Since the nearest land is 600 miles away, penguins are unable to migrate in search of food. During the 1998 El Niño researchers observed skin-and-bones adult penguins and no juveniles—suggesting either that the birds did not breed or, if they did breed, all of the chicks died.

In the aftermath of the El Niños of 1982–83 and 1997–98, the Galápagos penguin population has been reduced to half its 1970 size. At the end of 1998, they numbered less than 8,500.

Secondary effects on land animals El Niño's effects are felt by various species of land animals, namely those that feed upon marine animals and those whose habitats are affected by the changes in weather conditions. An example of a land animal that declines in number during El Niño years is the red fox. Red foxes that live on Round Island, Alaska, subsist mainly on the sea birds that nest there. When the warm waters appear and

Major adverse effects to the population of least terns at Venice Beach, California, existed for five years after the 1982–83 El Niño. ©GEORGE D. LEPP/CORBIS.

the fish disappear, the population of sea birds—especially common murres and black-legged kittiwakes—declines. El Niño's effect on the foxes is evident in their reduced numbers of offspring. In normal years the foxes have up to seven litters, with four or more pups per litter. In El Niño years foxes typically have just one litter of three or four pups.

Some animal species are harmed by drought-induced wildfires during El Niño years. For the animals that inhabit the Indonesian islands of Borneo and Sumatra, the results of the 1997–98 El Niño were disastrous. At least six million acres of rain forest burned, driving out or killing thousands of orangutans and other animals. Across the Pacific in drought-struck Mexico, fires also burned. Those fires destroyed the winter habitat of monarch butterflies. The monarchs either died or made their home elsewhere.

Effects of El Niño on human health Unusual weather produced by El Niño affects the health of human beings in many ways. For instance, hunger is a problem in areas where crops have failed due to drought. Respiratory ailments are common in regions ravaged by forest fires. Many diseases are spread by organisms that reproduce rapidly during El Niño years.

Cholera, dysentery, and typhoid are diseases that commonly spread during floods, when sewage treatment systems become overloaded and drinking water supplies become contaminated. An overabundance of standing water also enhances the breeding of mosquitoes, which carry malaria, dengue fever, yellow fever, and encephalitis (pronounced en-SEF-a-LIE-tus).

During the 1982–83 El Niño, flooding in Ecuador, Bolivia, Colombia, Peru, India, and Sri Lanka resulted in significant outbreaks of malaria. In early 1998, when El Niño–driven rains produced flooding, Peru experienced a malaria epidemic. In the Piura region of northwest Peru, where 1.5 million people reside, there were some 30,000 cases of malaria.

Also in 1983, the unusually mild and moist spring and summer in California gave rise to record numbers of fleas carrying the bubonic plague, an infectious disease that wiped out one-fourth of Europe's population during the Middle Ages (476–1453). Fleas spread the disease to mammals, which can pass on the illness to humans. In 1983, thirty-six people contracted the plague (all in western states), and six of them died. That outbreak was the most severe in the United States since the 1920s.

Warm El Niño waters threaten green algae, the main food source of the marine iguana. ©ROYALTY-FREE/CORBIS.

Another way that El Niño affects human health was discovered in 1993, following the outbreak of a deadly disease in the southwestern United States. The disease, caused by a type of virus called hantavirus, killed several people in the Four Corners region (the place where Arizona, Utah, Colorado, and New Mexico come together).

The hantavirus is carried by desert-dwelling rodents called deer mice. In normal years, the deer mouse population is small. Food for the rodents is in limited supply; and predators, such as owls and snakes, keep deer mouse numbers down. During the 1992 El Niño, however, the desert in the Four Corners region received a lion's share of rain. Plant life exploded, as did the deer mouse population.

Along with the greater numbers of deer mice came greater numbers of deer mouse droppings. People who either touched the droppings or breathed dust contaminated with the droppings risked exposure to the hantavirus. When the rains stopped and the desert returned to its arid state, the hantavirus outbreak subsided.

Did you know: El Niño bleaches coral reefs

Coral reefs, which are undersea ecosystems sometimes referred to as the rain forests of the oceans, are among the most species-rich places on Earth. Coral reefs are colonies of coral polyps (pronounced PALL-ups)—small, tube-shaped animals with hard exterior skeletons coated with colorful algae. The algae, which give the coral reefs the appearance of underwater gardens, are essential to the survival of the polyps.

Coral reefs are found in the warm, shallow waters of tropical oceans and can survive only within a small temperature range. An increase in temperature of just a few degrees can kill the algae. When the algae die, the coral bleaches (turns a whitish color). Bleaching typically leads to the death of a polyp colony.

Many coral reefs were bleached during the 1982–83 El Niño, when eastern Pacific Ocean temperatures increased by 4 to 5°F (2 to 3°C). Some coral species were wiped out entirely. The most extensive damage to coral reefs occurred off the coasts of the Galápagos Islands, Ecuador, Colombia, Panama, and Costa Rica. There the losses to three-hundred-year-old coral reefs ranged from 50 to 97 percent. Scientists estimate that it will take centuries for the corals in those areas to recover.

The bleaching of corals recurred during the 1997–98 El Niño. Significant damage was done to the reefs off the Pacific coasts of Panama, Costa Rica, and Mexico. The warm waters also wiped out an 18-mile (29-kilometer) long coral colony along the Great Barrier Reef of Australia. Varying degrees of bleaching also occurred in coral reefs off the coasts of French Polynesia, Kenya, the Galápagos Islands, the Florida Keys, Baja California, Mexico's Yucatan coast, the Cayman Islands, and the Netherlands Antilles. The corals at most of these sites were expected to recover once the water temperature returned to normal.

During the El Niño of 1997–98, the desert again received exceptional rainfall. With conditions ripe for a deer mouse population increase, the local population was instructed to steer clear of the rodents and their droppings.

The human factor: A possible link between El Niño and global warming

The strongest El Niños on record occurred in the 1980s and 1990s. That reality has prompted scientists to consider whether human activity—namely global warming—has an effect on El Niño.

Average temperatures around the world have risen over the last 100 years. Global warming is the theory that temperatures have begun to rise, and will continue to rise, due to an increase of certain gases, called

Orangutans struggle to survive

The effects of the 1997–98 El Niño pushed orangutans toward possible extinction. Orangutans that survived the wildfires brought about by the El Niño–induced drought in Indonesia faced starvation due to dwindling food sources. Baby orangutans, too weak to hold onto their mothers, reportedly dropped from trees and died. Prior to the wildfires, orangutans were already considered an endangered species (their population had been reduced by forest clearing and hunting).

The 1997–98 El Niño contributed to diminished populations of orangutans in Indonesia. ©W. PERRY CONWAY/ CORBIS.

greenhouse gases, in the atmosphere. Greenhouse gases are gases that trap heat in the atmosphere. The most abundant greenhouse gases are water vapor and carbon dioxide. Others include methane, nitrous oxide, and chlorofluorocarbons. The atmospheric increase of one particular greenhouse gas—carbon dioxide—is believed to be the primary reason for global warming. Carbon dioxide is produced by the burning of fossil fuels. It is emitted by factory smokestacks and cars.

Over the last century, the amount of carbon dioxide released into the atmosphere has increased by 30 percent. During that same time period, the planet has become, on average, slightly more than 1°F (0.5°C) warmer. The warmest year in U.S. history since the keeping of detailed records began in 1895 was 1998. The years 1997 and 1998 were the world's warmest two years of the last century.

The Intergovernmental Panel on Climate Change (IPCC), a group consisting of 2,500 of the world's leading climatologists, believes that the balance of evidence suggests that humans do have an effect on global climate. The question remains: Is that human influence affecting El Niño?

Arguments for and against the global warming connection Scientists were prompted to look at a possible connection between global warming and El Niño when the 1997–98 El Niño showed itself as the strongest episode in recorded history, just two years after the end of a five-year El Niño—the longest episode in recorded history. In addition, the 1997–98 El Niño came just fourteen years after the 1982–83 El Niño—previously the strongest episode on record. According to statistical models, such a sequence would occur naturally just once every two thousand years. That fact suggests that human-induced factors, rather than nature, may be responsible for the pair of unusually strong El Niños.

One theory explaining how global warming and increased El Niño activity are connected is that as the planet warms, heat builds up in the Pacific Ocean. El Niño acts as an escape valve for the excess heat, moving it eastward across the ocean and then releasing it into the atmosphere. Furthermore, computer simulations (computer programs that mimic real-world events) show that increased carbon dioxide levels in the atmosphere lead to an uneven heating of the planet. In the Pacific Ocean, the eastern portion warms to a greater degree than the western portion (exactly the conditions found during El Niño).

While many scientists believe that global warming may affect El Niño, few believe that is the entire reason. El Niño experts point out that huge shifts have occurred in the global climate over the past hundreds of thousands of years, without any human influence such as global warming. Natural variability in climate has ranged from ice ages to warm periods. At certain times in our planet's past, El Niño–like conditions have lasted for thousands of years.

Many scientists refuse to make conclusions about the impact of global warming on El Niño based on one century's worth of data. Those scientists argue that at least another century of careful measurement of El Niños is needed to make such a determination.

Why most scientists won't yet blame global warming While many scientists think that global warming may affect El Niño, few think there is sufficient evidence to be certain. El Niño experts point to the huge shifts that the global climate has experienced over the past hundreds of thousands of years, without the influence of humans. They refuse to make assessments based on spotty data from one century. (Detailed data collection on El Niño around the world only began in 1986.) They suggest that the recent series of unusually strong El Niños may be within normal limits of shifts in global climate.

One reason why it may be too early to blame global warming for increased El Niño activity is that there are many, many influences on global climate, most of them unrelated to human activity. Throughout the Earth's history, the natural variability in climate has ranged from ice ages to warm periods. At certain times in our planet's past, El Niño–like conditions have lasted for thousands of years.

Many members of the scientific community think that at least another century of careful measurement of El Niños is needed to determine whether or not global warming is a factor.

Why are a few degrees of warming such a big deal? You may be wondering why a warming of the ocean of just a few degrees has such a tremendous impact on weather. After all, slight changes in air temperature happen frequently with little consequence. In the case of El Niño, it is the heat contained in a tremendous volume of water (twenty to thirty times as much water as all the Great Lakes combined) that matters. A temperature increase of even 1°F throughout that volume of water results in a significant increase in the heat contained therein.

To understand El Niño's power, it is important to realize that heat and temperature are not the same thing. The difference between heat and temperature has to do with kinetic energy, the energy of motion. As molecules heat up, their kinetic energy increases. Heat is the total kinetic energy of a substance, whereas temperature is the average kinetic energy (also defined as the hotness or coldness) of a substance. In other words, heat takes into account the volume of a substance. If you take two volumes of liquid at the same temperature—say a bathtub and a coffee cup—the bathtub contains more heat.

Just how much kinetic energy does El Niño contain? It contains more energy than can be produced in one year by one million power plants, at 1,000 megawatts each; more energy than all the fossil fuel (gasoline, coal, and natural gas) that has burned in the United States since 1900; and as much energy as 500,000 twenty-megaton hydrogen bombs.

A key reference to: El Niños since 1950

The definition of a strong El Niño event (otherwise called an El Niño), established by the Japanese Meteorological Society and endorsed by the National Center for Atmospheric Research, is that Pacific Ocean temperatures along the equator from Papua New Guinea to the Galápagos Islands must be an average of 1°F (0.5°C) above normal for six months or more. According to that definition, there have been sixteen El Niños since 1950. The El Niños of 1991, 1992, 1993, 1994, and 1995 are separated by brief periods in which ocean temperatures were still above normal, yet less than the required 1°F above normal. Many meteorologists consider these periods to be a single, five-year-long event.

- August 1951–February 1952
- March 1953–November 1953
- April 1957–June 1958
- June 1963–February 1964
- May 1965–June 1966
- September 1968–March 1970
- April 1972–March 1973
- August 1976–March 1977
- July 1977–January 1978
- October 1979–April 1980
- April 1982–July 1983
- August 1986–February 1988
- March 1991–July 1992
- February 1993–September 1993
- June 1994–March 1995
- April 1997–May 1998

Technology connection: Predicting El Niños

Scientists have spent decades unlocking the secrets of El Niño and the Southern Oscillation. Now that a high level of understanding of these phenomena has been achieved, the most pressing task is predicting when they will occur. With advance warning of destructive weather, societies can make preparations to minimize the damage.

Predictions of El Niños remain of a general nature, such as whether conditions will be wetter, drier, colder, or warmer than usual. Crop growing season forecasts issued by international climate prediction agencies state one of the following: near-normal conditions; a weak El Niño with a slightly wetter than normal growing season; a full-blown El Niño with flooding; or cooler than normal waters offshore, with higher than normal chance of drought (in other words, La Niña conditions).

In recent years scientists have developed the tools to make predictions about the development, intensity, and effects of El Niño. They use a combination of computer models and measurements of air and water conditions in the tropical Pacific Ocean. The measurements are taken by a network of weather buoys (drifting or anchored floating objects containing weather instruments) and satellites, supplemented by readings taken on ships. With today's technology, meteorologists (scientists who study weather and climate) at weather prediction centers are able to observe changes in the ocean as they occur.

Computer-based prediction Beginning in the early 1980s, meteorologists have used computer models of climate change (also called climate modeling) in their attempts to predict El Niños. Climate modeling starts with a sophisticated computer program, called a numerical prediction model. The model incorporates mathematical equations that mimic processes in nature. The equations are based on the laws of oceanic and atmospheric physics, describing motion, thermodynamics (the relation of heat and mechanical energy), and the behavior of water.

When a set of data describing current conditions is entered into the computer, the program tells what is likely to happen up to several months in the future. The computer models are constantly fine-tuned based on data from the weather buoys and satellites.

Tropical Ocean-Global Atmosphere (TOGA) In the early 1980s the World Meteorological Organization, a Geneva, Switzerland–based agency of the United Nations, developed an ocean-monitoring system called the Tropical Ocean-Global Atmosphere (TOGA). The stated purpose of TOGA was to explore the predictability of the tropical ocean-atmosphere system and the impact on the global atmospheric climate on time scales of months to years. The development of TOGA was hastened by the strong 1982–83 El Niño, which took place during the planning stages of TOGA.

TOGA was coordinated by the National Oceanic and Atmospheric Administration (NOAA) of the United States and weather agencies of France, Japan, Korea, and Taiwan, with the participation of thirteen other nations. The program operated from 1985 to 1994. During that time TOGA researchers observed interactions between the air and sea in the equatorial Pacific and assessed how those interactions would affect changes in climate around the world.

TOGA used the following equipment to collect information: weather buoys, satellites, ships, and tidal gauges (instruments that measure the

Watch this: "Chasing El Niño"

In 1998, the PBS series NOVA broadcast an episode entitled "Chasing El Niño" that chronicles scientists' attempts to understand the causes of El Niño and make predictions on the magnitude and development of El Niño events. The documentary opens with a look at the Pacific Ocean, which is the largest feature of Earth's surface and has a huge influence on global climate. The program explores the history of El Niño prediction efforts in the Pacific, including the creation of the Tropical Atmosphere Ocean (TAO) array, a massive network of ocean buoys.

"Chasing El Niño" also explores the creation of the massive computer models scientists use to help predict El Niño's intensity. For those with a taste for more hands-on work, meteorologists are shown flying a plane directly into an oncoming storm! The scientists measure rainfall, temperature, wind speed, and air pressure in hopes of forecasting where the storm will fall. "Chasing El Niño" offers an informative and exciting look at the science of predicting one of the world's most mysterious weather effects.

Scientists adjust sensors on a TOGA-TAO buoy.

coming and goings of the tides). These instruments, collectively, measured water temperature at the ocean surface and to a depth of 1,650 feet (500 meters), as well as air temperature, relative humidity, ocean currents, sea level, and the speed and direction of surface winds. All data was transmitted daily, via satellite, to weather prediction centers.

Of the weather buoys, some were drifting and some were moored (anchored to the ocean floor). The drifting buoys, called Global Lagrangian Drifters, emitted signals that indicated their positions, and thus the direction of surface water motion. They also recorded air pressure and temperature of surface ocean water at various locations. The moored buoys measured surface winds and temperatures at various depths of the ocean.

The information collected by TOGA filled in many gaps of knowledge about El Niño's life cycle. The program also established the first means of monitoring the Pacific Ocean and the atmosphere in real time (at the present).

Tropical Atmosphere Ocean Array (TAO) Although the TOGA program ended in 1994, it initiated a permanent, international network of ocean-atmosphere monitoring. That system—which includes moored and drifting buoys, satellites, and research ships—is called the El Niño–Southern Oscillation Monitoring System. The central element of the monitoring system is the Tropical Atmosphere Ocean Array (TAO). Completed in December 1994 as TOGA was coming to an end, the TAO takes continuous ocean measurements. The purpose of the TAO is to detect El Niños in their earliest stages and improve forecasting.

One of TOGA's greatest achievements was the development of the TAO array. The TAO project is jointly coordinated by the NOAA and weather agencies in Japan, Taiwan, and France. Its headquarters are at the NOAA's Pacific Marine Environmental Laboratory (PMEL) in Seattle, Washington.

The TAO array consists of sixty-five moored buoys and five current meters (instruments that measure the strength and direction of currents), spanning the equatorial Pacific—covering one-third of the globe. The buoys and meters are stationed at intervals between longitudes of 135° east (near Indonesia) and 95° west (just west of Peru), and latitudes 10° north and 10° south (forming a wide band with the equator in the center). (Degrees of longitude are imaginary lines encircling Earth, perpendicular to the equator, that tell one's position east or west on the globe; degrees of latitude run parallel to the equator and tell one's position north or south on the globe).

TAO's buoys detect air temperature, surface wind speed and direction, relative humidity, sea surface temperature, and ocean temperature to a depth of 1,650 feet (500 meters). The buoys and current meters transmit information, via NOAA satellites, continuously to TAO project headquarters. The data is fed into high-speed computers and is analyzed, after which it is made available to weather prediction centers and climate researchers around the world.

TAO's computers combine the thousands of continuous readings from the buoys into a single picture. That picture appears on researchers' monitors as a checkerboard with different colored squares. The color of each square indicates the instruments' readings of ocean and atmosphere at a given location. New readings are entered, and the picture is updated several times a day. It is possible to view a series of pictures taken previously, in rapid succession—like a movie of ocean conditions. This technology allows researchers to literally watch El Niños unfold.

ATLAS buoys The TAO array's moored instruments are called ATLAS buoys. At the top of each buoy is a set of sensors measuring wind, humidity, and temperature; a data transmitter; and a satellite antenna. Beneath the floating portion of an ATLAS buoy hangs a 1,722-foot-long (525-meter-long) sensor cable. Temperature sensors are placed at various depths along the length of the cable. The cable ends with a 4,200-pound (1,900-kilogram) anchor.

Exploring: Take a virtual cruise on a research ship

A vital element of the TAO array is the National Oceanic and Atmospheric Association's (NOAA) research ship, the *Ka'imimoana* (means "ocean seeker"). The *Ka'imimoana* performs maintenance on the TAO's weather buoys. Scientists aboard the ship also take measurements of ocean currents, surface water temperature, and ocean temperature to depths of 4,957 feet (1500 meters).

The *Ka'imimoana* was constructed in 1989 and purchased by the NOAA in 1993. After being converted to an oceanic research vessel, the *Ka'imimoana* went into operation in April 1996.

Visit the *Ka'imimoana* home page at http://www.moc.noaa.gov/ka/index.html. There you will see the ship's officers and crew as well as photographs and data from the ship.

If governments are aware that unusual conditions will lead to crop loss or shortages of drinking water, they may stockpile food and water for their residents. Health precautions may be taken in areas where flooding is expected to produce outbreaks of waterborne or mosquito-borne diseases.

Predictions are also useful along the west coasts of South and North America, where high waves and flooding cause damage. If an El Niño is predicted, residents may build barriers to prevent beach erosion and work to reinforce bridges and other structures. At the same time, they may halt new construction projects.

The original ATLAS buoys had a life expectancy of one year, after which they required servicing or replacing. A new generation of ATLAS buoys was introduced in 1996, boasting longer lifetimes and greater measurement capabilities.

What's next for TAO The next phase in the prediction of El Niño will likely involve expanding the TAO array to the Indian Ocean, the tropical Atlantic Ocean, and throughout the northern and southern Pacific. Evidence indicates that climate variability in those regions is linked to El Niño. An NOAA program called the Pilot Research Moored Array (PIRATA) proposes to place buoys across the equatorial Atlantic Ocean early in the twenty-first century.

TOPEX/Poseidon satellite The TOPEX/Poseidon (TOPEX stands for Ocean Topography Experiment) satellite is another key player on the El Niño prediction team. This satellite—a joint project of the U.S. National Aeronautics and Space Agency (NASA) and the French space agency, Centre Nationale d'Etudes Spatiales (National Center of Space Studies)—was launched in 1992.

The TOPEX/Poseidon, orbiting the Earth at a height of 830 miles (1,336 kilometers), uses radar altimeters (instruments that measure altitude by bouncing radar beams off the ocean surface) to measure sea level heights. The measurements are accurate to within a few centimeters. Sea-surface heights are directly related to the heat content of the ocean. A rising sea level in the eastern Pacific is an important clue that an El Niño is underway.

The United States and France put into orbit another oceanographic (pertaining to the study of oceans) satellite in May 2000. The satellite replaced the TOPEX/Poseidon, which has lasted far longer than expected.

The benefits of El Niño prediction Once El Niño has been predicted, the challenge to researchers is how to make that prediction meaningful. The question for many experts is how El Niño predictions can be adapted to the needs of specific industries and people.

The task of making El Niño predictions useful has been assigned to the International Research Institute for Climate Prediction. That institute was established in 1996 at Columbia University's Lamont-Doherty Earth Observatory.

With advance warning of the destructive weather El Niño has in store, societies can make preparations to minimize the damage. El Niño predictions are most valuable to people involved in agriculture and fishing, especially in tropical nations. (The tropics generally suffer the greatest consequences of El Niño's droughts and flooding.) Other areas in which El Niño predictions are useful are public health, transportation, forestry, water resources, and energy production.

Among the countries that have used El Niño predictions to manage agriculture are Peru, Australia, Brazil, Ethiopia, and India. Farmers in these countries consider the expected precipitation levels and temperature when deciding which crops, and how much of each crop, to plant.

An example of the difference an El Niño prediction can make is the improvement in northeastern Brazilian agricultural yields in 1991 over those of 1987. Farmers in the state of Ceara in northeastern Brazil, in a typical year, produce 716,000 tons of rice, beans, and corn. In 1987 the region suffered from an El Niño–related drought, and crop production fell drastically to 110,000 tons. In 1991, in contrast, farmers heeded warnings of an impending El Niño–related drought. Government officials provided seeds that were drought-resistant and had shorter growing seasons, to willing farmers. As a result, 584,000 tons of crops were harvested.

A key reference to: El Niño warning signs

When any of the following trends are recorded by weather buoys or satellites, researchers take note that an El Niño may be brewing:

- The temperature of the surface water increases at progressively eastward locations.
- The water at great depths of the western Pacific cools (in other words, the pool of warm water in the western Pacific grows shallower).
- The air pressure in the western Pacific rises, or the air pressure in the eastern Pacific falls.
- The sea level in the western Pacific falls, or the sea level in the central or eastern Pacific rises.
- The speed of the easterly (from east to west) winds in the eastern Pacific decreases.
- The current, which typically runs from east to northwest, shifts direction.
- The relative humidity (amount of moisture in the air) falls over the western Pacific or rises over the central or eastern Pacific.

Farmers and fishermen in northern Peru made the most of predictions issued in advance of the 1997–98 El Niño. Anticipating heavy rains and the grass that would grow on normally dry land, farmers raised cattle. Farmers also planted rice—a crop that thrives in wet conditions (during dry years, in contrast, farmers may plant cotton—a crop that requires little rain). Fishermen planned for a harvest of shrimp, since those marine animals inhabit the warm waters that El Niño brings.

[*See Also* **Human Influences on Weather and Climate; Weather: An Introduction**]

For More Information

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Flood

A flood is the overflow of water onto normally dry land. Flooding results when the water level rises and overflows the banks of a river or some other low-lying channel, or when high ocean waters wash over the coast. Floods occur frequently in some parts of the world. While for some areas flooding spells disaster, for other areas yearly flooding is necessary to sustain crops.

Floods kill more people than any other weather phenomenon. Flash floods, which are sudden, intense, localized floods, are especially deadly. Worldwide, 40 percent of all deaths from natural disasters are due to floods.

There are two main types of floods: coastal floods and river floods.

Coastal floods

Coastal floods are floods that occur along the coasts of lakes and oceans. This type of flooding is of great concern in many countries because of the high population density along their coastlines. In the United States, for example, almost two-thirds of the U.S. population lives in states along the three major coasts—38 percent along the Atlantic Ocean, 16 percent along the Pacific Ocean coast, and 12 percent along the Gulf of Mexico. According to the National Oceanic and Atmospheric Administration, 53 percent of the U.S. population (153 million people) live in one of the 673 counties bordering the Great Lakes, the Atlantic, the Pacific, or the Gulf of Mexico.

There are two main causes of coastal flooding: high waters and the subsidence, or lowering, of coastal lands.

Hurricanes and tsunamis Most coastal flooding is produced by high waters associated with hurricanes. As a hurricane crosses over land, it produces a storm surge. A storm surge is a several-foot-high wall of water that results in the flooding of 40 to 100 miles (65 to 160 kilometers) of coastline.

WORDS TO KNOW

coastal flood: an overflow of water onto a coastal area caused by a storm surge, strong winds, or tsunami.

flash flood: a sudden rush of water in a low-lying area brought on by heavy rain or a dam break; flash floods can occur when the ground is so saturated with water that no more can soak in, or in desert regions where hard rocky soil is unable to absorb or hold water.

flood: an overflow of water on land that is normally dry.

precipitation: water in any form, such as rain, snow, ice pellets, or hail, that falls to Earth's surface.

river flood: a flood caused when a river spills over its banks.

sinkhole: a natural, steep depression in a land surface caused by collapse of a cavern roof.

stationary front: a boundary between two air masses at different temperatures which are not moving or are moving slowly.

storm surge: an abnormal rise of the sea over and above normal tides and due to strong winds and low pressure accompanying a storm or hurricane.

subsidence: a gradual sinking of the land surface relative to its previous level.

thunderstorm: a storm resulting from strong rising air currents; characterized by heavy rain or hail along with thunder and lightning.

tornado: a violent windstorm characterized by a twisting, funnel-shaped cloud.

tsunami: a huge ocean wave that can travel at speeds up to 600 mph (965 kph) for hundreds of miles over open ocean before it hits land; caused by an earthquake, underwater volcanic eruption, or underwater landslide.

wind wave: a wave caused by the action of wind on the water surface.

Large waves can also cause flooding. The most common type of waves, those driven by the wind, are called wind waves. The largest wind waves are generated by large, stationary storm systems. Wind waves tend to be largest in the open ocean and diminish in height as they approach land. Large wind waves have the greatest potential for flooding when accompanied by high tide.

The largest waves, however, are generated not by the wind but by submarine earthquakes, landslides, and volcanic eruptions. Waves produced by these forces are called tsunamis (tsoo-NAH-meez). Tsunamis start out small and grow larger as they near land. They travel at speeds of up to 600 mph (965 kph). It is typical for a tsunami to measure 60 to 100 feet (18 to 30 meters) in height by the time it reaches the shore.

Tsunamis occur most often in the Pacific Ocean. Several tsunamis have affected Alaska and Hawaii. In 1958, a tsunami over 200 feet (60 meters) in height, generated by a minor earthquake and resultant rock fall into the sea, crashed into Lituya Bay, Alaska. It destroyed great tracts of forest land as far as 1,700 feet (520 meters) above sea level. In December 2004, the deadliest tsunami in recorded history occured not in the Pacific, but in the Indian Ocean. A powerful earthquake triggered a series of tsunamis in Indonesia, Malaysia, and Thailand, killing nearly a quarter million people. Because tsunamis are not common in the Indian Ocean, there was little advance warning for the people of southeast Asia.

On the shelves: *The Epic of Gilgamesh*

The Epic of Gilgamesh is a four-thousand-year-old story about a king from the region that is now Iraq. The story includes a controversial episode concerning a great flood that some historians and theologians say compares to the worldwide flood mentioned in the Bible.

Subsidence Subsidence is the lowering of land in coastal areas. Subsidence may be caused by the gradual settling of subterranean rocks or sediments or by the removal of ground water by excessive pumping. Subsidence may also be rapid. For example, if the roof of a cave collapses, the result is a large depression called a sinkhole. Whatever the cause, subsidence in coastal areas makes them more susceptible to flooding.

Flooded Ohio River snaking through Cincinnati, Ohio, in 1997. AP IMAGES.

The Mississippi River in flood in St. Louis, Missouri, 1993. ©LES STONE/SYGMA/CORBIS.

River floods and flash floods

The banks of rivers and streams overflow due to many causes, including excessive rain, the springtime melting of snow, and blockage of water flow by ice. The failure of a dam or aqueduct is another source of flooding. The primary cause of flooding in large rivers is prolonged heavy precipitation over a large area. Large rivers such as the Mississippi, the Ohio, and the Missouri sometimes flood due to precipitation covering hundreds of square miles. In some areas, flooding occurs nearly every spring when the winter snow melts.

The most dangerous form of river flood is a flash flood. Flash floods are the number one weather-related killer in the United States. Throughout the 1980s, each year flash floods killed an average of 110 people and were responsible for an average of $3 billion in property damage. In the first half of the 1990s, the number of deaths due to flash floods rose to an annual average of 140.

A flash flood can be caused by persistent, torrential rain that falls from a slow-moving or stationary severe thunderstorm, which is itself a result of strong, rising air currents and characterized by thunder and lightning. A flash flood may also be caused by the failure of a dam or levee. A dam is a structure that controls the rate of water flow while a levee is a structure built to prevent water from overflowing the banks of a river.

Watch this: *River Voices: A Portrait of an American River Community*.

In this 2002 documentary, written and directed by Nathan Lorentz, survivors recall both the devastation and the outpouring of community strength caused by the great 1937 Ohio River flood in Portsmouth, Ohio.

Flash floods rise and recede much more quickly than other types of river floods. They are the most dangerous because they come on so fast that people are often unable to reach higher ground in advance of the floodwaters. A series of flash floods in the streams that feed into a large river may result in the flooding of the large river.

Flash floods can be caused by thunderstorms that are either slow-moving or stationary. The reason for their lack of movement is that the high-altitude winds that drive weather systems winds are nearly calm. These storms unleash large quantities of rain over a single area. Thunderstorms that move more quickly spread their rain across larger areas and typically don't produce flash floods.

Boating through a flooded street in Des Moines, Iowa, in 1993. ©REUTERS/BETTMANN/CORBIS.

Weather report: Flash flood alerts and safety procedures

A flash flood watch means that heavy rains may cause flash flooding within the designated area. This is the time to prepare to evacuate to higher ground.

A flash flood warning means that a flash flood has been reported and is imminent for the designated area. In some areas, a warning signal sounds when waters reach critical levels. When a warning is issued, it is imperative to move to safe ground immediately. You may only have seconds or minutes before waters become dangerously high.

If you live in an area that's prone to flash flooding, it's wise to take the following precautions:

- Learn the evacuation routes to higher ground.
- Keep your car's gas tank filled.
- Put together a supply kit for your home containing first aid materials, a battery-powered flashlight, a battery-powered radio, extra batteries, rubber boots, rubber gloves, nonperishable food, a non-electric can opener, and bottled water.
- Install check valves in your home's sewer traps to prevent flood water from backing up and coming in through your drains.
- Once a flash flood watch has been issued, fill your bathtub and large containers with water for drinking and cooking in case your local water source becomes contaminated.

If you encounter a flash flood, the most important thing to remember is to avoid the water. If you are driving, turn around and go the other way. If you are on foot, climb to higher ground. Do not try to walk, swim, or drive through flood water. The water is moving rapidly and carries dangerous debris. You can be knocked over by as little as 6 inches of rushing water. Deeper water can have an undertow that drags you beneath the surface.

If you are in a car during a storm, watch for flooding where the road dips down, under bridges, and in low areas. These are the places that fill with water first. If you see a flooded area, turn the vehicle around and go the other way. Be especially careful at night, when the beginnings of flash floods are harder to recognize.

If your car stalls or becomes blocked, abandon the car and seek higher ground. A car will float away in just 2 feet of water. Then it is at the mercy of the current, which may carry it into deeper water or overturn it in a ditch. Sixty percent of people who die in flash floods are either in a car or are attempting to leave a car that has been stranded in high water.

A flash flood happens when the amount of rainfall exceeds the capacity of the ground to absorb it. In that case, the rainwater runs over the surface, rather than sinking into the ground. The water flows to the lowest point, which is generally a river, stream, or storm sewer. If the quantity of water is greater than the capacity of the drainage channel, the channel overflows within a few minutes and a flash flood occurs.

As the banks overflow, water rushes forward at speeds of up to 20 mph (35 kph). It takes the form of a sediment-laden wall that can surge as high as 30 feet (10 meters). The floodwaters are capable of dislodging large objects weighing several tons, such as boulders, cars, and even locomotives. These objects may be carried several miles downstream. Flash floods are also known to tear out bridges in their path.

Flash floods are more common in mountainous areas. Rain runs down mountainsides and becomes concentrated in canyons and valleys. Arid and urban regions are also prone to flash floods, since very little rain can soak into hard desert surfaces or concrete. Most cities have storm sewer systems that direct water underground to nearby rivers. If the storm sewers become clogged or overwhelmed by the volume of water, the streets quickly become flooded.

Flash flooding may also result from rains associated with a hurricane, a break in a dam or levee, or the springtime melting of large quantities of snow and ice. Flooding may even be caused by a small amount of rain that falls on a blanket of snow. If the ground beneath the snow is frozen, the melting snow and rain will not soak into the ground, but will run off and drain into a river. The likelihood of flooding is increased if ice blocks water from flowing in the river.

Rising flash flood waters in Los Angeles, California, trapped this driver in an intersection, causing him to bail out of his car and jump from hood to hood to reach safety. © BETTMANN/CORBIS.

Did you know? Floods and the spread of disease

Cholera, dysentery, and typhoid are diseases that typically spread during floods, when sewage treatment systems become overloaded and drinking water supplies become contaminated. An abundance of standing water also promotes the breeding of mosquitoes, which may carry malaria, dengue fever, yellow fever, and encephalitis (pronounced en-cef-a-LIE-tis).

In 1982, flooding in Ecuador, Bolivia, Colombia, Peru, India, and Sri Lanka resulted in epidemics of malaria. In early 1998, a malaria outbreak hit Peru because of flooding. In the Piura region of northwest Peru, home to 1.5 million people, there were some thirty thousand cases of the disease.

Historically significant floods

In 1889, a dam break in Johnstown, Pennsylvania, resulted in the worst flash flood in the history of the United States. A wall of water 36 to 40 feet (11 to 12 meters) tall overwhelmed the town, killing over 2,200 people. A second flash flood hit Johnstown in 1977, in which seventy-seven people lost their lives.

The Great Mississippi River Flood of 1927 caused widespread damage over a large area, extending from southern Illinois to the Gulf of Mexico. Flooding began after a year of above-normal precipitation. Water levels along the Mississippi, and rivers flowing into the Mississippi, were already high when 9 inches (22 centimeters) of rain fell on southern Missouri and most of Arkansas in April.

Beginning in April, the river flooded over hundreds of square miles. Levees failed in more than 120 places on the Mississippi and its tributaries. Over twenty-six thousand square miles (seven thousand square kilometers) were flooded

Flash flooding caused the Big Thompson River to swell onto Highway #34 in Loveland, Colorado, in 1976.

across seven states. Six hundred thousand people were forced from their homes and, despite advance warnings, 246 people were killed.

In the summer of 1993, excessive rains caused what is called "The Great Flood of 1993," one of the largest floods in the history of the United States. Water overflowed the banks of the Mississippi and Missouri Rivers, inundating 16,000 square miles (41,000 square kilometers) of land in Iowa, Illinois, Minnesota, Missouri, Wisconsin, South Dakota, Nebraska, and Kansas. The Mississippi River swelled to over 7 miles (11 kilometers) wide in some places. Fifty-six small towns along the river were completely submerged in water.

The flooding was preceded by heavy snowfalls throughout the Midwest in December 1992. The snow melted in March, and then 16 inches (41 centimeters) of rain fell in the upper Mississippi Valley in April. The rains continued through July. In mid-June, a stationary front, which is a slow-moving boundary between two air masses at different temperatures, formed across the upper Midwest and began producing daily thunderstorms.

The water reached record heights at many points along the Mississippi River and more than 60 percent of levees on the river were destroyed. Forty-eight people died. There was $6.5 billion in crop damage, out of a total property damage of $15–20 billion. Eighty-five thousand people were evacuated from their homes. Forty-five thousand homes were damaged or destroyed and 404 counties were declared disaster areas. Counties that are designated "federal disaster areas" are eligible to receive federal disaster aid including low-interest loans.

Another of the worst floods in U.S. history ravaged parts of the Midwest and Southeast in March 1997. The disaster was touched off when a series of severe thunderstorms and tornadoes, violent funnel-shaped windstorms, swept through Arkansas, Tennessee, and Mississippi

Extreme weather: Killer flash floods

One of the most destructive flash floods in recent history occurred in Colorado's Big Thompson Canyon, in the mountains west of Denver, in July 1976. Ten to twelve inches (25 to 30 centimeters) of rain, over half the yearly average rainfall for that location, caused the overflow of the river running through the narrow canyon floor. A wall of water 20 feet (6 meters) high rushed forward, killing at least 139 people. More than 400 houses were destroyed, many roads were washed away, and 197 vehicles were lost in the flood. Approximately one thousand people were rescued by helicopter.

In June 1990, a flash flood occurred in Shadyside, Ohio, when 4 inches (10 centimeters) of rain fell in less than two hours. The resultant 30-foot (9-meter) wall of water killed twenty-six people and caused around $7 million in damages.

Cheyenne, Wyoming, was beset by a flash flood in August 1985, after 6 inches (15 centimeters) of rain fell in three hours. The streets were filled with more than 6 feet (about 2 meters) of water. The flood caused the deaths of twelve people and more than $65 million in damage.

Watch this: *The Johnstown Flood.*

Using archival film and photographs, this documentary recreates the story of the Johnstown flood of 1889. The South Fork Dam burst due to very heavy rains and poor maintenance, sending a wall of water and debris downstream to flood the industrial city of Johnstown, Pennsylvania. The film, written and directed by Charles Guggenheim and released in 1989, won an Academy Award for best documentary, short subject.

and killed at least twenty-five people. Flash floods and gusting winds killed thirty-six more people in Kentucky, Ohio, West Virginia, and Tennessee, bringing the death toll to sixty-one.

Due to the tornadoes, eleven counties in Arkansas were declared federal disaster areas. Due to floods, sixteen counties in Ohio and sixty-three counties in Kentucky were also declared federal disaster areas.

During the floods, occasional heavy rains continued to fall throughout the region, accompanied by melting snow. On a single day, March 1, nearly a foot of rain fell on north-central Kentucky, southern Ohio, and West Virginia. New rainfall records were set in Louisville, Kentucky, on that day. Two days later, up to 9 more inches (23 centimeters) of rain fell on the same area.

As a result, flooding occurred along the Ohio, Missouri, and Mississippi Rivers, as well as on numerous tributaries. Rivers throughout Kentucky rose to record levels. Many river towns in Ohio, Kentucky, Tennessee, and West Virginia were swamped. Thousands of people from

Drawing by W. A. Rogers of the flood at Johnstown, Pennsylvania, 1889.

China's Joy; China's Sorrow

Somewhere between nine hundred thousand and two million five hundred thousand people living in the crowded river valleys perished during the 1887–88 flooding of China's Huàng Hè (Yellow River). This flood was, by far, the most devastating in recorded history.

The Yellow River, nicknamed "China's Sorrow," is one of the world's most flood-prone rivers. Records show that there have been around 1,500 floods on the Huàng Hè over the last 3,500 years, many of which killed large numbers of people.

A park pavilion along the Yellow River in China is flooded. ©BOHEMIAN NOMAD PICTUREMAKERS/CORBIS.

flooded river towns were left homeless. The estimated flood damage in Kentucky was $232 million and in Ohio, $40 million.

According to reports by CNN news on March 7, 1997, Falmouth was one of the hardest-hit areas. The town was built on the banks of the Licking River, a tributary of the Ohio River. When Falmouth residents were allowed to return and survey the damage, they saw extensive damage to their homes and businesses. Houses were moved from their foundations, their walls warped and roofs collapsed. The National Guard had plowed the streets, but a thick layer of brown, gooey mud coated everything else. The *Cincinnati Enquirer* reported on March 2, 1997, on a helicopter flight taken by Kentucky State Police Trooper Jan Wuchner over Falmouth. Wuchner was stunned. His report was short and to the point: "There is no Falmouth."

Did you know? Dams for flood control

The construction of river dams is a common method of storing water and lessening the impact of drought. Dams are also used in flood control. A dam is a barrier that blocks a river and controls the flow of water. When a river is dammed, the water backs up in the area behind the dam, creating an artificial lake or reservoir (pronounced REH-zer-vwar). Pipes carry the water from the reservoir to factories, homes, and farms. This ready supply of water is especially useful during times of drought. By the year 2000, there were more than sixty thousand dams in use worldwide.

Large dams, defined as those that are more than 492 feet (150 meters) high, or holding back more than 19.6 million cubic yards (15 million cubic meters) of water, have a significant impact on the surrounding community and environment. When a dam is constructed in a valley, it floods the area upstream, putting homes, farmland, and even whole villages underwater. In the process, it displaces the people who inhabit the area. Dams also disrupt a river's natural cycle of flooding. When a river floods a valley, it deposits a layer of silt that enriches the soil. After the river is dammed, the fertile soil is lost. (The soil upstream is buried beneath the reservoir, and the soil downstream remains exposed but becomes less fertile over time.) Dams also disrupt the balance of the river ecosystem, destroying the habitat of birds, fish, and other animals, as well as many species of plants.

Recent devastating floods

In July 2006, news media reported that floods in North Korea caused at least hundreds and maybe even thousands of deaths and left many more people homeless. Since North Korea is a closed country that tightly controls information, exact figures on losses of life and property are hard to determine. But the United Nations Food Agency reported sixty thousand homeless, seven thousand homes destroyed or damaged, and almost forty thousand acres (sixteen thousand hectares) of farmland washed away. One indication of the size of the disaster is that the government of North Korea cancelled the Arirang Festival of dance and mass gymnastics, which is a major tourist attraction and a key source of income for the nation. North Korea also closed its border to tourists from China, another major source of income.

China also suffered disastrous floods from at least eight typhoons during the storm season of 2006. On August 10, 2006, Typhoon Saomai struck China's southeast coast with winds of 170 mph (270 kph). It was the most powerful typhoon to hit China in fifty years. The storm sank over one thousand ships and destroyed or damaged at least fifty thousand houses. More than 1.6 million people fled their homes to avoid the storm and at least 399,999 acres (122,000 hectares) were flooded. Saomai was the second major typhoon to strike China that same month. The government reported that prior to Saomai, economic losses in China already exceeded $9.4 billion.

India has also suffered severe flooding. In 2005, the Indian state of Maharashtra, which includes Mumbai (formerly Bombay), experienced floods that caused the deaths of at least one thousand people. The flooding was caused by the eighth heaviest rainfall ever recorded within a twenty-four-hour period. Then, during July 25 and 26, 2006, 37.2 inches (944 mm) of rain fell. Heavy rains continued over the next few days and forced the closing of schools in Mumbai and surrounding areas.

Later that summer, widespread flooding due to the summer monsoon (seasonal rains caused by shifts in prevailing winds) displaced at least 4.5 million people in the states of Orissa and Gujarat. Rajasthan also suffered unusually heavy flooding due to monsoon rains, with over eight hundred thousand people affected and tens of thousands displaced.

Floods in popular music

There have been many songs written about great floods. Some of the songs have become classics of popular music. The song by Randy Newman, "Louisiana 1927," is a heavily sarcastic and fictional account of the government's response to the Great Mississippi River Flood of 1927. It has been recorded many times by different performers. "Requiem" is a song by Eliza Gilkyson that she composed in response to the floods from the Indian Ocean tsunami of 2004. Both of these songs were played often on many radio stations after the floods in New Orleans and other parts of the Gulf Coast caused by Hurricane Katrina.

After the flood waters that devastated the Gulf Coast in 2005 receded, many other performers and songwriters performed or composed songs in response to the tragedy. An unprecedented number of New Orleans tribute records and benefit concerts appeared, with pop stars such as Norah Jones, Prince, and the Dixie Chicks, among others, trying to help. Many of New Orleans's musicians and songwriters have also composed responses to the storm. Allen Toussaint teamed with Elvis Costello to create *The River In Reverse.* New Orleans native Dr. John's jazz offering was *Sippiana Hericane.* It included the heart-wrenching song and plea "Clean Water."

Flooding and climate change

In any given week, a river flood or other flood is certain to be happening somewhere in the world. However, in recent years floods seem to be getting more severe. According to the World Meteorological Organization, floods affected 1.5 billion people in the last decade of the twentieth century alone.

While climate researchers and other scientists have not come to universal agreement on whether there is a direct link between short-term extreme weather and long-term climate change, many of the weather patterns observed are similar to those predicted by models of climate change. For example, the landmark Second Assessment Report (AR2) published in 1995 by the United Nations Intergovernmental Panel on Climate Change (IPCC), predicted that global warming would leave southern China drenched with more rains, while the north and west of the country would suffer

Extreme weather: The Grand Forks flood of 1997

In April 1997 entire towns were submerged in floodwaters when the Red River, which runs between North Dakota and Minnesota, overflowed its banks. The floods took seven lives in North Dakota and four in Minnesota. In North Dakota about ninety thousand head of livestock died. Property damages throughout the Red River Valley (the areas of North Dakota and Minnesota along the banks of the Red River) totaled $3 billion. Most of the destruction occurred in Grand Forks, North Dakota, 90 percent of which was flooded.

Floods for the region had been predicted as early as February because of the several heavy snowstorms that took place that winter. In North Dakota, houses were buried up to their roofs in snow. In March the snow began to melt and, as predicted, the rivers overflowed.

Submerged cars in downtown East Grand Forks, Minnesota, after the nearby Red River overflowed in 1997. AP IMAGES.

worsening droughts. This is very similar to the observed pattern, with droughts in the northern provinces and floods in the south.

In any case, the main cause of loss of life and damage to property due to flooding is the tendency of humans to build homes and other structures near water. For thousands of years, humans have depended on rivers for food, for transportation, for reliable sources of drinking water, and for water used in agriculture. Similarly, the oceans have long been an important food source. While many people do need to live and work near the water, the continued building of homes and recreational housing in flood-prone areas will only make the problems of damage and loss of life more difficult to control.

[*See Also* **Climate Change and Global Warming; Human Influences on Weather and Climate; Hurricane; Local Winds; Thunderstorm; Tsunami; Weather: An Introduction**]

For More Information

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Fog

Fog is a cloud that forms near the ground. Like clouds at higher altitudes, fog is formed when water vapor condenses in the air so that the moisture becomes visible. The process of water turning from vapor into liquid is called condensation. In temperate regions, fog is composed of water droplets. In polar and arctic regions, fog may be composed of ice crystals. Technically, fog is defined as condensation in the air that restricts visibility to a bit more than 0.5 mile (1.0 kilometer). If water has condensed in the low-lying air, yet visibility is greater than 0.5 mile (1.0 kilometer), the condition is defined as mist.

Fog production differs from cloud production in one significant way: While a cloud is usually formed as air rises and cools to the dew point (the temperature at which a parcel of air can no longer hold water in its vapor state), fog is formed within surface-level air. This happens in one of two ways. The air may be cooled to the dew point by contact with a cold surface. Or it is brought to the saturation point, the point at which it contains the maximum amount of water, when water vapor is added to the air by evaporation, the process by which water changes from a liquid to a gas.

On clear nights, surfaces that are open to the sky often cool faster than the air above them. When condensation takes place directly on these cooler surfaces due to contact between warmer air and the cooler surface, it is called dew or frost. Fog, on the other hand, is condensation in the air due to the air cooling below the dew point.

Radiation fog

Radiation fog is the fog that forms after sunset on clear summer nights when the air is almost, but not quite, still. The ground loses heat to space by radiation and cools to below air temperature. The cooler ground then conducts heat away from the layer of air just above the ground. This layer

A northern Ohio highway is partially immersed in a thin layer of radiation fog just after sunrise. FMA, INC.

of air is cooled to below the dew point and fog forms. The fog layer can be anywhere from a few feet (around 1 meter) to a thousand feet (around 300 meters) thick. The layer of air above the fog layer is warmer, so the fog layer is stable, at least until the sun rises and warms the ground again.

A light wind of less than 5 miles (8 kilometers) per hour promotes the circulation of the lowest layer of air, bringing all of it in contact with the cold surface. In this way the entire layer of air loses heat and cools to the dew point. If the winds are completely calm, only the very bottom of the surface air layer will come in contact with the ground. In that case, rather than producing radiation fog, moisture will either condense in a very shallow (less than 2 feet, or .6 meter) layer of air, forming ground fog, or it will condense only on the ground and form dew or frost.

Winds also hinder the formation of radiation fog. Winds stronger than 5 miles (8 kilometers) per hour will cause mixing of surface air with warmer, drier layers of air above it. This either prevents the surface air from cooling to the dew point or, if the air does reach the dew point and fog develops, the wind rapidly disperses the fog.

Valley fog is radiation fog that forms in valleys. It may develop into a layer over 1,500 feet (450 meters) thick. Radiation fog forms in low-lying areas because of two factors. In the first place, cold air (in this case, air that has undergone radiational cooling) is heavier than warm air and flows

Ground fog in the early evening hours. FMA, INC.

downward into the valley. In addition, valleys often contain rivers which increase the amount of moisture in low-lying air.

In most cases, radiation fog evaporates within a few hours after sunrise, after the air and ground have warmed up. It typically reveals clear skies, since the absence of clouds was required for the formation of fog. Sometimes, however, the fog is so thick that it effectively blocks the sunlight from reaching the ground, and the ground remains cold. In such cases, which usually occur in winter, the fog may persist all day.

Radiation fog is most likely to form during long nights, when the surface air has more time to cool to its dew point. Thus, this type of fog is seen most often during winter, late fall, and early spring. Visibility in thick radiation fog may be reduced to as little as 10 feet (3 meters).

Advection fog

In contrast to radiation fog, in which a layer of air is cooled as the ground loses heat, advection fog is formed when there is horizontal movement of a warm, moist layer of air over a cold surface. The newly arrived air loses heat to the cold surface below by conduction, the process by which energy is transferred through contact between substances. Conduction lowers the air temperature. Once the air cools to the dew point, fog is formed. While it bears a resemblance to radiation fog, advection fog moves with the wind-blown warm air mass whereas radiation fog is stationary. In

Experiment: Make fog in a jar

This simple experiment allows you to create fog conditions inside a glass jar. All you need for this experiment are:

- a glass jar
- strainer
- hot water
- ice cubes

First, fill up the jar with hot water and let it sit for about a minute. Then pour most of the water out, leaving about a finger's width at the bottom. Put the strainer over the top of the jar and place ice cubes on the strainer. In a little while, you will see fog in the jar. This is caused by the cold air from the ice cubes hitting the warm, moist air in the jar causing the water to condense into fog.

addition, while radiation fog usually forms at night, advection fog may form at any time.

In the spring, advection fog results when a mild breeze passes over ground that has not yet thawed. Throughout the summer, advection fog is produced by warm, moist air blowing across a lake that remains cold, such as one of the Great Lakes.

Another kind of advection fog happens in the winter, when warm air is carried northward. When this warm air encounters cold ground, it cools to the dew point and advection fog results. For instance, warm air from over the Gulf of Mexico may travel as far as the central United States before encountering a sufficiently cold surface for advection fog to form.

Advection fog is the thickest and most persistent type of fog. It sometimes reduces visibility to 650 feet (200 meters), the point at which airports are forced to close. Advection fog can form in layers that range anywhere from very shallow to 1,000 feet (300 meters) deep.

Valley fog in the rolling terrain of western Wisconsin. FMA, INC.

WORDS TO KNOW

advection: the horizontal movement of a mass such as air or an ocean current.

condensation: the process by which water changes from a gas to a liquid.

conduction: the transfer of heat from one molecule to another.

dew point: the temperature at which a given parcel of air reaches its saturation point and can no longer hold water in the vapor state.

evaporation: the process by which water changes from a liquid to a gas.

radiational cooling: the loss of heat from the ground upward into the atmosphere.

relative humidity: a measure of humidity as a percentage of the total moisture a given volume of air, at a particular temparature, can hold.

saturation point: the point at which a given volume of air contains the maximum possible amount of water vapor.

supercooled water: water that remains in a liquid state below the freezing point.

Sea fog

Sea fog is a special form of advection fog that only occurs at sea and in coastal areas. It is produced by the interaction of two adjacent ocean currents, the major routes through which ocean water travels, of different temperatures. A prime example of sea fog occurs in the Atlantic Ocean off the coast of Newfoundland, in Canada. There the warm Gulf Stream flows northward, parallel to the cold, southward-flowing Labrador Current. When the air that is warmed by the Gulf Stream travels over the iceberg-filled Labrador Current, it is cooled and moisture condenses, forming fog. For two out of every three summer days, the coastal region off Newfoundland is shrouded by the famous "Grand Banks fog."

This process is also responsible for the thick fog that is common in parts of the British Isles. In that case, the warm air comes from above the Gulf Stream and blows across cooler British coastal waters.

Sea fog is also well-known to the residents of San Francisco, California, and other West Coast communities. It forms in the summer when warm air from over the Pacific Ocean is carried shoreward by westerly winds. As the air moves over the colder, coastal surface water, the air cools and fog forms. The fog is then blown inland by a sea breeze. This explains the fog that can often be seen rolling in past the Golden Gate Bridge on a

Weather report: Smothered by sea fog

The town of Argentia, situated on the Avalon Peninsula of southeastern Newfoundland, averages 206 days per year of thick fog. This makes it the foggiest place in Canada and among the foggiest places in the world. Argentia's fog is sea fog, generated by the passage of warm air over cold North Atlantic ocean water.

A similar process produces the fog at Cape Disappointment, Washington, one of the foggiest places in the United States. Cape Disappointment is situated at the point where the Columbia River flows into the Pacific Ocean. It is blanketed by sea fog 29 percent of the time, or about 106 days each year.

breezy summer day. Conversely, if a land breeze is blowing out to sea, it will take the fog out with it.

As sea fog moves farther inland, it crosses over warmer ground and dissipates. The bottom of the fog layer evaporates first, revealing a low layer of gray clouds. As the surface temperature increases, ever-higher layers of the fog evaporate until it has completely disappeared. Fog also dissipates at a given location as the air becomes progressively warmer throughout the day. For this reason, coastal areas often have fog in the morning and at night, with clear skies in the afternoon.

Sea fog is extremely important to the vegetation of northern coastal California. Throughout the dry summers, the fog condenses on objects in its path. It provides moisture to the redwood trees; the redwoods absorb moisture through their needles. Some water drips off the trees and onto the ground, where it is absorbed by the trees' shallow roots.

Evaporation fog

Evaporation fog is formed in a completely different manner than the other types of fog discussed so far. Rather than being formed when warm air cools to the dew point, evaporation fog is formed when water evaporates into cool air and brings that cool air to its saturation point. The water may evaporate from a wide range of sources, such as a puddle, a lake, a river, an ocean, or even exhaled breath.

The reason why water molecules evaporate into unsaturated air (air which has less than 100 percent relative humidity) has to do with equilibrium. Water molecules are continually entering and leaving the surface of a body of water. If the relative humidity is less than 100 percent, water molecules will leave the surface faster than they enter. Thus the number of water molecules in the air will increase. At 100 percent relative humidity, the rates of entering and leaving are equal. The water vapor in the air is at equilibrium with the liquid water.

Steam fog rises from Lake Michigan on a sub-zero January morning. FMA, INC.

There are two main types of evaporation fog: steam fog, which occurs over a body of water, and frontal fog, which accompanies the passage of a cold or a warm front (the line behind which a cold or a warm air mass is advancing).

Steam fog The production of steam fog requires cold air to travel over a warmer body of water. Steam fog can often be seen over inland lakes and rivers in the fall, when the air is cool but the water is still warm. Water evaporates from the lake or river, saturates the cold air, and condenses into a shallow (less than 2 feet, or .6 meter) layer of steam fog.

Steam fog occurs all year long over the thermal ponds (hot springs) in Yellowstone National Park. The reason for this pattern is that the temperature of the water is always greater than that of the air. In the winter, it is common to see steam fog over large bodies of water, such as the Great Lakes, which can take several weeks to cool to air temperature. The fog there sometimes forms in dense, rising, swirling columns known as steam devils, because of their similarity to dust devils in the American Southwest.

In arctic regions, where the air is always extremely cold and dry, steam fog occurs over unfrozen waters on a large scale. Commonly called arctic sea smoke, this form of steam fog is patchy and wispy in appearance.

Did you know? Driving in fog

Most people, when driving along poorly lit roads at night or in other conditions of reduced visibility, instinctively turn on their high-beam headlights. However, this is not a wise strategy for driving in fog. Light is scattered by fog droplets and is reflected into the driver's eyes. High-beam lights merely illuminate the fog directly ahead of the vehicle and make it difficult to see anything beyond. Close to the ground, the fog is usually less dense. Low-beam headlights point lower toward the ground than do high-beam headlights and are thus more appropriate for foggy, nighttime driving. Fog lamps are often installed just above or below the front bumper. This low mounting position reduces the amount of light scattered back to the driver's eyes.

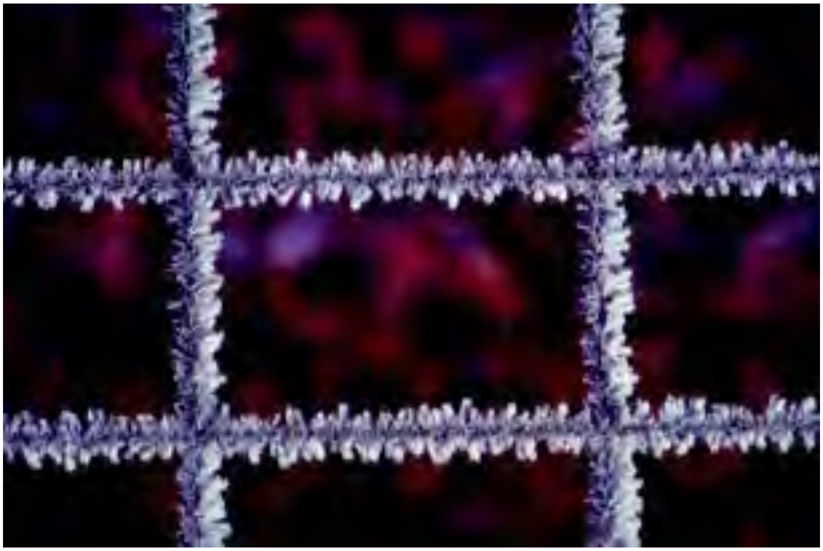
Frontal fog Frontal fog, sometimes called precipitation fog, is a type of evaporation fog that forms when a layer of warm air rises over a shallow layer of colder surface air. The uplift of warm air forms clouds that often yield precipitation, or falling water particles. The precipitation, usually rain, is warmer than the cold air beneath it and evaporates into the air. This raises the cold air to its saturation point and fog is produced.

This type of fog is called frontal fog because the conditions that give rise to it occur just before the arrival of a warm front or just after the passage of a cold front.

Upslope fog

Upslope fog is formed by the slow passage of a moist parcel of air up the side of a hill or mountain. As the air rises, it expands adiabatically; that is, with no heat transfer. When air expands, it cools. Once the air cools to the dew point, condensation occurs. Upslope fog generally covers a large area, sometimes hundreds of miles, and may persist for days.

Ragged patches of upslope fog form as moist air moves up a forested mountain slope. FMA, INC.



Rime ice covers fence wires after a cold fog. COURTESY WALTER A. LYONS.

Upslope fog is common in all mountain ranges. It is prevalent on the eastern slopes of the Rocky Mountains in the winter and spring. It occurs when cold air, following in the wake of a cold front, drifts westward from the Great Plains and rides up the gentle slopes. A similar phenomenon occurs in eastern Australia. There, moist air from the Tasman Sea is blown to shore and travels along the eastern slopes of the Great Dividing Range to a level where fog forms.

Freezing fog

Freezing fog is the term used to describe fog that develops in air that has a temperature below freezing. In most cases, freezing fog is comprised of supercooled water droplets. Supercooled water is water that exists in the liquid state below its freezing point. Freezing fog freezes onto any solid surface it comes in contact with, such as trees, telephone poles, cars, and roadways.

When freezing fog encounters a surface, it deposits a layer of frost called rime. Rime is not crystalline like true frost, which is called hoar frost. Rather, it is ice that contains trapped air, giving it a whitish appearance. Rime often persists long after the fog has cleared. It creates extremely hazardous driving conditions and is nearly impossible to walk on without slipping.

A dense winter fog stratus. FMA, INC.

In very cold air, at temperatures below –22°F (–30°C), water droplets in freezing fog will freeze into ice crystals, becoming ice fog. One way in which ice fog is formed is from the water vapor released by the breathing of a herd of caribou or reindeer. Another way it is formed is from the passage of moist, marine air over an icy surface. Ice fog is the least dense type of fog. It glitters in the sun, earning it the nickname diamond dust.

Fog stratus

Fog stratus, also called high fog, is a layer of fog that does not reach all the way to the ground. Rather, it hovers a short distance above ground. Fog stratus represents the intermediate stage through which a layer of fog (most commonly valley fog) passes as it dissipates.

Typically, fog forms at night. When the sun rises the next morning it begins to warm the ground. This, in turn, warms the lowest layer of air, from which the fog evaporates.

Sometimes the process of fog evaporation proceeds smoothly, from the bottom to the top of the layer, in a relatively short time. Other times, however, the fog is so thick that little sunlight penetrates it, and the air remains cold enough that fog stratus persists. Fog stratus also requires calm conditions, since winds promote mixing of the air layers and speed up evaporation.

Fog stratus usually clears by late morning. Occasionally, however, when clouds have moved in and inhibit the sunlight's warming of the ground, fog stratus may persist all day. A thick enough layer of fog stratus may even bring drizzle or snow flurries.

[*See Also* **Clouds; Weather: An Introduction**]

For More Information

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Hurricane

When Katrina struck the coasts of Louisiana and Mississippi on August 20, 2005, it reminded us that hurricanes certainly deserve the title "greatest storms on Earth." No other storm system has the power of a hurricane. To get a sense of the power contained in a hurricane, consider the following: 1) Just 1 percent of the energy in an average hurricane could supply the entire United States with electric power for one year; and 2) the energy unleashed by a hurricane in one day is equal to the energy of four hundred 20-megaton hydrogen bombs.

Hurricanes that strike populated areas are among the deadliest and most destructive of all natural disasters. A single strong hurricane can kill hundreds or thousands of people. Fortunately, the number of deaths caused by hurricanes has declined greatly in recent years (particularly in the United States) due to the development of early detection systems. Historically, hurricanes have been directly responsible for an average of 162 deaths per year. However, this includes the Galveston, Texas, hurricane of 1900 in which 6,000 people lost their lives. Since 1965, hurricanes have accounted for about 20 to 30 deaths per year in the United States.

Population growth and the construction of vacation and retirement homes in hurricane-prone areas raise the risk of increased losses from property damage. However, the cost of property damage from hurricanes has not shown a steady increase. According to information from the National Oceanic and Atmospheric Administration (NOAA) the increase is very slight in inflation-adjusted dollars from 1971 to 2000. In 1992, there was a loss of nearly forty billion in inflation-adjusted dollars. If this spike is not included, the cost of property damage would show a slight decrease. On the other hand there were huge property losses in 2004 and 2005. When these numbers are included, property damage losses from 1971 to 2006 show a slight but definite upward trend. However, it is not a steady increase, since some years are high and some are low.

The word "hurricane" is used to refer to tropical cyclones that form in the northern Atlantic Ocean or in the eastern Pacific Ocean off the coasts of Mexico and Central America. A tropical cyclone is any rotating weather system that forms over tropical waters, which are within the area of 23.5° north latitude and 23.5° south latitude. Hurricanes that occur in the western North Pacific and China Sea region are called "typhoons" (pronounced TIE-foons). The word "typhoon" may come from *taaîfung,* which is Cantonese for "great wind." It is also possible that the word comes from the ancient Greek word *tuphon*, which means whirlwind. Hurricanes that form over the Indian Ocean are called "cyclones" (pronounced SIGH-clones).

Hurricane Katrina devastates New Orleans, Gulf Coast

Hurricane Katrina shocked the world after hitting the U.S. Gulf Coast on August 29, 2005. Katrina was the third most powerful hurricane ever to make landfall, or come across a land mass, in the United States. Until this disaster, recent advances in early detection systems had helped to decrease the disastrous effects of hurricanes. From 1965 to 2005, deaths from hurricanes in the United States were around twenty to thirty people per year. In contrast, Katrina alone claimed over eighteen hundred lives and caused up to $100 billion in damage. This storm, which displaced at least a half-million people, will be remembered as one of the deadliest and costliest natural disasters in U.S. history.

Katrina first made landfall on August 25 in Florida as a Category 1 storm according to the Saffir-Simpson intensity scale. The storm caused some damage and loss of life across the state before exiting land and beginning a path through the Gulf of Mexico toward Louisiana. In the warm waters of the gulf, Katrina intensified to a Category 5 storm. The Gulf Coast braced itself for the oncoming hurricane.

Katrina lost momentum as it moved toward the Gulf Coast. The storm gradually reduced to a Category 3 on its path toward landfall. However, since the storm was a Category 4 just before the eye of the storm made landfall, the area experienced sustained winds of more than 130 miles (209 kilometers) per hour. Katrina made landfall near New Orleans, Louisiana, setting off a disastrous chain of events.

Katrina hit Louisiana just after 6 AM on a Monday. Within hours, low-lying parts of New Orleans and surrounding parishes stood under water of up to 10 feet (3 meters) deep. The city of New Orleans, which

WORDS TO KNOW

air mass: a large body of air with approximately the same temperature and humidity throughout.

air pressure: barometric pressure; the force exerted on a surface due to the weight of air.

anemometer: an instrument that measures wind speed.

cirrostratus cloud: a thin layer of high-altitude clouds that cover most of the sky, but are semitransparent.

cirrus cloud: a wispy, high-level cloud.

cold front: the leading edge of a moving cold air mass.

condensation: the process by which water changes from a gas to a liquid.

convergence: where things come together, such as the trade winds blowing from the north and south near the equator.

Coriolis effect: the deflection of a moving object such as an air mass due to the rotation of Earth.

cumulonimbus cloud: a tall, vertically developed cloud reaching to the top of the troposphere or above and capable of producing heavy rain, high winds, and lightning.

cumulus cloud: fluffy, white, mid-level cloud.

cyclone: a weather system characterized by air that flows inward and circulates around a low pressure area.

eye: an area of clear sky and warm, dry, descending air at the center of a hurricane.

eye wall: a vertical area of thick clouds, intense rain, and strong winds marking the outer boundary of the eye.

flood: inundation by water of normally dry land.

front: the boundary between two air masses of different temperatures.

hurricane: a tropical cyclone that forms in the northern Atlantic Ocean or in the eastern Pacific Ocean.

hurricane warning: hurricane landfall is imminent.

hurricane watch: hurricane landfall is possible.

Intertropical Convergence Zone: the area of rising air near Earth's equator where the trade winds converge.

inversion, atmospheric: a stable reversal of the normal pattern of atmospheric temperature, formed when a warm air mass sits over a cold air mass near the surface.

jet stream: a fast-flowing, relatively narrow air stream found at an altitude of approximately 36,000 feet (11,000 meters).

landfall: the point on a coast the center of a hurricane first crosses.

latent heat: the heat that must be removed from a quantity of water vapor to cause it to turn into a liquid, or that must be added to a quantity of liquid water to cause it to turn into a vapor; called latent because the temperature of the quantity of water or water vapor does not change.

lies below sea level, is protected from the waters of Lake Ponchartrain and the Mississippi River by a 350-mile-long (563-kilometer-long) series of levees. Soon after the storm hit, three of these protective levees failed, and

Hurricane Katrina slams Gulfport, Mississippi, 2005. ©JIM REED/CORBIS.

water poured in, filling the city like a bathtub. By the end of the first day, entire neighborhoods were completely underwater. At the disaster's height, 80 percent of the city was submerged.

Calls for evacuation of New Orleans began on Friday and Saturday, a few days before the storm hit the Gulf Coast. However, thousands of people were still in New Orleans when the storm hit. Many people had no access to transportation—by some estimates, one-third of New Orleans' population did not own a car. Some were elderly or in poor health, some had small children, and some simply did not want to leave their homes. Around the time the storm hit, citizens who remained in New Orleans were advised to head for the Louisiana Superdome or the convention center, which were being used as temporary shelters for evacuees. Many found refuge in these shelters, but thousands were left behind in homes, hospitals, jails, and the streets.

The rest of the world watched in horror as tragedy unfolded. Parts of the city remained submerged for weeks. Fires raged as the floodwaters became increasingly polluted with gasoline, landfill contents, industrial waste, snakes, and rats. Many people were stranded in the hardest-hit areas, which were mostly poor neighborhoods. Rescue workers used helicopters and boats to navigate the floodwaters in order to rescue people from trees and rooftops. Hundreds waited on highway overpasses to be rescued as the water rose. The region lacked electricity and drinkable water. Civil unrest mounted as military and police forces tried to keep the peace.

Weather extremes: The Galveston disaster

Before Hurricane Katrina, the worst hurricane disaster and the worst weather disaster in the United States occurred on September 8, 1900, in Galveston, Texas. It was the worst storm of the twentieth century in terms of lost lives. Initial estimates were that more than six thousand people died when a storm surge 20 feet (6 meters) in height swept across the low-lying barrier island. Modern estimates put the death toll closer to seventy-two hundred.

Galveston's residents had received warning from the U.S. Weather Bureau on September 6 that a tropical storm was detected near Cuba. However, they did not pay much notice. After all, other tropical storms had come their way but had inflicted only minor damage. Galveston residents had no way of knowing the power of the storm that was about to strike them.

It was not until the morning of September 8 that the higher-than-usual tides and strong winds hinted at the severity of the approaching storm. However, rather than evacuating the island, most residents merely took shelter in brick houses at higher elevations. The problem with that strategy was the highest point on the island, at that time, was only 9 feet (about 3 meters) above sea level. That meant that no place on the island was safe from the storm's rushing waters.

The hurricane's assault on Galveston lasted for several hours, starting at about 4 PM. Winds gusting to 100 miles (160 kilometers) per hour were recorded before the island's anemometer, an instrument that measures wind speed, was destroyed. A 20-foot (6-meter) storm surge crashed onto shore and entirely submerged the island. The storm leveled almost every structure within three blocks of the south shore and severely damaged many others. As buildings collapsed, the wreckage was carried inland to smash into other buildings. Many people were thrown into the water, where high winds and surging water battered them with the debris. To add to the misery of the survivors, 10 inches (25 centimeters) of rain fell during the night. Once the storm had passed and flood waters subsided, very few structures were left standing in the town.

Since that time, Galveston has been rebuilt and extensive measures have been taken to prevent future disasters. The residents have constructed a seawall facing the Gulf of Mexico that is 17 feet (5 meters) tall and 3 miles (5 kilometers) long. They also brought in sand and raised the elevation of the island, at some points as high as 17 feet (5 meters) above sea level.

Though much of the public focus on Hurricane Katrina was on the New Orleans tragedy, the storm pulverized a long stretch of the Gulf Coast region, including Florida, Mississippi, Tennessee, and Alabama. Storm surges, or abnormal sea rises, occurred as far away as Mobile, Alabama. Hundreds of people died, and thousands upon thousands lost their homes and livelihoods.

The tragedy of Hurricane Katrina reminded the United States and the world of the complicated social and political aspects of natural

Hurricane Katrina hits Mobile, Alabama, 2005. ©WARREN FAIDLEY/CORBIS.

disasters. Residents of the hardest-hit areas in the Gulf Coast region were among the nation's poorest people. Two-thirds of New Orleans residents were African American, a fact that caused a number of leaders to speculate that the government's botched relief efforts reflected a lack of concern for minorities.

Recent events: Catastrophic hurricanes since 2000

Hurricane Katrina is not the only recent hurricane to have caused substantial destruction and economic loss in the United States. The years since the turn of the twenty-first century have been very active in the formation of hurricanes. With the exception of Hurricane Katrina, most of these storms did not cause extensive loss of life. However, they have been extremely costly. Hurricanes that have made landfall in the United States since 2000 have caused more than $148 billion in damage.

Hurricane Isabel Hurricane Isabel was the only Category 5 storm of the 2003 Atlantic hurricane season. It made landfall as a Category 2 storm on September 18, 2003, just south of Cape Hatteras, North Carolina. It produced storm surges as high as 10 feet (3 meters) above normal tide levels and spun off a number of tornadoes, violently rotating winds capable of great destruction, in the days following its landfall.

Isabel caused damage from South Carolina all the way to Ontario, Canada. The official damage estimate was $3.37 billion. As with many hurricanes, the majority of that damage resulted from flooding, which affected more than sixty million people in the mid-Atlantic region. The flooding also caused extensive crop damage in several states. All told, fifty people died: sixteen as a direct result of the storm and thirty-four indirectly.

Hurricanes Charley, Frances, Ivan, and Jeanne In 2004, four separate hurricanes bombarded the state of Florida over a six week period, causing more than $30 billion in damage and claiming more than sixty lives in Florida alone. Hurricane Charley was the first to hit, a Category 4 storm that made landfall in southwest Florida on August 14. It was the strongest hurricane to hit the United States since Hurricane Andrew in 1992. Because Charley was predicted to make landfall further north, near Tampa Bay, many residents in the affected parts of Florida were caught off guard. The storm claimed ten lives and caused $15 billion in losses, making it the third-costliest hurricane in U.S. history.

Just weeks later, on September 4 and 5, Hurricane Frances battered both the east and west coasts of Florida. After initially making landfall on the eastern seaboard near West Palm Beach, Frances traveled across the Florida peninsula and into the Gulf of Mexico. It once again hit Florida, this time in the panhandle in the northwest portion of the state. Frances caused forty-two deaths in the United States and about $9 billion in losses.

Hurricane Ivan was the strongest storm of the 2004 Atlantic hurricane season. After causing major damage in Grenada, Jamaica, and the Cayman Islands, Ivan made landfall as a Category 3 storm in Alabama on September 16. On September 20 it looped back across the Florida peninsula, doing most of its damage in the state's panhandle near the Alabama border. Ivan killed sixty-four people in the Caribbean and fifty-seven people in the United States, including fourteen in Florida, and caused $13 billion in damage.

Less than two weeks later, on September 25, Hurricane Jeanne made landfall on Florida's east coast, just two miles north of Frances. Where Frances traveled west after making landfall, Jeanne turned north and headed up the coastline to Georgia. Jeanne killed five people and caused about $6.9 billion in damage in the United States, but the worst of its damage came in Haiti, where more than three thousand people died in flooding and mud slides caused by the storm.

Hurricane Isabel seen from space via NASA's Aqua satellite in 2003. © CNP/CORBIS.

The 2005 Atlantic hurricane season Charley, Frances, Ivan, and Jeanne combined to make the 2004 Atlantic hurricane season one of the deadliest and costliest ever, with losses of more than three thousand lives and $42 billion. The 2005 Atlantic hurricane season was even more severe. It was the most active hurricane season to date. Tropical storms, which are storms that have sustained winds of 39 to 73 miles (63 to 117 kilometers) per hour, are given names from a pre-determined list. During the 2005 Atlantic hurricane season, there were twenty-seven named tropical storms. This number included fourteen hurricanes and seven major hurricanes.

Three of the six most powerful hurricanes ever recorded in the Atlantic basin formed in 2005, including Wilma, the most powerful in history. In addition to Hurricane Katrina, the most destructive hurricane in U.S. history, hurricanes Dennis, Rita, and Wilma all caused significant damage. All told, damage from the 2005 Atlantic hurricane season topped $100 billion.

Hurricane Dennis made landfall as a Category 3 storm in the Florida panhandle in July, less than a year after Hurricane Ivan struck the same area. Dennis claimed eighty-nine lives, including fifteen in the United States, and did more than $2.2 billion in damage.

Hurricane Rita, a Category 5 storm, was the first hurricane to make landfall in the United States after Hurricane Katrina, hitting near the Texas-Louisiana border on September 24. Rita had been projected to make landfall near Houston, Texas, prompting nearly three million residents of the greater Houston area to evacuate. The evacuation created an enormous gridlock, with the trip from Houston to Dallas, normally three or four hours, taking between twenty-four and thirty-six hours to complete. After it made landfall, Rita caused $10 billion in damage. Though only seven direct deaths were recorded, 113 people died from indirect causes, many in the evacuations that preceded the storm.

With the formation of Hurricane Wilma in October, the 2005 Atlantic hurricane season surpassed the 1933 season as the most active in history. After setting the record as the most powerful hurricane in Atlantic basin history, Wilma devastated the Yucatán peninsula in Mexico and then traveled east and made landfall in southwest Florida on October 24. Wilma caused more than $12 billion in damage and killed thirty-five people in Florida.

The year 2005 saw so many hurricanes that, for the first time since the practice of naming hurricanes began in 1950, all of the allotted names

Motorists clog a Houston, Texas, highway as they evacuate before the arrival of Hurricane Rita in 2005. © CJ GUNTHER/ EPA/CORBIS.

were used, and the later storms of the season were named using letters of the Greek alphabet. Tropical Storm Zeta, the sixth storm to be named with a Greek letter, was the final storm of the 2005 season.

The components and causes of a hurricane

A hurricane is the most intense form of tropical cyclone, which is any rotating weather system that forms over tropical waters. Winds blow inwards toward, and rotate around, an area of low pressure. Cyclones rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. To qualify as a hurricane, a storm must have a well-defined pattern of rotating winds with maximum sustained winds greater than 74 miles (119 kilometers) per hour. Sustained winds are winds that blow continuously for at least one minute.

A hurricane is made up of a series of tightly coiled bands of thunderstorm clouds. These bands spiral around an almost totally calm region, called the eye, at the center of the hurricane. A hurricane may have within it hundreds of strong thunderstorms, which have the very tall cumulonimbus clouds producing rain and thunder. The diameter of an average hurricane is about 350 miles (560 kilometers) while the diameter of the largest hurricanes approaches 900 miles (1500 kilometers).

Is global warming producing more hurricanes?

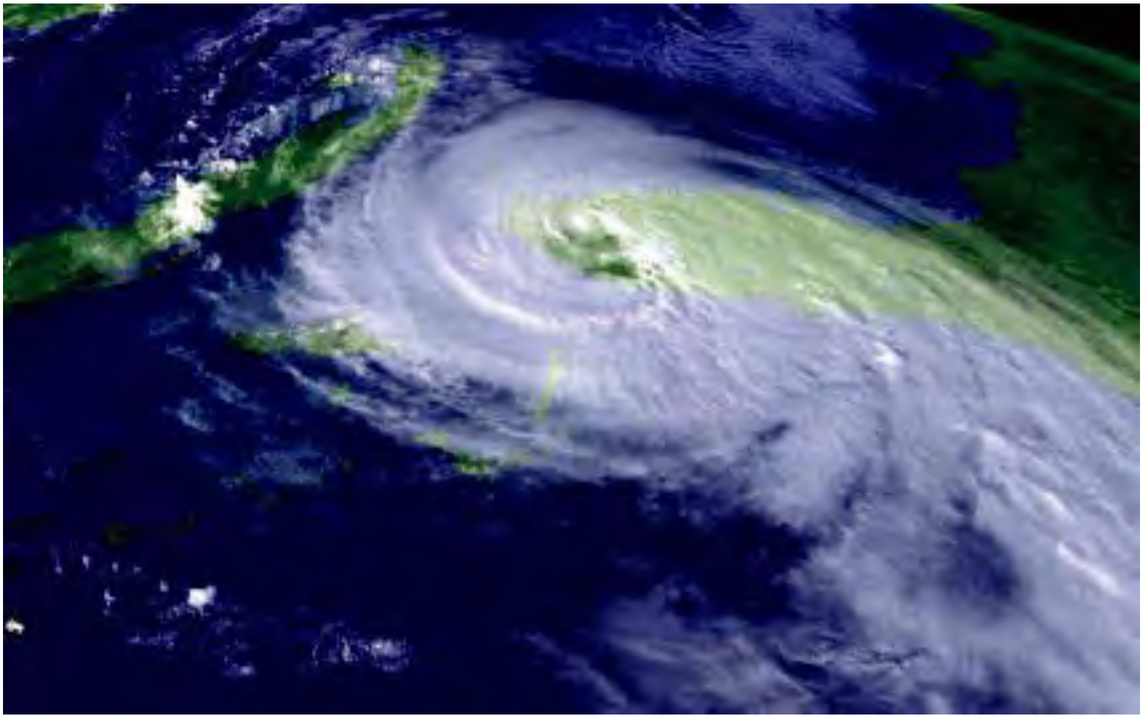
Atmospheric scientists have determined that Earth's temperature is increasing. This phenomenon is called global warming. Since one of the effects of global warming is to heat up tropical ocean water, many scientists expect hurricanes to become more frequent. Warmer water also contains more energy for hurricanes, so global warming may give rise to storms more powerful than ever witnessed before. The world's hurricane breeding regions are expected to expand as well, as a larger area of water warms to 80°F (27°C)—the minimum water temperature necessary for hurricane formation.

Recently, hurricanes have been forming more frequently and with greater ferocity. Hurricanes' duration and strength have increased by about 50 percent over the last thirty years. The 2005 Atlantic hurricane season was the most active season on record. In the eleven years between 1995 and 2005, twenty-nine Atlantic hurricanes were so destructive and costly that their names were permanently retired from the National Hurricane Center's list of available storm names. In the thirty-three years preceding, only twenty-eight storms had been retired.

It is not yet clear whether this increase in hurricane activity is attributable to global warming. Historically, hurricane activity has been cyclical, with several decades of high activity followed by several decades of fewer storms. For instance, the 1920s–30s and 1950s–60s were very active periods, while the 1970s–80s were relatively calm. Whether the frequent hurricanes of the 1990s and early twenty-first century are part of a long-term trend toward more hurricanes or simply another cycle of high activity is an ongoing scientific debate. While there is a near consensus in the scientific community that one of the effects of global warming will be more frequent and powerful hurricanes, some scientists caution against attributing any particular hurricane or weather phenomena to global climate change.

Less intense forms of tropical cyclones are referred to as tropical storms, tropical depressions, or tropical disturbances. A tropical storm is similar to a hurricane in that it has organized bands of rotating strong thunderstorms, yet its maximum sustained winds are only 39 to 73 miles (63 to 117 kilometers) per hour. A tropical depression, the weakest form of tropical cyclone, consists of rotating bands of clouds and thunderstorms with maximum sustained winds of 38 miles (61 kilometers) per hour or less. A tropical disturbance is a cluster of thunderstorms that is beginning to demonstrate a cyclonic circulation pattern. Tropical disturbances frequently occur over tropical waters. Only a small percentage of these disturbances, however, become hurricanes.

A hurricane starts out as a tropical disturbance and passes through the stages of tropical depression and tropical storm on its way to maturity. A hurricane will continue to grow as long as there is a fresh supply of warm,

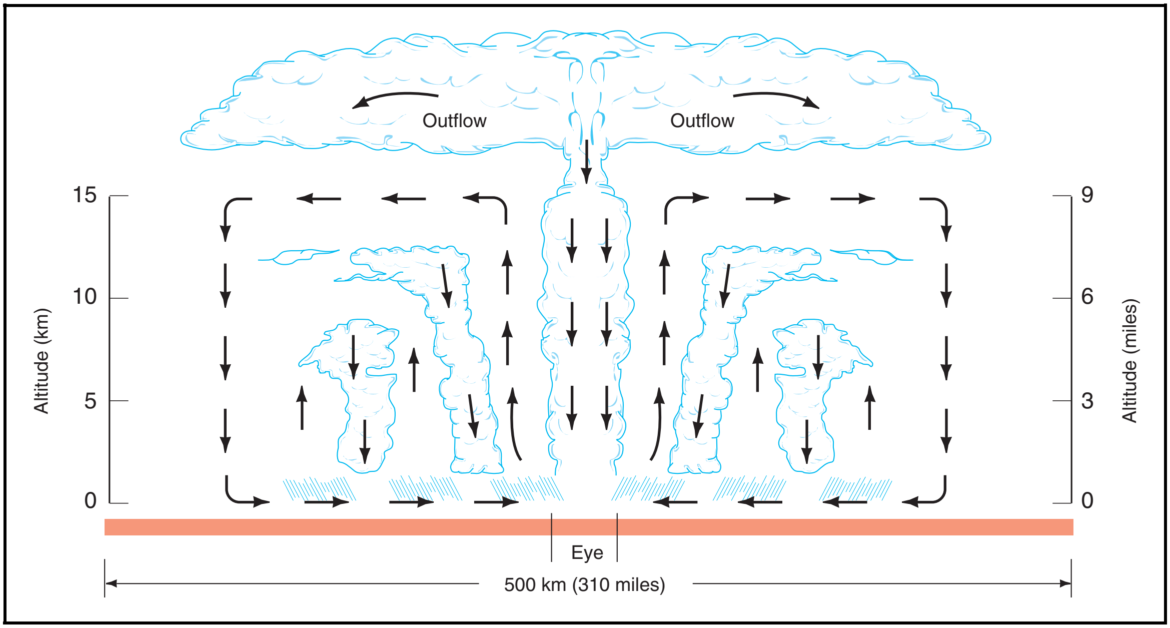


Hurricane Wilma over the Florida Peninsula as seen from space, 2005. ©NOAA/HANDOUT/REUTERS/CORBIS.

humid air. Once the hurricane crosses over colder waters or land, its supply of warm, humid air is cut off and it weakens. A typical hurricane lasts about thirteen days. A hurricane may pass back through those weaker stages, in reverse order, as it dissipates.

Over the ocean, a hurricane generates waves 50 feet (15 meters) or greater in height. When a hurricane reaches land, it may pound the shore with a wall of water up to 20 feet (6 meters) high. This wall can produce severe flooding across 100 miles (160 kilometers) of coastline. Hurricanes also bring fierce winds and intense downpours of rain. It is not unusual for coastal and inland communities to receive 6 to 12 inches (15 to 30 centimeters) of rain when a hurricane comes onshore. For its onshore finale, a dissipating hurricane may spin off numerous tornadoes.

What is the structure of a hurricane? A hurricane consists of spiraling bands of clouds called rain bands, around a calm, low-pressure center, the eye. The rain bands, which are tightly coiled around the eye, produce



Air flow within a hurricane.

heavy rains and forceful winds. Surrounding the outer edge of the rain bands is a region of wispy, high-level cirrus or cirrostratus clouds.

The hurricane's eye has an average diameter of 12 to 40 miles (20 to 65 kilometers). Within the eye, winds are light and skies are partly cloudy or clear. The reason that clouds break up in the eye of a storm is that air sinks in that region. Air warms as it falls and the water droplets within it evaporate.

The lowest pressure of the storm exists in the eye. Typically, pressure there dips to 950 millibars (28 inches, or 71 cm), although measurements as low as 900 millibars (26.5 inches, or 67.3 cm) have been recorded. By way of comparison, the average pressure at sea level is 1013.25 millibars (29.92 inches, or 76.00 cm).

It may take an hour or more for the eye of the hurricane to pass over an area. The calm weather associated with the eye sometimes fools the residents of that area into thinking the storm is over when, in fact, the heavy winds and rain will soon resume.

The region immediately surrounding the eye, called the eye wall, is the strongest part of the storm. The eye wall is a loop of thunderstorm clouds that produce torrential rains and forceful winds. The closer one

Weather report: Comparing hurricanes and extratropical storms

Hurricanes are tropical cyclones. An extratropical cyclone is a large-scale storm that forms in the middle latitudes. Extratropical cyclones are produced by interactions between contrasting warm and cold fronts.

Tropical and extratropical storms have different mechanisms of energy supply. An extratropical cyclone gets its energy from temperature contrasts between the air masses found on either side of a front, while a hurricane gets energy from warm ocean waters and the latent heat released as the moist surface air rises.

Both extratropical cyclones and hurricanes are centered around an area of low pressure, a hurricane has a much steeper pressure gradient. The air pressure at the center of a hurricane is typically much lower than it is at the center of an extratropical cyclone.

Other differences between the two types of cyclones include:

- The diameter of the typical extratropical cyclone is three times the size of the diameter of the typical hurricane.
- Hurricanes weaken with height while extratropical cyclones intensify with height.
- Air sinks in the center of a hurricane while it rises in the center of an extratropical cyclone.
- Air at the center of a hurricane is warmer than the surrounding air while the air at the center of an extratropical cyclone is colder than the surrounding air.
- The winds of a hurricane are strongest at the surface while the winds of an extratropical cyclone are strongest at upper levels, in the jet stream.

Despite all these differences, it is possible for hurricanes to transform into extratropical cyclones. This happens when a hurricane moves across a front and draws in air of different temperatures. Then the hurricane, which was weakening as it traveled over land, intensifies as it becomes linked with a low-pressure area aloft.

An example of a hurricane that became linked with an extratropical storm is Hurricane Agnes of 1972. After combining with a low-pressure system in the Northeast, Agnes produced heavy rains and extensive flooding. Harrisburg, Pennsylvania, for instance, received 12.5 inches (32 centimeters) of rain in twenty-four hours. The rising waters in central Pennsylvania forced the evacuation of more than 250,000 people. Agnes caused a total of 122 deaths and $6.4 billion in property damage. The floods were responsible for around half of the deaths and about two-thirds of the property damage.

gets to the center of the storm without actually entering the eye, the faster the winds blow. Within a radius of 6 to 60 miles (10 to 100 kilometers) of the eye, winds may reach speeds of 100 to 180 miles (160 to 300 kilometers) per hour.

The winds are a result of the pressure gradient, which is the difference in air pressure between high- and low-pressure areas relative to their distance apart. The pressure gradient between the edge of the storm and the eye drives the winds of a hurricane. The closer in to the eye, the steeper the pressure gradient becomes and the faster the winds blow. At points farther away from the eye of the storm, the pressure gradient becomes more gradual and the winds become weaker.

The most violent part of the hurricane is the side of the eye wall in which the wind blows the same direction that the storm is progressing. In that region, the hurricane's winds combine with the winds that are steering the hurricane, to create the storm's fastest winds.

The cyclonic wind circulation of the hurricane weakens with height, starting at about 9,800 feet (3,000 meters). The airflow actually reverses direction at heights greater than approximately 50,000 feet (15,000 meters). That means that while the eye of the storm and the surface beneath it are intensely low pressure areas, a high pressure area exists above.

The fact that a hurricane has a ceiling below the top of the troposphere, the lowermost portion of Earth's atmosphere, makes it possible to fly above a hurricane in an aircraft and take aerial photographs of the entire system. It is not possible to do this in a middle-latitude thunderstorm since the mature cumulonimbus clouds in that system, the clouds that produce the lightning, extend to the top of the troposphere and sometimes beyond.

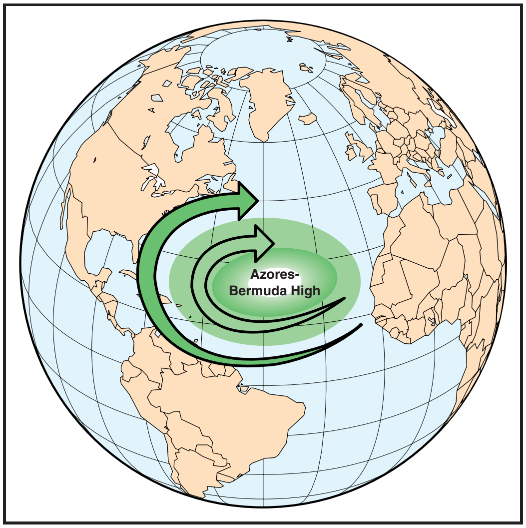
Interesting facts: "Hurricane Huron"

In September 1996 an extratropical cyclone formed over the Great Lakes. It formed from what meteorologists call a cut-off low-pressure area (a low-pressure area that has become separated from other weather systems and may remain stationary). This was a particularly intense low. It started out as a typical "cold-core" extratropical cyclone, but over time it evolved into a "warm-core" system, similar to a hurricane, with an eye and spiral bands of gusty rain squalls.

The storm likely formed because the low pressure area stalled over Lake Huron. At the time, the lake waters were at their maximum seasonal high temperature, 70°F (21°C). This would be too low under normal conditions for tropical storm development. But over time, the water warmed the air enough that the storm developed its warm core. From a satellite, it strongly resembled a tropical storm, and researchers at Pennsylvania State University dubbed it "Hurricane Huron." This incident is thought to be the only such storm ever documented over the Great Lakes.

Where do hurricanes form? Hurricanes are tropical phenomena. The tropics are defined as the region of Earth bounded by 23.5° latitude, north and south. The tropics receive the most direct sunlight of anywhere on the planet, making that region the world's warmest.

The heating of Earth's surface leads to the daily formation of cumulus clouds and afternoon thunderstorms. While these thunderstorms are generally not severe individually, they sometimes become organized in



Direction of hurricane movement in the North Atlantic.

lines called tropical squall clusters or squall lines, which are severe. These are similar to squall lines of thunderstorms that form over land in the middle latitudes.

Hurricanes generally form only within specific areas in the tropics, between 5° and 20° north and south, although they occasionally form as far north and south as 30°. At higher latitudes, the water is too cold for hurricanes to form.

The reason hurricanes won't form between 5° north and 5° south has to do with the lack of Coriolis effect at and near the equator. The Coriolis effect is the gradual change in direction of global winds due to the rotation of Earth. The Coriolis effect is necessary for the formation of rotating tropical storms. When the trade winds, which are prevailing winds that blow northeast north of the equator and from the southeast south of the equator, meet at the equator the Coriolis effect is canceled out.

Hurricane-breeding areas are found in several clusters over the warmest regions of the world's tropical oceans. The six primary hurricane-breeding regions are:

- The eastern North Atlantic Ocean, west of Africa and westward to the Caribbean Sea and the Gulf of Mexico.
- The eastern Pacific Ocean, west of Mexico.
- The western portion of the North Pacific Ocean, east of China.
- The South Indian Ocean, east of Madagascar.
- The North Indian Ocean and the waters surrounding India—the Bay of Bengal and the Arabian Sea.
- The portions of the Pacific and Indian Oceans adjacent to northern and western Australia.

The South Atlantic and the eastern portion of the South Pacific Ocean on either side of South America, where water temperatures are cooler, are notably free of hurricanes. The map in this section shows the primary hurricane breeding regions.

When do hurricanes form? The annual hurricane season, for any given location, is during the months when ocean temperatures are highest. This period lags behind the year's warmest months on land, since it takes the oceans longer than the land to both warm up and cool down.

For the Northern Hemisphere, hurricane season is roughly June through November. In the Southern Hemisphere, hurricanes occur most frequently between December and May. The exception to this rule is the western portion of the North Pacific Ocean, where hurricanes form year-round.

Within the long hurricane season, there are peak months for hurricane formation that vary with location. For instance, the maximum number of hurricanes in the North Atlantic—hurricanes that threaten the U. S. eastern seaboard—occur in August and September.

How do hurricanes form? The first step in the formation of a hurricane is the development of a cluster of thunderstorms, called a tropical disturbance. Tropical disturbances develop regularly over tropical waters. Only a small percentage of these disturbances, however, evolve into hurricanes. According to a study conducted by examining satellite photos, only 50 of the 608 tropical disturbances detected in a six year period over the Atlantic Ocean grew into tropical storms, and only about half of those developed into hurricanes.

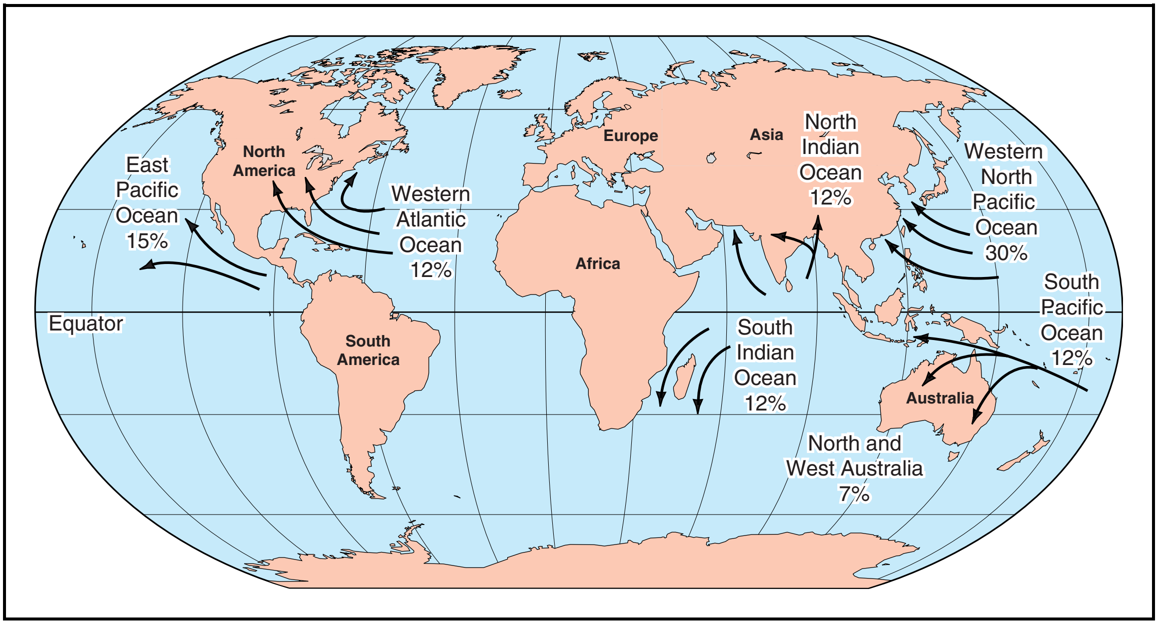
The reason that hurricanes are not more common is that hurricane formation requires a very specific set of atmospheric conditions. Some of the factors necessary for hurricane formation are similar to those necessary for thunderstorm formation. These include a warm, moist air mass and an unstable atmosphere. In the case of a hurricane, the air is warmed and made moist by ocean water that is at least 80°F (27°C). Since ocean water is stirred up by storms, this water must be warm to a depth of about 200 feet (61 meters).

Hurricane formation also requires that the air, from the surface up to about 18,000 feet (5,500 meters), be extremely humid. The higher the temperature of the ocean water, the more water evaporates. That, in turn, raises the humidity of the surface air. The warm surface air cools as it rises

Hurricane Linda sets a record

Hurricane Linda, which hit in September 1997, was the strongest hurricane ever record in the eastern Pacific. Linda was so powerful that meteorologists proposed adding a new category, Category 6, to the Saffir-Simpson Scale. The scale is used to measure destructive potential; it presently goes up to 5. Linda packed sustained winds of 185 miles (298 kilometers) per hour with gusts greater than 200 miles (322 kilometers) per hour. By way of comparison, Hurricane Andrew, which did extensive damage to Florida in 1992, had maximum sustained winds of 140 miles (225 kilometers) per hour.

Linda's record-setting winds were measured on September 12, when the hurricane was still about 500 miles (800 kilometers) south of Mexico's Baja California Peninsula. Luckily, the hurricane took a northwesterly route and remained at sea. The hurricane was about 1,000 miles (1,600 kilometers) west of Baja's southern tip when it broke up on September 18. Linda's only effects on land were huge waves that pounded the Baja Peninsula, the west coast of mainland Mexico, and coastal Southern California.



The world's hurricane breeding regions.

and the moisture within it condenses, or turns into water. When moisture condenses, it releases latent heat, the heat removed from a quantity of water vapor to cause it to turn into a liquid, and that heat provides additional energy to the storm system.

Another necessary ingredient for the formation of a hurricane is surface winds that are converging, or blowing toward a common point. Where winds converge at the surface, air rises. A number of events can trigger surface air convergence. One is that a front, a leading edge of an air mass of warm or cold air, moves into the tropics from the middle latitudes. By the time the front reaches the tropics, the temperatures on either side of the front have equalized. However, the front still has an associated low pressure area aloft. The winds at the surface converge to a point beneath that low pressure area and rise.

Another source of convergence of surface winds is the meeting of the trade winds from the north and the south, along the intertropical convergence zone, or ITCZ. Convergence at the ITCZ promotes hurricane development only during the of winter and summer when the ITCZ is located furthest from the equator. At other times of year, when the sun is directly over the equator, the ITCZ also sits very close to the equator. At those times the ITCZ does not experience the Coriolis effect. Once the ITCZ shifts to a point 4 or 5 degrees from the equator, however, the Coriolis effect is apparent.

A third possible source of converging winds is an easterly trade wind that flows in a wavelike fashion from Africa. As the trade wind proceeds westward, a low pressure trough may flow over the tropical waters, triggering surface winds to converge beneath it.

Hurricane formation also requires ideal conditions in the winds aloft. Namely, the winds at all altitudes need to be light and blowing in approximately the same direction and speed, so as not to scatter the moisture and dissipate the developing storm. Hurricane formation is most likely to occur when the upper air is cold, a factor that contributes to the low pressure.

Most often, there is some condition in the winds aloft that prohibits hurricane development. For instance, in some latitudes, particularly between 20 and 30 degrees, the upper-level air sinks. It warms as it falls, creating an inversion, or reversal of the normal temperature pattern, that prevents the upward development of thunderstorms.

Another condition that works against hurricane formation is a relatively dry middle layer of air. The amount of latent heat necessary to generate a hurricane requires condensation to occur at all heights throughout the system. Moisture will not condense until the relative humidity of the air, which is the amount of water vapor in an air mass for a particular temperature, has reached 100 percent.

How do hurricanes unfold? Let's assume that the following atmospheric conditions exist: warm, humid surface air; cold air and low pressure aloft; converging surface winds; and light winds and high humidity at all altitudes. The stage has been set for the development of a hurricane.

The most widely accepted model of how a hurricane forms is called the Organized Convection Theory. According to this theory, the first step in the development of a hurricane is the formation of large thunderstorm clouds. That proceeds as follows: As warm air rises to the region of low pressure above, condensation occurs. Latent heat released during condensation warms the air at greater and greater heights. Eventually, the cold layer of upper air also becomes warm. As a result, its air pressure increases.

When the low pressure region aloft becomes transformed into a high pressure region, the thunderstorm ceases to develop upward. Rather, at that height air diverges outward, away from the high pressure area at the

Extreme weather: Sea Islands storm

On the night of August 27, 1893, a fierce hurricane laid waste to the South Carolina Sea Islands off the coast of Beaufort, South Carolina. Some two thousand (some sources claim as many as five thousand) islanders perished in the storm. Virtually all survivors on the islands were left homeless and penniless.

The primary reason the hurricane took so many lives was not that it was an unusually large storm, but because the islanders had no advance warning and no way to escape. The National Weather Service, which had issued a hurricane warning to mainlanders, could not get word to the islanders for lack of telegraph or telephone links.

Most of the island's thirty thousand residents were former slaves. Prior to the Civil War (1861–1865), the slaves had worked on plantations on the islands. Near the start of the war, the plantation owners had fled, leaving behind their former slaves. The plantations were then divided, and the newly freed slaves were given small pieces of land. In the years since the end of slavery, the islanders had built thriving communities.

The hurricane generated tides nearly 20 feet (6.1 meters) above average sea level and winds of 120 miles (193 kilometers) per hour. After the storm passed, survivors found a grisly scene of death and destruction. Bodies littered the beaches and marshes. The destruction of buildings and crops was near total. Most sources of fresh water had been contaminated with sea water. Virtually all animal life on the island had died.

News of the islanders' plight reached the mainland some two days after the hurricane. It took nearly a month for a large-scale assistance campaign to begin. Until that time, island residents survived mainly by eating berries. The American Red Cross coordinated the relief effort under the direction of its founder, Clara Barton. Arriving in the area on September 30, Barton organized deliveries of food, clothing, medicine, and supplies to the islands. Many African American Civil War veterans also volunteered their services in the relief effort. By the following July, reconstruction of the Sea Islands communities was nearly complete.

center of the cloud. The air flows to the edge of the cloud and then sinks back to the surface.

As the same time that the pressure aloft rises, the pressure at the surface falls. It is the formation of the surface low, at the center of the storm, that is the most essential factor in hurricane development. The winds begin to circulate in a counterclockwise pattern (in the Northern Hemisphere) around the center of, but not directly into, this surface low. At the center of the storm, the air sinks directly from the high pressure area above to the low pressure, below.

The winds increase in speed the closer they get to the center. In the process, they generate large ocean waves. These waves create friction on the wind, interrupting the air flow and causing the air to converge. Where the air converges, it rises, carrying moisture and warmth upward to form new thunderstorms.

WORDS TO KNOW

Organized Convection Theory: a widely accepted model of hurricane formation.

pressure gradient: the difference in air pressure between a high and low pressure area relative to the distance separating them.

rain band: a band of heavy thunderstorms forming a tightly coiled spiral around the center of a tropical storm.

relative humidity: the amount of water vapor in an air mass relative to the amount of water in a saturated air mass of the same temperature.

Saffir-Simpson Hurricane Damage Potential Scale: a scale devised by Herbert Saffir and Robert Simpson intended to be used to predict a hurricane's destructive potential.

squall line: a moving band of strong thunderstorms.

storm surge: an abnormal rise of the sea over and above normal tides due to strong winds and low pressure accompanying a storm or hurricane.

thunderstorm: a rainstorm accompanied by thunder and lightning and produced from a cumulonimbus cloud.

tornado: a violently rotating column of air that reaches the ground and is attached to a cumulonimbus cloud; it is nearly always observable as a "funnel cloud."

trade winds: an area near the equator of prevailing winds that blow from the northeast north of the equator and the southeast south of the equator.

tropical cyclone: any rotating weather system that forms over tropical waters.

tropical depression: a storm with rotating bands of clouds and thunderstorms and maximum sustained winds of less than 38 miles (61 kilometers) per hour.

tropical disturbance: a cluster of thunderstorms that is beginning to demonstrate a cyclonic circulation pattern.

tropical storm: a storm with organized rotating bands of strong thunderstorms and maximum sustained winds between 39 to 73 miles (63 to 117 kilometers) per hour.

tropical wave: an elongated area of low air pressure, oriented north to south, causing areas of cloudiness and thunderstorms.

tropics: the region of Earth between 23.5° north latitude and 23.5° south latitude.

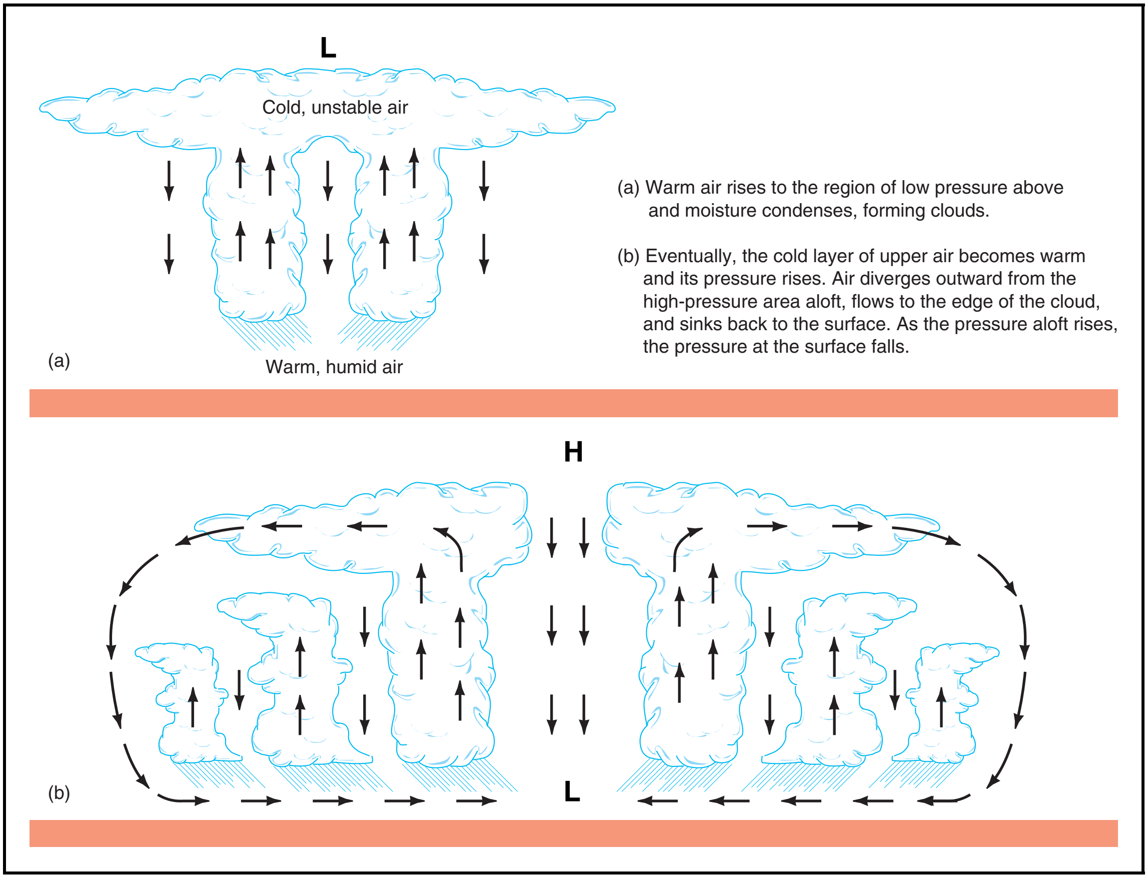
troposphere: the lowest atmospheric layer, where clouds exist and virtually all weather occurs.

typhoon: tropical cyclone that form in the China Sea or in the western North Pacific Ocean.

warm front: the leading edge of a moving warm air mass.

westerlies: an area at middle latitudes of prevailing winds that blow toward the northeast in the Northern Hemisphere.

The rising air increases the air pressure aloft. As a result, the surface air pressure becomes even lower. A chain reaction is set in motion: new thunderstorms are formed, the upper-level high pressure area becomes



Formation of a hurricane according to the organized convection theory.

higher, and the surface low pressure area becomes lower. Each process drives the other as the storm grows into a mature hurricane.

A hurricane continues to grow as long as a fresh supply of warm, humid air is available. Once the hurricane crosses over colder waters or land, its source of energy is cut off, and it begins to dissipate.

As long as more air flows out from the top of the storm center than flows into the storm from the surface, the hurricane continues to intensify. The point at which that trend reverses the hurricane begins to die.

The level of air flow is a indication of air pressure. A rapid outflow at the top of the hurricane indicates that pressure is high at upper levels and, consequently, low at the surface. However, when the outflow slows, the pressures at the top and bottom of the storm center begin to equalize. In the absence of a strong surface low, the winds weaken. Then there is nothing to support the coiled organization of thunderstorms. The system unwinds and individual thunderstorms dissipate.

How long do hurricanes last? The life cycle of a typical hurricane is about thirteen days. It starts out on day one as a cluster of thunderstorms, a condition that meteorologists call a tropical disturbance. By day three, the thunderstorms have become organized into bands that swirl about a low-pressure center. The system, at this point, is called a tropical depression.

The surface air pressure drops, the winds intensify, and the storm continues to grow. By day five, winds are blowing faster than 39 miles (63 kilometers) per hour. At this stage, the system is upgraded to a tropical storm. By day seven winds are blowing faster than 74 miles (118 kilometers) per hour. The storm is now classified as a hurricane.

For the next few days, as the hurricane moves across the warm water, it maintains its strength and integrity. About day twelve it crosses onto land and weakens. By day thirteen it has dissipated.

How do hurricanes move across the world? Hurricanes that form over the northern Pacific and northern Atlantic oceans are guided to the west-northwest by easterly trade winds. These winds blow a hurricane along at about 10 miles (16 kilometers) per hour. Once a hurricane encounters the Azores-Bermuda High, the semipermanent high pressure system in the eastern Atlantic, it is directed to the northwest, through the Caribbean and toward the East Coast of the United States.

If the hurricane travels so far northward that it reaches the middle latitudes, it will be steered to the northeast by the westerlies, which are prevailing winds in the middle latitudes that blow towards the northeast in the Northern hemisphere. The westerly winds blow the hurricane along at about 55 miles (88 kilometers) per hour, which is significantly faster than the trade winds. This faster movement at higher latitudes makes it more challenging to get advance warning to communities in the hurricane's path.

While the trade winds, Azores-Bermuda High, and westerlies establish a general hurricane route, the specific path taken by a hurricane is much more difficult to predict. The specific path depends on the structure of the hurricane and how it interacts with its environment. Exactly how these factors influence hurricane movement is not well understood.

Tracking Katrina

Hurricane Katrina formed over the southeastern Bahamas as Tropical Depression Twelve on August 23, 2005. It formed from a combination of a tropical wave (a north-south trending low-pressure area) and the remnants of Tropical Depression Ten. The system strengthened to a tropical storm on August 24 and was given the name Katrina. The tropical storm headed towards Florida and became a hurricane only two hours before its first landfall between Hallandale Beach and Aventura, Florida, on the morning of August 25.

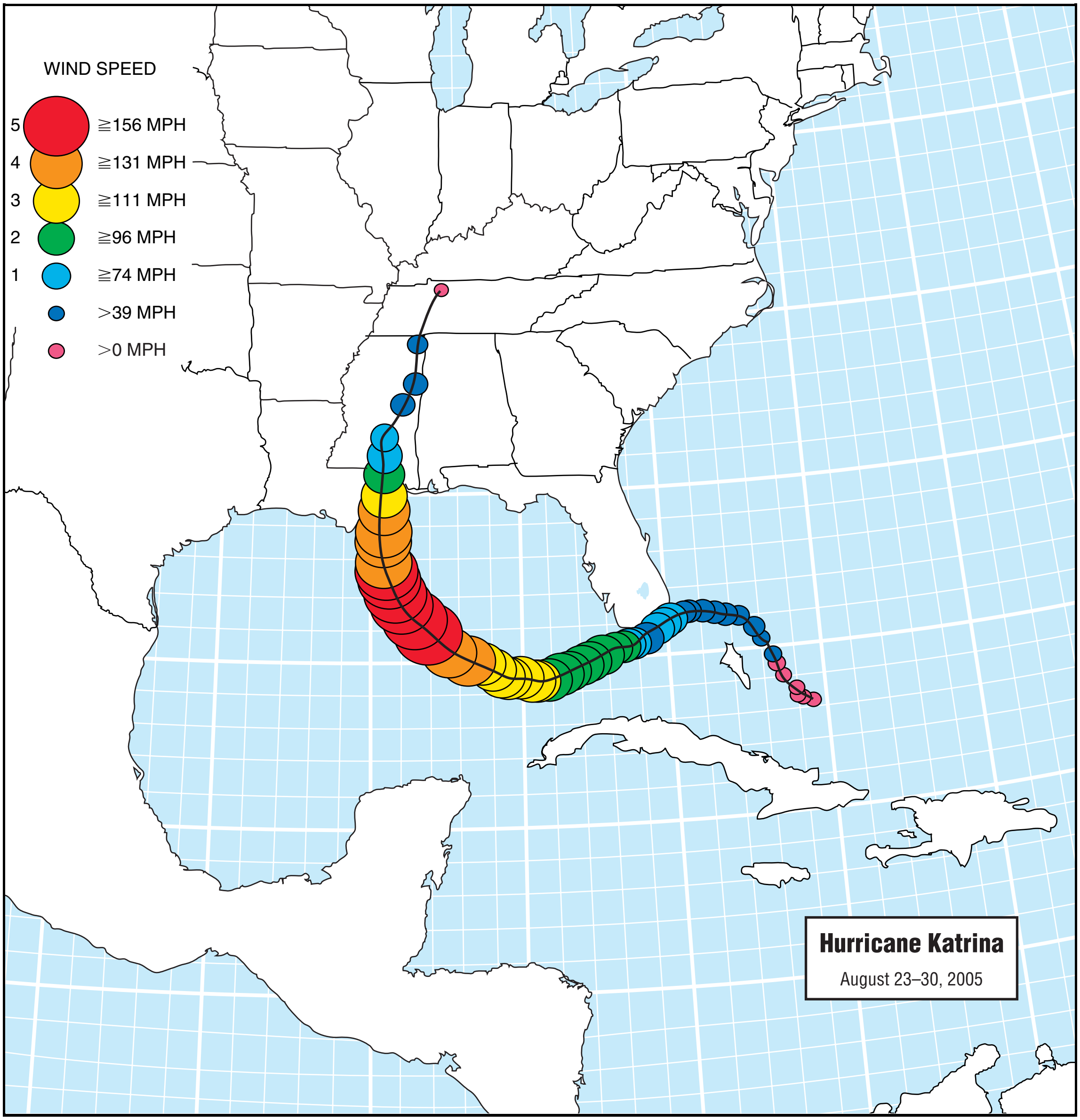
Like most storms, Katrina weakened as it passed over land, but quickly regained hurricane status after entering the warm waters of the Gulf of Mexico. On August 27, the storm reached Category 3 intensity on the Saffir-Simpson Hurricane Scale, becoming the third major hurricane of the 2005 season. Katrina continued to intensify and reached Category 5 status on the morning of August 28. It attained its maximum intensity at 1 PM Central Daylight Time on August 28, with maximum sustained winds of 175 miles (280 kilometers) per hour and a minimum central pressure of 902 millibars. The pressure measurement made Katrina the fourth most intense Atlantic hurricane on record at the time and the most intense storm ever recorded in the Gulf of Mexico. However, it held these records for only a short time. Both records were broken by Hurricane Rita a few weeks later.

Katrina weakened in intensity as it approached land but remained a dangerous storm. It made its second landfall on the Louisiana coast southeast of New Orleans at 6:10 AM CDT on August 29 as a Category 3 hurricane with sustained winds of 125 miles (205 kilometers) per hour. At landfall, hurricane-force winds extended outward 120 miles (190 kilometers) from the center and the storm's central pressure was 920 millibars After moving across the Mississippi Delta and over Breton Sound, Katrina made its third landfall near the Louisiana-Mississippi border with sustained winds of 120 miles (195 kilometers) per hour—still a Category 3 storm.

Katrina maintained its status as a hurricane until it moved over 150 miles (240 kilometers) inland. It was finally downgraded to a tropical storm as it passed near Jackson, Mississippi, and to a tropical depression near Clarksville, Tennessee. The remnants of Katrina were still recognizable as it entered the Great Lakes region on August 31. It was then absorbed by a frontal boundary and became an extratropical cyclone. This storm then moved into Ontario and Quebec where it caused additional flooding and isolated several small villages.

The path also depends on the size and location of the Azores-Bermuda High, which varies over the course of the year.

Some hurricanes follow a smooth course, while others move erratically, shifting direction suddenly and inexplicably. For instance, some hurricanes that seem certain to spare the U.S. Atlantic Coast will turn to the west and crash onto shore. On the other hand, coastal communities may brace for a hurricane's onslaught only to be spared at the last minute as the storm turns back to sea.



Path of Hurricane Katrina, August 2005.

Hurricanes that form over the eastern Pacific, off the west coast of Mexico, generally move to the west or northwest and travel over the ocean until they dissipate. That is the reason we hear so little about those hurricanes. Occasionally, however, a Pacific hurricane will turn to the north or northeast and strike the west coast of Mexico. A handful of such hurricanes have devastated Mexican coastal communities over the past several decades. The remnants of those hurricanes have brought heavy rains and flooding to the U.S. Southwest and West Coast.

One would expect Hawaii to suffer from a large number of hurricanes, given that Hawaii lies in the path of hurricanes formed off the west coast of Mexico. But that is not the case. As it turns out, Hawaii is located far enough to the west that by the time most hurricanes reach it, they have been significantly weakened.

There have been exceptions to this rule, however. About once a decade, Hawaii is struck by a major hurricane. A notable hurricane in recent history is Hurricane Iniki, which hit the island of Kauai on September 11, 1992. Iniki caused $1.8 billion worth of damage and seven deaths.

The hurricanes that directly affect the United States are typically those formed over the tropical North Atlantic, the Caribbean, or the Gulf of Mexico. On average, six hurricanes form over those waters during each hurricane season, two or three of which strike the U.S. Atlantic or Gulf coasts. The primary factor that determines whether a hurricane hits the United States is the location at which the hurricane moves to the northeast. If a hurricane is still over the ocean when it changes course from northwest to northeast, it will miss the coast. However, some hurricanes move over land before they change direction.

The U.S. West Coast is rarely struck by hurricanes, because storms that form in the eastern Pacific are normally blocked by cold ocean currents. In September of 1932 a hurricane moved up the Gulf of California, producing gusty winds and heavy rainfall in the Arizona desert. In September of 1939, a tropical storm slammed into San Diego with winds of 52 miles (84 kilometers) per hour. In September 1976, a hurricane gusted to 76 miles (122 kilometers) per hour at Yuma, Arizona.

The effects of hurricanes

When a hurricane moves onto land, it is capable of causing tremendous damage. A hurricane's winds are assumed by most people to be its most destructive element, but this is often not the case. The winds do cause a great deal of damage, but floods caused by ocean swells and torrential rains cause the most hurricane damage. Floodwaters, both in coastal and inland areas, account for about 90 percent of hurricane fatalities. Another

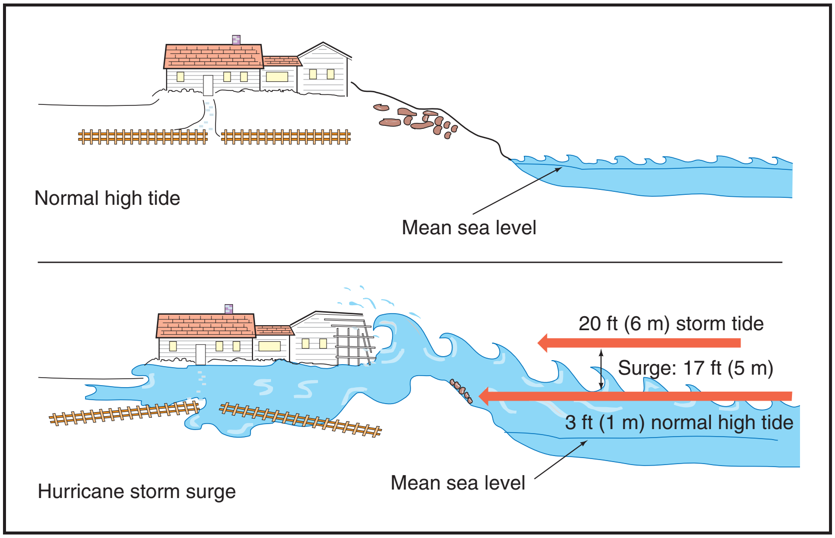
Buildings in downtown Kapaa, Hawaii, rest with their roofs split open in the aftermath of Hurricane Iniki. ©REUTERS/ CORBIS.

destructive force of hurricanes is the tornadoes that hurricanes spawn in their final stages.

Storm surges In coastal areas, most of the property damage, as well as about 90 percent of deaths, are due to the hurricane's storm surge. A storm surge is a wall of water that sweeps on shore when the eye of a hurricane passes overhead. Storm surges range from 3 to 6.5 feet (1 to 2 meters) in a weak hurricane, to over 16 feet (5 meters) in a strong hurricane. A storm surge affects a stretch of coastline between 40 to 100 miles (65 to 160 kilometers) long. It levels any structure in its path. When squeezed into narrow channels, a storm surge produces flooding of inland bays and rivers.

The abnormal swelling of the ocean that produces a storm surge is caused by the combined effects of a storm's pressure gradient and high winds. In the open ocean, strong winds and high pressure around the edges of the hurricane push down on water, lowering its level. The displaced water flows toward the center of the storm, where pressure is lowest. The water at the center rises and then spirals downward to about 200 feet (60 meters) beneath the surface, where it flows outward.

When the storm moves into shallow waters, there is no place for the mound of water beneath the storm center to descend. Thus, the water there is forced to pile upward. The mound of water reaches its greatest



A hurricane storm surge.

height where it crashes onto shore. The storm surge is highest in strong hurricanes, especially where the ocean floor slopes gradually to the shore.

The largest storm tide in recent U.S. history was 25 feet (8 meters). It was caused by Hurricane Camille in August 1969, which made landfall in Pass Christian, Mississippi. The storm tide destroyed more than 5,500 homes. In addition, it damaged around 12,500 homes and 700 businesses. The area of greatest destruction was along a 60 mile (97 kilometer) stretch of coastline in Mississippi, Alabama, and Louisiana. As far as 125 miles (201 kilometers) away, the water level was 3 feet (.9 meters) higher than usual.

The largest recorded storm surges have occurred in other parts of the world. In 1737, a storm surge estimated to be 40 feet (12 meters) tall struck the Bay of Bengal, killing more than three hundred thousand people. A storm surge of 42 feet (13 meters) inundated Bathurst Bay, Australia, in 1899.

The destructive capabilities of a storm surge are the result of two factors: the density of the sea water, which is about 64 pounds per cubic foot (1030 kilograms per cubic meter); and the debris that the water sweeps along. Debris may include boats that were ripped from their moorings by the waves, pieces of destroyed buildings, trees, and sand. As the water plus this debris moves farther onshore, it batters and flattens

Ten Deadliest Hurricanes to Strike the United States Since 1900

Hurricane	Year	Category	Deaths
Texas (Galveston)	1900	4	8,000–12,000
Florida (Lake Okeechobee)	1928	4	2,500–3,000
Katrina (Lousiana, Mississippi)	2005	3	1,836
Florida (Keys and S. Texas)	1919	4	600
New England	1938	3	600
Florida (Keys)	1935	5	408
Audrey (Louisiana and Texas)	1957	4	390
Northeast U.S.	1944	3	390
Louisiana (Grand Isle)	1909	3	350
Louisiana (New Orleans)	1915	4	275

anything in its path. A storm surge also destroys structures such as buildings, roads, and sea walls by eroding the sand and soil beneath them, causing them to buckle or collapse.

A storm surge may also have the secondary effect of causing flooding of inland bays and rivers. This flooding results when storm surge water is squeezed into narrow channels. Sometimes inland waters rise even higher above normal levels than coastal waters in the wake of a storm surge.

Winds The winds of a hurricane also cause a significant amount of damage to coastal areas. Hurricane winds range between 75 and 180 miles (120 and 290 kilometers) per hour. Winds of this strength can damage buildings and homes and knock down trees and telephone poles, as well as cause beach erosion. A hurricane's winds can totally demolish lightweight structures such as mobile homes and poorly constructed buildings.

Part of wind damage is due to objects that are picked up and hurled through the air. Shingles, metal siding, road signs, and any items left outdoors become deadly missiles during a hurricane.

Most wind damage from a hurricane occurs within 125 miles (200 kilometers) of the coast. Once a hurricane travels farther inland, it generally begins to weaken. Occasionally a hurricane will retain its strength for greater distances. In 1989, for example, Hurricane Hugo ripped through Charlotte, North Carolina, with winds gusting to 100 miles (160 kilometers) per hour. Charlotte is about 175 miles (280 kilometers) inland.

Heavy rain and flooding A hurricane's destruction is certainly not limited to coastal areas. To the contrary, for hundreds of miles inland,

The winds of Hurricane Beulah topple shrimp boats in Brownsville, Texas, in 1967.

and for several days after the hurricane-strength winds have died down, the storm may continue to produce torrential rains and flooding. When an area receives more than 6 inches (15 centimeters) of rain, flooding is likely. Hurricanes typically drop 5 to 10 inches (13 to 25 centimeters) on the land in their path. Some hurricanes have produced more than 25 inches (63 centimeters) of rain in a period of twenty-four hours.

Inland flooding is the most destructive element of some hurricanes. Examples of this include:

- Hurricane Diane in 1955 brought rains and flooding to Pennsylvania, New York, and New England. The flooding caused nearly 200 deaths and $4.2 billion in damage.
- Hurricane Camille in 1969 brought 9.8 inches (25 centimeters) of rain to Virginia's Blue Ridge Mountains. The storm resulted in 150 deaths.
- Tropical storm Claudette in 1979 dumped 45 inches (114 centimeters) of rain outside of Alvin, Texas, resulting in over $600 million in damage.

Heavy rains due to hurricanes are not always harmful. These rains may spell relief for regions with parched soil and withering crops. In some cases, the value of saved crops in one region is greater than the value of property destroyed by the flooding in another region. In some areas of the world, particularly in the Far East, farmers are dependent on annual hurricane rains for their economic survival.

Tornadoes Tornadoes are another hazard of hurricanes. About one-quarter of all hurricanes that come on shore in the United States produce tornadoes. A single hurricane, on average, spawns ten tornadoes.

The thunderstorms embedded in the outer regions of a hurricane are the most likely to spawn tornadoes, although tornadoes also form in thunderstorms close to the eye wall. The greatest number of tornadoes are produced in the portion of the hurricane that is northeast of the eye.

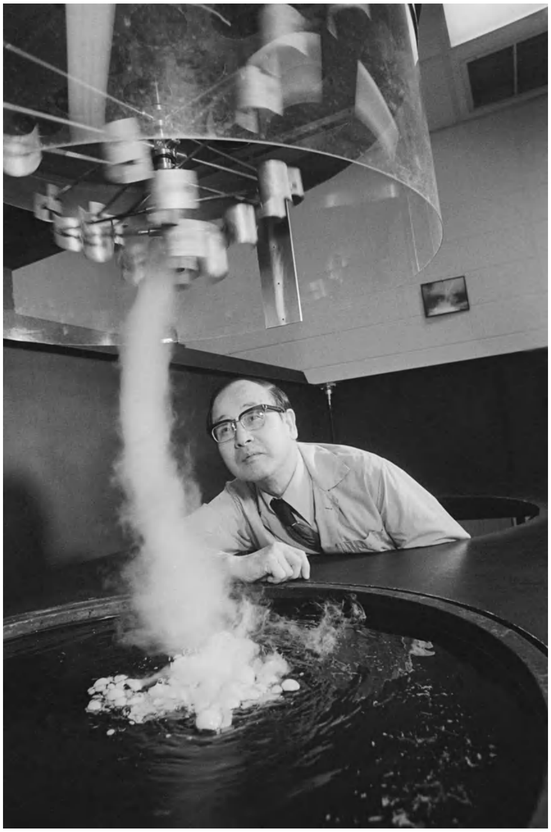
Theodore Fujita, a tornado specialist from the University of Chicago, is the author of a recent theory that the greatest damage from hurricane-induced tornadoes is caused by small funnels called spin-up vortices. These vortices are each 9 to 30 feet (3 to 10 meters) in diameter and last only about ten seconds. The hurricane winds combine with the tornado winds, so the vortices produce winds of around 200 miles (320 kilometers) per hour.

Ranking hurricanes by strength As with tornadoes, hurricanes are ranked according to their strength. However, there is one main difference: Tornadoes are classified *after* they have struck an area based on the *actual* damage they have created, while hurricanes are categorized *before* they strike land based on their *potential* damage to coastal areas.

Each hurricane is placed into one of five categories according to its strength, described in the Saffir-Simpson Hurricane Damage Potential Scale. This scale was developed in the early 1970s by Robert Simpson, then director of the National Hurricane Center, and Herbert Saffir, an engineer who designed Miami's hurricane-proof building code.

According to the Saffir-Simpson scale, hurricanes in Category 1 are the weakest and hurricanes in Category 5 are the strongest. The factors that determine a hurricane's strength include: air pressure at the eye of the storm; range of wind speeds; potential height of the storm surge; and the potential damage caused. The categories of potential damage are defined as follows: 1) minimal; 2) moderate; 3) extensive; 4) extreme; and 5) catastrophic. A hurricane's ranking is upgraded or downgraded as it goes through its stages of development.

Saffir-Simpson hurricane intensity scale Most of the hurricanes that strike the United States are Category 1 or 2. Only two hurricanes ranked as Category 3 or higher strike the United States every three years, on average.



Theodore Fujita works with his tornado simulator. ©BETTMANN/CORBIS.

Of the 126 tropical storms or hurricanes that hit the United States between the years 1949 and 1990, only 25 were Category 3 or higher. Those twenty-five storms, however, caused three-quarters of all property damage done by tropical storms or hurricanes during that period.

Category 5 hurricanes are the rarest kind—the United States only experienced three of them during the entire twentieth century. The first was a hurricane on Labor Day, 1935 (the practice of hurricane naming did not begin until 1953), the second was Hurricane Camille in 1969, and the third was Hurricane Allen in 1980. (The hurricane that leveled Galveston, for example, would have been listed as a Category 4.)

The human factor

People have always settled in hurricane-prone regions. This creates great risk for property damage when hurricanes strike. The effects of global warming, reportedly made worse by pollution, may be having an effect on hurricanes. The world—including the oceans—has been warming at a dramatic rate in recent years. Many scientists claim that as temperatures continue to rise, we can expect hurricanes to increase in number and size.

For people who live in areas affected by hurricanes, it is essential to understand and follow safety procedures. That includes making preparations before the hurricane season begins, knowing what to do when a hurricane watch or warning is issued, and how to respond once a hurricane has passed.

To prepare for hurricane season, you must understand the risks that hurricanes pose to your area, learn the evacuation routes inland, and find out where emergency shelters are located. It is also crucial to develop a safety plan for your family and keep a disaster kit on hand. A kit should include the following for each person: nonperishable food; three gallons of bottled water; one change of clothing and footwear; one blanket or sleeping bag; first aid kit; flashlight, radio, and batteries; extra set of car keys; credit card or cash; and diapers for infants.

The U.S. government's failed Katrina response

The destruction caused by Hurricane Katrina shocked the world. Almost as surprising, though, was the state and federal government's slow and awkward response to the disaster. Thousands of people were stranded for days on rooftops and highway overpasses, and in homes, hospitals, the Superdome, and the convention center. Food, water, and basic supplies were delayed for days. Many people died while a horrified nation looked on.

The first failures in dealing with Hurricane Katrina were failures of prevention and readiness. Experts from the U.S. Army Corps of Engineers had long predicted that the New Orleans levee system would not withstand a "megahurricane." For years the Army Corps had been asking the federal government for money to bolster the levees, but they would have needed to have begun the work long before in order to prevent the Katrina breaches.

Once the storm neared land, the government urged evacuation. However, the evacuation plan left thousands behind. It is estimated that as many as one-third of the citizens of New Orleans did not own a car, and thus many of those people were left without a way to flee.

The Federal Emergency Management Agency, or FEMA, which falls under the department of Homeland Security, is the primary agency responsible for handling a disaster like Katrina. In the days following the hurricane, President George W. Bush praised FEMA, saying they were doing a "heck of a job." However, the realities of the situation in New Orleans were bleak. People were desperate and starving, and the city began to descend into a state of civil unrest. President Bush decided to survey the area by airplane, flying low over the Gulf Coast Region so he could get a first hand look at the devastation. By Friday of that week, Bush declared that government response was "not acceptable." That same week Congress called for an investigation of the botched response to the disaster. Further investigation revealed that FEMA chief Michael Brown was possibly not qualified to lead such a major disaster relief effort.

Other parts of the relief efforts were troubled as well. On Thursday after the hurricane, Homeland Security Chief Michael Chertoff claimed on National Public Radio to be unaware of the sickness, hunger, and unrest at the Superdome. State and local agencies were at times reluctant to cooperate with FEMA, and communication failures abounded. One of the major lessons of Hurricane Katrina was that federal, state, and local government entities need to improve their cooperation and preparedness for major hurricanes like Katrina.

Hurricanes in the United States

The part of the United States that experiences the greatest number of hurricanes is the Florida Keys. Forty-three hurricanes have hit the Keys in the last one hundred years. The places where hurricanes pose the greatest threat to humans, however, are the barrier islands that exist along portions of the Atlantic Coast and Gulf Coast. In the United States, people place themselves in the path of danger by settling in those areas most vulnerable to hurricane damage—the barrier islands.

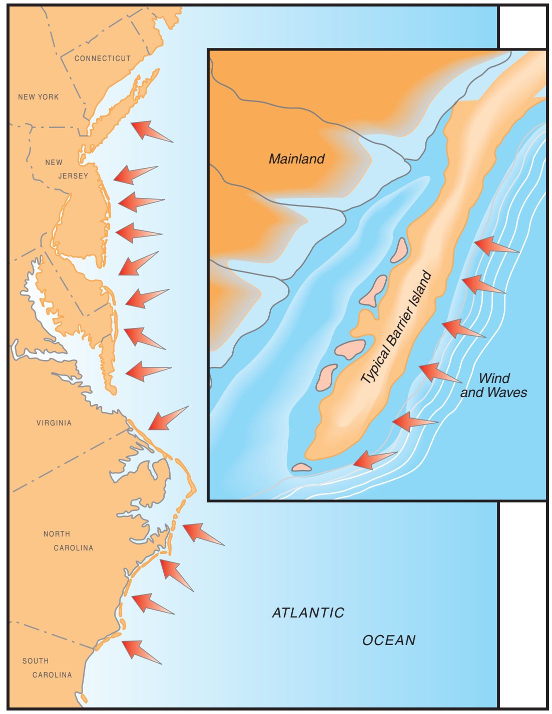
The barrier islands are long, narrow strips of sand that run parallel to a 2,000-mile-long (3,200-kilometer-long) Atlantic and Gulf coastline from New York to Texas. Examples of barrier islands include New York's Fire Island, Texas's Galveston Island, North Carolina's Outer Banks, and the Sea Islands off the coasts of South Carolina and Georgia. Barrier islands, which stand only 5 to 10 feet (1.5 to 3 meters) above sea level, bear the brunt of a hurricane's wind and waves and provide the mainland with a buffer from the storm. The islands respond to hurricane beatings by moving—the sand actually becomes redistributed by the waves.

Despite the fact that living on the islands is known to be dangerous, people continue to settle there. In fact, in recent years the islands have seen a huge increase in construction of housing, hotels, and businesses geared toward tourism. In some parts of the world, people have no choice but to live in hurricane-prone regions. Bangladesh, for instance, is a magnet for hurricanes (called cyclones in that region of the world). Its coastal region endured seven of the nine deadliest hurricanes of the twentieth century. Bangladesh is also a densely populated, desperately poor country. For residents of the coast, moving inland would mean squeezing into already overflowing urban slums. But in the United States, people happily choose to settle on hurricane-prone barrier islands. Drawn by the beauty of the ocean, they pay top dollar for beach residences and flock to the islands for their vacations.

Before 1940, only 10 percent of Atlantic and Gulf Coast barrier islands held houses or hotels. Development steadily increased from that time. Many islands today are wholly buried under concrete and buildings.

Hurricane Fran, in 1996, battered North Carolina's southeastern barrier islands. Houses, cottages, condominiums, and cars were strewn across the beach and washed out to sea. Twenty-four people died in the storm, and property damage totaled $2 billion. The following week, people began rebuilding on those islands. Barrier island development is such an attractive business proposition, in part, because U.S. taxpayers—through the National Flood Insurance Program, the Federal Emergency Management Agency's Disaster Relief Program, and the Army Corps of Engineers' shoreline stabilization projects—regularly pay for storm damage.

Another danger specific to barrier islands is that once a hurricane warning has been issued, evacuation is difficult. Since construction of evacuation routes has not kept pace with the islands' population growth, bridges connecting the islands to the mainland become choked with traffic.



Atlantic coast barrier islands.

Hurricane watches and warnings The ability of weather forecasters to warn the public of potential hurricane strikes has greatly increased in recent decades. Some of the sophisticated technologies that are now used to detect and track tropical cyclones include radar, weather satellites, and weather aircraft. Although the erratic nature of hurricanes makes it impossible to predict exactly when and where they will strike, forecasters can now guess at the answers to these questions with a fair degree of certainty.

When a hurricane threatens a coastal area, hurricane watches and warnings are issued. If the hurricane is predicted to be life threatening, the residents of that area are evacuated. Hurricane watches and warnings are issued by the Tropical Prediction Center (formerly the National Hurricane Center), a branch of the National Weather Service.

A hurricane watch is issued when a hurricane is headed in the general direction of an area. It means that hurricane conditions are *possible* in the area. Hurricane watches are announced at least thirty-six hours, and sometimes several days, in advance.

If a hurricane is poised to strike an area within twenty-four hours, a hurricane warning is issued. It means that hurricane conditions are *expected* in the area. For each community within the warning area, meteorologists will also issue the probability of the hurricane's center coming within 65 miles (105 kilometers) of that community. The probability is intended to give residents an idea of the type of damage likely to occur in their area. It is also considered in the decision as to whether or not evacuation is necessary.

This distance is about three times the area that will actually be affected once a hurricane comes onshore. The reason the warning area is so large is that

Hurricane Andrew: The costliest natural disaster of the twentieth century

In August 1992, Hurricane Andrew struck Florida and Louisiana, causing fifty-eight deaths and $30 billion in damage. Over 200,000 homes and business were damaged or destroyed, and 160,000 people became homeless. Andrew, which made landfall as a Category 4 hurricane, was the costliest natural disaster of the twentieth century in the United States.

On August 21, Andrew, which was then classified as a tropical storm in the Atlantic, appeared to be weakening. However, it then moved over warmer waters and rapidly gained strength. On August 21, its winds were only 52 miles (84 kilometers) per hour. Two days later, its winds had increased to 140 miles (225 kilometers) per hour, and Andrew had developed into an intense hurricane.

Andrew came on shore at Homestead, on the southern tip of Florida, on August 24. With winds that peaked at about 200 miles (320 kilometers) per hour and a storm surge 16.9 feet (5.1 meters) tall—a record for Florida—Andrew devastated the town. It leveled trees, utility poles, and fifty thousand homes.

Andrew then traveled westward, over land, and into the Gulf of Mexico. While Andrew had weakened during its journey across the land, it regained strength over the Gulf's warm waters. On August 25, Andrew blew into Louisiana with winds of 138 miles (222 kilometers) per hour. There, Andrew continued its relentless destruction of property.

Andrew's death toll was relatively low due to the efficiency of prediction and warning systems. Over 1 million people in Florida and 1.7 million people in Louisiana and Mississippi were evacuated from areas in the storm's path. Had Andrew occurred in the first half of the 20th century, before the development of sophisticated hurricane-detecting technology, the death toll would have certainly been much higher.

it is possible for a hurricane to change course at any time, making it impossible to predict the exact point at which the hurricane will make landfall.

For people who live in areas affected by hurricanes, it is crucial to know and follow certain safety procedures. These procedures include making preparations before the hurricane season begins; knowing what to do when a hurricane is in progress; and taking certain steps after the hurricane has passed.

For more information about the dangers hurricanes pose to your area and hurricane preparedness, contact your local office of the National Weather Service, American Red Cross, or Federal Emergency Management Agency.

What to do when you are within a hurricane watch area:

- Stay tuned to radio or television reports of the storm's progress.
- Fill your car with gas and get cash, if needed.

- If you live in a mobile home, make sure it's securely fastened, then evacuate.
- Cover all windows and doors with shutters or plywood.
- Check your supply of nonperishable food and water.
- Gather first aid materials and medications.
- Bring lawn furniture, garbage cans, garden hoses, and other lightweight items inside.
- If you have a boat, be sure it is properly secured.
- Evacuate if you live in a mobile home or high-rise, on the coastline, on an offshore island, or near a river or flood plain.

What to do when you are within a hurricane warning area:

- Stay tuned to radio or television reports of the storm's progress.
- Finish covering your windows and doors and prepare your home for evacuation.
- Evacuate immediately upon the orders of local officials and travel inland, to the home of a friend or relative, a low-rise motel, or an emergency shelter.
- Notify someone outside of the hurricane warning area of your evacuation plans.
- If you have pets that you are unable to take with you, leave them plenty of food and water.

If you are staying at home:

- Fill the bathtub and containers with drinking water, unplug small appliances, turn off propane tanks, and turn your refrigerator to its coldest possible setting.
- In case of strong winds, close all outside and inside doors and go into a small interior room or hallway on the first floor, away from windows and doors. If possible, crouch beneath a sturdy piece of furniture.

What to do after the hurricane:

- Stay tuned to the radio or television for information.
- Don't return home until your area has been declared safe.
- Don't attempt to drive around a barricade; if you encounter one, turn around and take a different route.
- Don't drive on roads or bridges in flooded areas or on washed out roads.

- Inspect your gas, water, and electrical lines for damage before using.
- Be sure that your tap water is not contaminated before drinking or cooking with it.
- Make as few calls as possible so you don't tie up phone lines.

Naming hurricanes Before 1950, hurricanes were identified primarily by their latitude and longitude. This practice became confusing as hurricanes moved about, especially if there was more than one hurricane at the same time on the same ocean.

In 1950, meteorologists began the practice of assigning names to all hurricanes and tropical storms that formed in the western North Atlantic, Caribbean, and Gulf of Mexico. They began naming eastern Pacific storms in 1959. From 1950–53, names were taken from the international radio codes words that corresponded with letters of the alphabet. For instance, the first three letters—"a," "b," and "c"—had the names Able, Baker, and Charlie.

In 1953, meteorologists began giving the storms female names. The names were assigned in alphabetical order, starting with the "As" for each new season. Since 1978 in the eastern Pacific, and 1979 in the northern Atlantic, male names, as well as names in French and Spanish, have also been used.

Names are now assigned in advance for six-year cycles. The names are submitted by countries that lie in the path of hurricanes and must be approved by the Region 4 Hurricane Committee of the World Meteorological Organization, which is made up of representatives of countries affected by hurricanes.

After the six-year cycle has ended, the names are reused, except for names that are retired. The names of hurricanes that cause extensive damage or loss of life, such as Gilbert, Isabel, and Andrew, are removed from the list for at least ten years. Katrina was retired from the list after the 2005 season and was replaced by Katia. A total of five names—Dennis, Katrina, Rita, Stan, and Wilma—retired in 2005 breaks the previous single-season record of four retired names, reached in 1955, 1995, and 2004.

The list for the tropical North Atlantic normally includes twenty-one names. The letters Q, U, X, Y, and Z are not used. In a typical year, twenty-one names are more than enough. But 2005 set a record for the

Names for Hurricanes Through the Year 2011

Eastern Pacific Hurricane Names

2007	2008	2009	2010	2011
Alvin	Ima	Andres	Agatha	Adrian
Barbara	Boris	Blanca	Blas	Beatriz
Cosme	Cristina	Carlos	Celia	Calvin
Dalila	Douglas	Dolores	Darby	Dora
Erick	Elida	Enrique	Estelle	Eugene
Flossie	Fausto	Felicia	Frank	Fernanda
Gil	Genevieve	Guillermo	Georgette	Greg
Henriette	Hernan	Hilda	Howard	Hilary
Ivo	Iselle	Ignacio	Isis	Irwin
Juliette	Julio	Jimena	Javier	Jova
Kiko	Karina	Kevin	Kay	Kenneth
Lorena	Lowell	Linda	Lester	Lidia
Manuel	Marie	Marty	Madeline	Max
Narda	Norbert	Nora	Newton	Norma
Octave	Odile	Olaf	Orlene	Otis
Priscilla	Polo	Patricia	Paine	Pilar
Raymond	Rachel	Rick	Roslyn	Ramon
Sonia	Simon	Sandra	Seymour	Selma
Tico	Trudy	Terry	Tina	Todd
Velma	Vance	Vivian	Virgil	Veronica
Wallis	Winnie	Waldo	Winifred	Wiley
Xina	Xavier	Xina	Xavier	Xina
York	Yolanda	York	Yolanda	York
Zelda	Zeke	Zelda	Zeke	Zelda

North Atlantic Hurricane Names

2007	2008	2009	2010	2011
Andrea	Arthur	Ana	Alex	Arlene
Barry	Bertha	Bill	Bonnie	Bret
Chantal	Cristobal	Claudette	Colin	Cindy
Dean	Dolly	Danny	Danielle	Don
Erin	Edouard	Erika	Earl	Emily
Felix	Fay	Fred	Fiona	Franklin
Gabrielle	Gustav	Grace	Gaston	Gert
Humberto	Hanna	Henri	Hermine	Harvey
Ingrid	Ike	Ida	Igor	Irene
Jerry	Josephine	Joaquin	Julia	Jose
Karen	Kyle	Kate	Karl	Katia
Lorenzo	Laura	Larry	Lisa	Lee
Melissa	Marco	Mindy	Matthew	Maria
Noel	Nana	Nicholas	Nicole	Nate
Olga	Omar	Odette	Otto	Ophelia
Pablo	Paloma	Peter	Paula	Philippe
Rebekah	Rene	Rose	Richard	Rina
Sebastien	Sally	Sam	Shary	Sean
Tanya	Teddy	Teresa	Tomas	Tammy
Van	Vicky	Victor	Virginie	Vince
Wendy	Wilfred	Wanda	Walter	Whitney

Watch this: *When the Levees Broke: A Requiem in Four Acts*

Director Spike Lee created this wrenching 2006 HBO (Home Box Office) documentary about Hurricane Katrina and its aftermath using new footage and interviews with government official and survivors. The documentary includes very little narration. Instead, Lee lets the images and the people tell the story themselves.

number of named storms. The letters V and W were used for the first time (for Hurricanes Vince and Wilma). Even those were not enough. When the names in a list are exhausted, the World Meteorological Organization specifies that letters of the Greek alphabet be used. For the 2005 season, six letters were necessary. The twenty-eighth and last named storm of 2005 was Tropical Storm Zeta, which formed on December 29, well past the normal end of the hurricane season.

Presently, each hurricane-producing region of the world (except the northern Indian Ocean, where cyclones are not named) has its own lists of names, drawn up years in advance. Each storm is automatically assigned the next name on the alphabetical list.

Technology connection

The ability of weather forecasters to warn the public of potential hurricane danger has greatly increased in recent years. Forecasters are presently able to predict, within 200 to 250 miles (320 to 400 kilometers), where a storm will be three days in the future. Forecasters at the National Hurricane Center in Miami issued their most accurate prediction yet in September 1999, when they stated that Hurricane Floyd would spare Florida and head north before striking North Carolina. As it was, Floyd missed the Florida coast by a mere 50 miles (80 kilometers).

Predictions of where a hurricane will hit land are used by public officials when calling for evacuations. Forecasters want to be as certain as possible in their predictions before recommending evacuations. If an area is evacuated only to be spared by the hurricane, residents become less likely to heed evacuation notices in the future. That attitude is perilous, since the next evacuation could be a matter of life and death. Forecasters also wish to avoid unnecessary evacuations because they are very costly. Each day of evacuation represents $1 million of lost business revenues for every mile of coastline.

Two of the most useful instruments used by hurricane researchers to detect and track tropical storms are weather aircraft and weather satellites.

Gulfstream II flies over Los Angeles, California. ©TECMAP CORPORATION/ERIC CURRY/CORBIS.

Weather aircraft Weather aircraft determine the intensity of hurricanes by probing storm clouds in upper levels of the atmosphere. They measure temperature, air pressure, and wind speed and direction. These planes have reinforced wings and bodies, in order to withstand the hail, ice, and strong winds they encounter within the clouds. The weather instruments are carried in pods beneath the plane's wings or attached to its nose cone.

In 1996, the U.S. National Oceanic and Atmospheric Association (NOAA) acquired a hurricane research jet, called the Gulfstream IV-SP. The jet can cruise right through these storms at heights of up to 45,000 feet (13,725 meters). It contains sensors that measure air pressure, temperature, humidity, and wind speed at the edges and the core of the storm. It also releases hundreds of dropwindsondes, also called dropsondes, which are instruments that transmit data on atmospheric conditions as they fall through the storm. The information collected by the jet is combined with readings taken at ground stations in order to better determine where a hurricane is headed.

Weather satellites Weather satellites, which circle the globe in space, provide meteorologists with pictures and other information about hurricanes and tropical storms. The first weather satellite, launched in April 1960, was TIROS 1—Television InfraRed Observation Satellite. In September 1961 weather satellites proved their value when they broadcast images of Hurricane Carla. Information from these images resulted in the nation's first widespread evacuation when 350,000 people along the Gulf Coast were removed from the path of the killer hurricane.

For most people, the words "weather satellite pictures" conjure up images of swirling clouds that are seen on television newscasts. While weather satellites do produce those photos, their function is far more extensive than that. Weather satellites determine the temperature at various atmospheric levels—from the cloud tops down to the land and oceans. They also measure humidity and wind speeds in the upper air and even track plumes of invisible water vapor and relay information from one ground station to another and pick up and transmit distress signals from vessels in the air and at sea. Today, several nations operate satellites that continuously monitor global weather.

[*See Also* **Clouds; Forecasting; Thunderstorm; Tornado; Weather: An Introduction**]

For More Information

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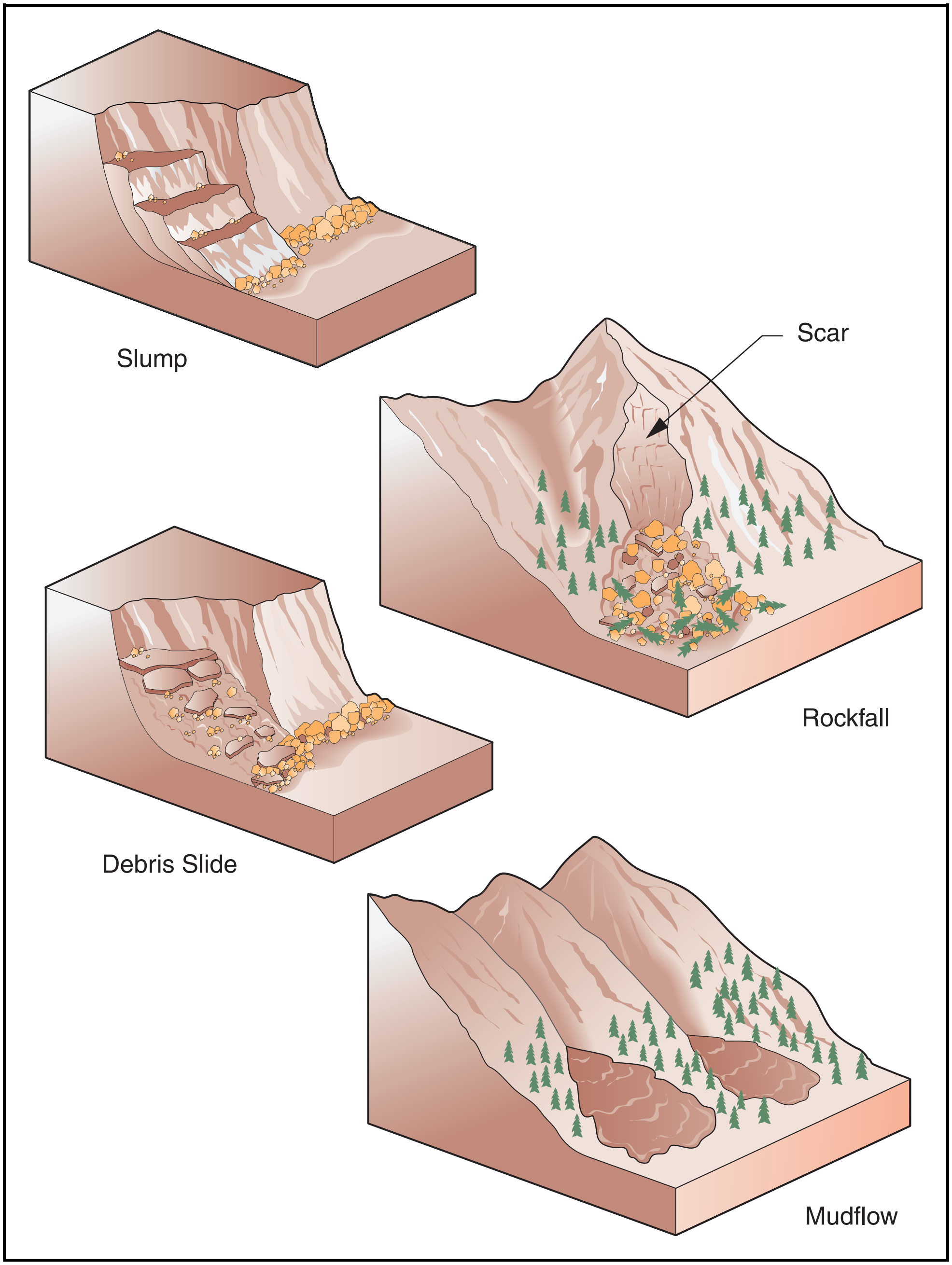
Landslide

A landslide is the movement of large amounts of soil, rocks, mud, and other debris downward along a slope. The movement is caused by the pull of gravity and occurs when a mountainside or hillside weakens and is unable to support its own weight. The amount of material that falls in a landslide can be as small as the size of a refrigerator or as large as an entire mountainside. The falling material can move slowly or quickly, and may travel a few feet (meters) or several miles (kilometers) before it stops. Some landslides move only a little each year. Such movement may be irregular, or it may happen at the same time each year, such as in the spring, when the snow melts.

The most common cause of landslides is excessive moisture in the ground, because of heavy rains or melting snow. When the ground becomes so full of water it cannot hold any more, the soil loses its ability to stick together. It also becomes heavier, which hastens its movement down the slope. Not all landslides are caused by water. Earthquakes, the sudden movements of earth which release huge amounts of energy, trigger the largest and most devastating landslides. Other events that cause landslides include volcanoes and vibrations from explosions or heavy traffic. Human activities, such as mountainside development and mining, also contribute to instability on slopes. Forest fires are indirect causes of landslides, since they remove the vegetation and roots that hold the soil in place.

While rapid landslides cause the greatest loss of life and property, even slow landslides can cause structural damage to buildings and rupture underground power lines and water mains. Each year in the United States, landslides cause between twenty-five and fifty deaths and up to $2 billion in damage. In less developed nations, where there are often less strict zoning laws (allowing construction in landslide-prone areas), higher population densities, and a lack of protective structures, the death tolls and amount of property damage are much higher.



Four different types of landslides.

WORDS TO KNOW

debris avalanche: a downward slide of loose, earthen material (soil, mud, and small rocks) that begins suddenly and travels at great speeds; similar to a snow avalanche. It builds into a fearsome mass of mud, trees, and rocks that can cause much damage.

debris slide: a slide of small rocks and shallow layers of loose soil that commonly follows volcanic eruptions.

deforestation: the removal of all or most of the trees from a region.

earthflow: a landslide that consists of material that is moist and full of clay, yet drier than the material in mudflows.

earthquake: a sudden shifting of masses of rock beneath Earth's surface, which releases enormous amounts of energy and sends out shock waves that cause the ground to shake.

erosion: the removal of soil by water or wind. This is especially harmful when the uppermost layer of soil, called the topsoil, is stripped away, because this is the layer where plants grow.

fall: the downward motion of rock or soil through the air or along the surface of a steep slope.

lahar: a mudflow composed of volcanic ash and water that occurs in the wake of a volcanic eruption.

landslide: the movement of large amounts of soil, rocks, mud, and other debris downward and outward along a slope.

mudflow: a landslide consisting of soil mixed with water. It is wetter than the material in an earthflow.

rock slide: a cascade of rocks (of any size) down a steep slope at high speeds.

saturated: containing the maximum amount of water a material can hold.

slump: the slow downhill movement of large portions (called blocks) of a slope. Each block rotates backward toward the slope in a series of curving movements.

solifluction: the most rapid type of earthflow, occurring when snow or ice thaws or when earthquakes produce shocks that turn the soil into a fluid-like mass.

volcano: an opening in Earth's surface through which gases, hot rocks, and ash are ejected from the heated inner portion of the planet.

The Frank slide

In the early morning hours of April 29, 1903, a block of limestone approximately 0.5 square miles (0.8 square kilometers) in area cascaded onto the coal mining village of Frank in south-central Alberta, Canada. The limestone, which weighed 50 million to 90 million tons (45 million to 82 million metric tons) and was 500 feet (152 meters) thick, came hurtling down from a height of 3,100 feet (945 meters) between two peaks of Turtle Mountain. Seventy-six people were killed instantly in the

The Frank Slide Interpretive Center near the site of a 1903 rock slide that buried the town of Frank in Alberta, Canada. ©DAVE G. HOUSER/CORBIS.

landslide, although some records place the number as high as ninety. In addition to burying part of the town, the fallen rock dammed the Crowsnest River and created a new lake.

Native inhabitants feared the mountain The native people, who were the original inhabitants of the region, recognized the dangers of Turtle Mountain. The mountain had been named for its shape, which resembled a turtle's shell and had a slab of limestone sticking out like a turtle's head. To the Indians, it was "the mountain that walked." Fearing a rock slide, the native people shunned the idea of settling, or even so much as camping, at the base of the mountain.

Turtle Mountain was indeed geologically unstable, meaning it had little resistance to sliding or collapsing. The twin-peaked mountain was composed of weather-worn limestone near its peak and soft stone laced with veins of coal at lower altitudes. The angle of the mountain was especially steep on the eastern slope, and the face had developed cracks. Along the cracks, the rock was fragmented. An earthquake two years prior to the rock slide had made the rock fragmentation worse. Further weakening of the rock foundation was brought about by the tunneling of coal mining shafts, which were dug about 1 mile (1.3 kilometers) into the mountain.

Frank established as a mining town The town of Frank was incorporated on September 10, 1901, just eleven months after a coal deposit had been discovered at the base of the mountain. It was named after H. L. Frank, a banker from Montana who had funded a mining operation to extract the coal. He persuaded adventurous frontiersmen, many of them recent arrivals from Europe, to travel to Turtle Mountain and work in the mine. He also paid the Canadian Pacific Railway to run railroad tracks from the main line to the mine entrance. By the time the town of Frank was established, miners were extracting hundreds of tons of coal each day.

The town of Frank looked just like a Hollywood set for a Western movie. Among the company buildings—miners' cabins, office buildings, and a boarding house—sprang up hotels, saloons, and casinos. The miners spent a significant portion of their earnings on drinking and gambling. By the spring of 1903, Frank had a population of approximately six hundred people.

The mountain tumbles down In the months prior to the landslide, miners had reported numerous sounds that should have been taken as warnings of the mountain's instability. The wooden supports in the tunnels groaned loudly and the tunnel walls shook. The vibrations had become so violent that coal literally dropped from the ceiling, forming piles that the miners merely had to shovel into cars. The night before the landslide, the mountain emitted a rumble that could be heard throughout the valley. Area residents ignored the noise and went to sleep.

Disaster struck at 4:10 AM the next morning. According to Sid Choquette, a brakeman on the railroad who had been walking alongside a slow-moving train, the mountain began to creak and groan loudly, then emitted an eerie whistling roar. Next Choquette heard a sound like cannon fire and saw a huge slab of rock racing down the slope, right toward the town. Choquette jumped aboard the train and the engineer set the controls on full-throttle. The train raced for the bridge that spanned the Crowsnest River and made it across just moments before the avalanche of rocks wiped out the bridge. The railroad crew watched, stunned, as millions of tons of limestone plowed through the south side of Frank, continued 2.5 miles (3.2 kilometers) across the valley floor, and then climbed 400 feet (122 meters) up the opposite slope.

In a little more than a minute the rock slide, plus a wall of cold air that forcefully thrust ahead of it, leveled much of the town of Frank, killing many of its residents. Three-quarters of the houses were destroyed, as were the electric power plant, the livery stable, the shoe store, the miners' temporary quarters, the construction camp, the cemetery, and more than 1 mile (1.6 kilometers) of the Canadian Pacific Railroad. The debris tumbled into the river, blocking the flow of water, and portions of the railroad tracks were covered by rocks 100 feet (30 meters) deep. Structures were ripped apart, flung across the valley, and then buried forever by the massive limestone boulders. Only twelve bodies were recovered, and the exact number of dead was never determined. Because there were no accurate records of the number of inhabitants at the time, it was impossible to compile a list of the missing.

Trapped miners dig themselves out When the rocks fell, seventeen workers were inside the mine and three others were taking a lunch break outside the entrance. The rock slide fell on the entrance, killing the three men outside and trapping the others inside. The miner most familiar with the mine's layout informed his trapped co-workers that they were at least 295 feet (90 meters) from the edge of the mountain. The miners knew they had to act quickly if they were going to get out alive. They realized the airshafts were probably blocked, meaning that breathable air would be in short supply. They were also concerned that explosive and lethal gases might be escaping from cracks in the rock walls.

The miners first tried to tunnel outward, but made little progress. Every time they dug into the wall, more rock tumbled down to fill in the space. After a few hours they tried a new strategy: digging upward, along a vein of coal. The coal was softer and easier to remove than the limestone. Three men dug at a time. They worked in shifts, making slow but steady progress. About thirteen hours after the rock slide, the miners reached the surface. They climbed out onto the mountainside and looked in horror upon the devastation below.

Rescue efforts People in Frank not directly in the rock slide's path were shaken from their slumber by the loud roar. Stunned, they staggered into the streets to see what had happened. Seeing fires and hearing screams for help, some people grabbed their lanterns and rushed toward the wreckage. The avalanche, however, spared few of those it touched. Rescuers only found twenty-three people alive in the landslide's path.

At one ruined home, merchant Alex Leitch and his wife and four sons were found dead. At another home, Sam Ennis had dug himself out of the rubble and worked with rescuers to free his wife, Lucy, from a beam that had fallen on her. Even while trapped, Lucy Ennis had managed to save their baby daughter, Gladys, who was choking on a clod of dirt. Sam

Ennis' brother-in-law, James Warrington, was also buried beneath a pile of rocks. Warrington warned rescuers to dig gingerly, since he felt something soft beneath him. It turned out that Warrington had landed on top of his next-door neighbor, Mrs. Watkins, who had been thrown from her own house.

On the railroad tracks, brakeman Sid Choquette, still shaken from his brush with death, turned his attention to the passenger train that was due to arrive in an hour. If it wasn't warned, the train would crash into the rock-covered tracks. He made his way through the cloud of dust that hung in the air and across rocks the size of small buildings until he arrived at the tracks on the east side of the rockpile. With only minutes to spare, he was able to flag down the train and prevent a second disaster.

The aftermath of the slide It was later determined that the slide had been set in motion when a sudden cold spell caused water from melting snow to freeze within the cracks. The freezing water had expanded as it turned to ice and had forced the cracks to widen, sending the rocks tumbling down the slopes.

The mine reopened briefly after the landslide, only to be shut down by a fire in 1905. H. L. Frank suffered a nervous breakdown and was placed in a mental institution; he died there in 1908. The mine reopened one more time, but was permanently closed in 1918. Today, about two hundred people live in the town of Frank.

Recent devastating landslides

On February 17, 2006, a series of mud slides caused widespread damage and loss of life in the Philippine province of Southern Leyte. Over 80 inches (200 cm) of rain had fallen in ten days, loosening the soil. Deforestation, the removal of all or most of the trees, of mountain slopes may have contributed to the unstable conditions. The actual landslide was triggered by small earthquake of magnitude 2.6 on the Richter scale.

Devil's Slide is an area of California State Highway 1 that suffers from frequent blockage and damage due to slides and slumps, which are slower downhill movements. The most recent closure was in April of 2006, when longitudinal cracks appeared in the roadway. The highway was reopened for limited use in August 2006. Efforts to build a bypass around Devil's Slide that would have bisected a California state park were opposed by environmentalists concerned with loss of valuable and ecologically sensitive coastal habitat. Instead, California is constructing a tunnel, with completion set for 2011.

Mudflows strike southern Italy

Two days of heavy rains set off deadly mudflows in the Campania region of southern Italy on May 5, 1998. The rivers of mud that rushed down from the mountains flowed into several towns across a 35-mile (60-kilometer) stretch from Sarno to Naples. One week after the disaster the death toll was 139, with an estimated 146 people still missing. The majority of the fatalities occurred in Sarno.

The mudflows were so forceful that they inundated buildings, destroyed homes, and buried people. At least fifteen hundred people were left homeless. After the disaster, the streets of the affected towns were wastelands of mud, wood, boulders, and other debris. Telephone, electricity, and water service were cut off. The mudflows were among Italy's worst natural disasters of all time; they were nicknamed by the Italian media the "Pompeii of the Year 2000," after the famous volcanic eruption that took thousands of lives in 79 CE.

Several thousand soldiers, firefighters, and military personnel from a nearby U.S. Navy base searched for survivors. They freed several people trapped in homes or cars. Searchers found a man who, for three days, had been buried up to his neck in mud in his cellar. Rescue workers used bulldozers and shovels to clear streets of hardened mud, which in some places was 10 feet (3 meters) high.

The damage from the mud slide was blamed on lax construction codes, which allowed the building of houses in areas known to be vulnerable to mud slides. Another factor was the illegal building of houses in areas where construction had been off-limits. The intensity of the mud slides was due, in part, to recent forest fires that had stripped the slopes of vegetation.

Mud slides devastate the south of Naples in 1998. ©CORBIS SYGMA.

Experiment: What triggers a landslide?

You can trigger a landslide right in your own home or classroom. Here is what you will need:

- newspaper or plastic sheeting—this is a messy experiment!
- a cardboard milk carton with one side cut away
- "land" materials, like pebbles, sand, dirt, and clay
- small watering can or a soda bottle
- graduated cylinder or measuring cup

Remember, there are different variables—such as slope, type of earth, amount of water—that contribute to landslides. This experiment helps determine how landslides occur given different variables. To set it up, fill your milk carton half way with a mixture of your "land" material. Record what type of mixture you use. Next, prop one end of your carton up with a couple of books. You may have to place another book at the other end (under the plastic) to keep the whole thing from sliding. Pour a measured amount of water on the higher end of the soil mixture in the carton until it is soaked but not sliding. You will need to do this gently, so use your watering can and pour slowly. Once the material is soaked, you are ready to trigger the landslide. You can choose to do this in a couple of ways: make the angle of the slope steeper gradually, an inch or two at a time, until the land material slides or begin slowly pouring a measured amount of water over the land material until a slide begins. Record exactly the angle of the slope or the amount of water used to trigger the slide.

You can repeat this experiment with different variables and compare the results. For example, try using different mixtures of land materials and see how results differ. Try setting similar land mixtures at different slope angles and see how results differ. What type of land material is most prone to landslides?

The eruption of Mount St. Helens on May 18, 1980, produced a series of lahars, or volcanic mudflows. The lahars (pronounced LAH-hahrs) flowed many miles down the Toutle River and Cowlitz River, destroying bridges and lumber camps. A total of 3.9 million cubic yards (3.0 million cubic meters) of material was transported by the lahars.

Dangerous science: How landslides happen

Landslides are classified into three groups: slides, falls, and flows, depending upon the type of material involved, the amount of air and water they contain, and the speed with which they fall. Another group, called, slumps, are sometimes included in the definition of a landslide.

Slides A slide consists of rock, mud, soil, water, or debris—or any combination of those materials—that goes tumbling down a steep slope

Repairs are made to the Devil's Slide stretch of Pacific Coast Highway in Pacifica, California, after heavy rains caused it to crack and sink in 2006. AP IMAGES.

at high speeds. A slide typically destroys everything in its path before finally coming to rest on a plateau or in the valley below. Rock slides are common in the European Alps, the U.S. Appalachians, and the Canadian Rockies, especially on slopes with few trees. They are frequently triggered by heavy rains, but can occur at any time without an obvious cause. Debris slides, made up of small rocks and shallow layers of loose soil, commonly follow volcanic eruptions.

A debris avalanche, a particularly dangerous variety of slide, begins suddenly and travels at speeds as fast as hundreds of miles (kilometers) per hour. Debris avalanches, which resemble their snowy cousins, occur most frequently on mountains in humid climates. They begin when soil at the top of a slope becomes saturated with water. That material begins to slide downward, building into a fearsome mass of mud, trees, rocks, and anything else in its path. A debris avalanche that occurred in 1977 in the Peruvian Andes, for example, contained between 20 million and 45 million cubic yards (15 million and 34 million cubic meters) of material traveling at about 100 miles (160 kilometers) per hour. The debris fell upon a city in the foothills, killing some nineteen thousand people.

Falls A fall involves rock or soil dropping from an overhanging cliff or a steep slope. The most dangerous type of fall is a rockfall. Huge boulders may fall freely through the air or race down a mountainside, fragmenting into small pieces as they descend and becoming a raging current of debris.

Rockfalls typically occur where cliffs have become steepened by erosion, the removal of soil, by rivers, glaciers, or waves. The rocks may be pried loose from the cliff or mountain by the freezing and thawing of water in the slope's cracks. Evidence of rockfalls can be seen in the piles of rock and debris at the base of steep slopes.

Large rockfalls can cause terrific damage. In 1970, for instance, a rockfall from the peak of the Huascarán volcano in Peru, triggered by an earthquake, created a debris avalanche that buried villages at the base of the volcano and killed almost twenty thousand people.

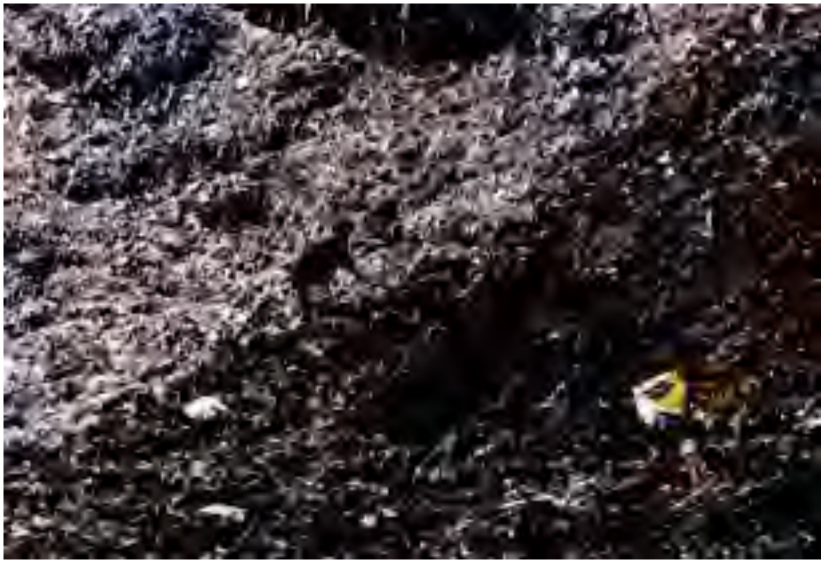
A geologist who witnessed the 1970 rockfall reported:

> I heard a great roar coming from Huascarán. Looking up, I saw what appeared to be a great cloud of dust and it looked as though a large mass of rock and ice was breaking loose from the north peak. . . . The crest of the wave [of rock and ice] had a curl, like a huge breaker coming in from the ocean. I estimated the wave to be at least 80 meters [260 feet] high. I observed hundreds of people in Yungay running in all directions and many of them towards Cemetery Hill. All the while, there was a continuous loud roar and rumble. I reached the upper level of the cemetery near the top just as the debris flow struck the base of the hill and I was probably only ten seconds ahead of it. . . . It was the most horrible thing I have ever experienced and I will never forget it.

Flows A flow is a landslide of wet material, which may contain rock, soil, and debris, combined with water. Mudflows are the most common, most liquid, and fastest type of flow. They contain water and soil, with a consistency somewhere between soup and freshly poured concrete.

Mudflows frequently occur in dry or semidry mountains and on steep-sided volcanoes that receive sudden, heavy rainfall. Loose, weathered rock and steep slopes with little or no vegetation are prone to mudflows. Mudflows can travel as fast as 55 miles (88 kilometers) per hour and have enough force to pick up and carry along debris the size of boulders, cars, trees, and houses. They typically spread out across great distances on valley floors, depositing a thin layer of mud mixed with boulders. In the United States, mudflows do millions of dollars of damage every year. One region vulnerable to mudflow damage is Southern California, especially the hilly suburban communities.

Another type of flow, called an earthflow, consists of material that is moist and full of clay, yet drier than the material in mudflows. Earthflows



Heavy rains loosened a mountain of garbage in a dump in the Philippines, causing a massive landslide that killed hundreds of people in 2000.
AP IMAGES.

are most often set in motion by heavy rains and move at a variety of speeds and distances, yet are generally slower and travel shorter distances than mudflows. Slow earthflows creep along, stopping and starting, moving sometimes just several feet per year. They are common on hillsides on the California coast where the soil has a high clay content.

A type of earthflow that occurs on slopes at high elevations and in polar regions is solifluction (pronounced so-lih-FLUK-shun; also called soil fluction); this action is not included in narrow definitions of landslide. Solifluction involves sensitive layers of silt and clay that underlie level terraces. It takes place, at speeds ranging from very slow to very fast, when snow or ice thaws or when earthquakes produce shocks that turn the soil into a fluid mass. This flow of watery sediment is common in Scandinavia and on the slopes above the St. Lawrence River valley in Quebec, Canada. In 1971, a solifluction earthflow at St.-Jean Vianney in the St. Lawrence River valley swept away thirty-eight homes and took thirty-one lives.

There are also earthflows of dry material that move very quickly, sometimes for great distances, over gentle slopes. Dry-material earthflows can be triggered by earthquakes or the falling of rock from steep slopes above. An earthquake in 1920 in the Gansu (formerly Kansu) province in China set into motion the massive flow of dry loess (pronounced LOW-ess; wind-deposited silt), which resulted in the deaths of tens of thousands of people.

Slumps A slump, which is included in broad definitions of landslide, is the slow, downhill movement—7 feet (2 meters) per day or slower—of portions of a slope. Slumps take place on slopes where there is a strong surface layer of rock or sediment and a weaker layer of material underneath. When the lower layer is no longer able to support the surface material, both layers slip downward together. A slump may range in size from a few square yards (square meters) to thousands of square yards (square meters). As the ground moves, it tilts, or rotates, backward toward the slope in a series of curving downward and outward movements. On a slope on which slump is occurring, steplike depressions are created, and a bulge of earth forms at the base of the slope. A curved scar is left in the area where the material existed before the slump.

Slumps often occur on sea cliffs, the bases of which have been cut away by currents or waves. They can also be seen on slopes that have been eroded by a stream or glacier, as well as those that have been made steeper by construction, such as along roads and highways. They are usually triggered by heavy, prolonged rains or earthquakes.

Landslides prompted by heavy rains One cause of landslides is the saturation of soil on steep slopes, caused by prolonged or heavy rainfall (such as from severe storms) or the melting of large quantities of snow or ice. Once the soil on the surface becomes saturated, the water makes its way down to lower layers. Those layers become slippery at the same time that the surface material is made heavier by the water. At some point the soil, pulled downward by gravity and lubricated by the water underneath, slides away from the slope. On January 11–13, 1966, for instance, heavy rains gave way to landslides on the mountainsides above Rio de Janeiro, Brazil. The cascading mud and debris killed some 550 people and brought transportation and communication systems to a halt.

Similarly, on April 26, 1974, driving rains caused a landslide on a mountain above the Mantaro River in Huancavelica Province, Peru. The

Garbage landslide in the Philippines

One of the strangest and most tragic landslides happened on July 10, 2000, in Manila, capital of the Philippines. A mountain of garbage in the metropolitan dump, saturated (filled with water to the absolute maximum) from monsoon rains, collapsed and swept away hundreds of shacks and huts used by locals who scavenged the dump for usable materials and food. The shanty town was nicknamed "Promised Land" because of the opportunity it offered to make a little money. Estimates of the number of lives lost range from two hundred to more than eight hundred.

A landslide approaching farm buildings in California. JLM VISUALS.

falling debris landed on twelve small villages, causing the deaths of two hundred to three hundred people. It also blocked the river, backing up the water into a natural reservoir 8 miles (13 kilometers) long, 200 yards (183 meters) wide, and 10 to 20 yards (9 to 18 meters) deep. The landslide caused about $5 million in damages. The greatest cost was for the repair of the Huancayo-Ayacucho Highway. In 1990 a rain-induced landslide again occurred in Peru, this time in the village of San Miguel de Río Mayo, some 500 miles (800 kilometers) north of the capital city of Lima. About two hundred people were unaccounted for and presumed dead after mud flooded the town.

In the low, rolling mountains capped with red sandstone above the Gros Ventre River in northwestern Wyoming (just south of Grand Teton National Park), several days of heavy rain, coupled with melting snow, caused the largest landslide in U.S. history on June 23, 1925. Some 50 million cubic yards (38 million cubic meters) of rock and debris fell into the

Gros Ventre River, creating a natural dam 350 feet (107 meters) in height. The 5-mile-long (8-kilometer-long) and 225-foot-deep (68-meter-deep) body of water created behind the dam was named Slide Lake by local residents. On May 18, 1927, almost two years after the landslide, melting snow flooded the river and the dam broke loose. Luckily there had been plenty of advance warning, and most of those living in the area evacuated before floodwaters destroyed their downriver settlement.

Intense rainfall from hurricanes can cause multiple landslides. In August 1969, for instance, Hurricane Camille dumped 27 inches (68 centimeters) of rain on the Appalachian Mountains in central Virginia over an eight-hour period. The soil at the top of steep slopes became saturated and set in motion dozens of debris avalanches. About 150 people were killed by the flowing material. Throughout the region, houses were destroyed and roads and bridges were buried or washed out.

Earthquake-generated landslides Earthquakes that occur in areas with steep slopes can cause the slipping of surface soil and rock, and the collapse of cliffs. The shock waves produced by earthquakes send material hurtling downward in violent landslides. Earthquake-induced landslides happen in mountainous regions such as China, parts of Southern California, Alaska, Turkey, and Iran.

One landslide produced by a severe earthquake occurred in Montana, west of Yellowstone Park, on August 17, 1959. In that case, 40 million cubic yards (30 million cubic meters) of rock tore off the wall of the Madison River Canyon and slid into the river below at a speed of about 100 miles (160 kilometers) per hour. The rocks killed twenty-six people and blocked the river. A lake 6 miles (9.7 kilometers) long and 180 feet (55 meters) deep was formed in the process. After the landslide, a spillway (a passageway near the top of a dam through which water from the reservoir travels when the water level becomes high) was carved out of the natural dam and lined with large blocks of rock, creating sufficient drainage to handle heavy rains and keep the dam from collapsing.

In Kashmir (a region in southwest Asia adjacent to India and Pakistan) in 1840, an earthquake sparked a landslide that dammed the Indus River, forming a lake about 40 miles (64 kilometers) long and 1,000 feet (300 meters) deep. In 1949 in Tajikistan (then part of the Soviet Union), earthquakes in the Pamir Mountains set off landslides that buried the town of Khait, killing all of its twelve thousand residents. Today, Russian

Sinkholes

The movement of Earth's surface sometimes takes the form of a vertical drop, in which case a sinkhole is formed. A sinkhole is a large depression in the ground, often shaped like a bowl or a funnel. Sinkholes vary greatly in diameter from several feet to several miles, and may attain depths of 100 feet (30 meters) or more. Some sinkholes become clogged with clay and then collect water, forming small lakes.

One cause of sinkholes is that the underlying layer of water-soluble rock, such as limestone, marble, or dolomite, is dissolved by groundwater. As the rock dissolves, underground spaces form and the support for the ground is reduced. When the spaces grow large or numerous and the remaining rock can no longer hold the land above it, the surface collapses.

Large sinkholes form when cave ceilings weaken, become unable to support the weight of the ground above them, and collapse. Another cause of sinkholes is the depletion of aquifers, which are underground layers of spongy rock, gravel, or sand in which water collects. Aquifers become depleted when the underground water is pumped out of the ground faster than it can be replenished by rainwater. A sinkhole may also be formed when pockets of underground gas escape, such as during an earthquake.

In the United States, sinkholes have caused the greatest damage in Florida, Texas, Alabama, Missouri, Kentucky, Tennessee, and Pennsylvania. The country's largest sinkhole on record, called the "December Giant," formed in the woods near Montevallo, Alabama, in Shelby County, on December 2, 1972. The sinkhole, discovered by hunters, was 425 feet (130 meters) long, 350 feet (107 meters) wide, and 150 feet (45 meters) deep. Two days prior to the discovery, a resident in the vicinity had reported that his house shook, trees broke, and he heard a roaring noise.

seismologists (scientists who study earthquakes) operate a laboratory for earthquake prediction research near Khait.

Landslides triggered by volcanic eruptions Volcanic eruptions often produce a type of mudflow called a lahar. The material in a lahar is created when volcanic ash mixes with water; the water comes from the melting of snow and glaciers around the volcanic crater. The lahar may be very hot and can travel down the steep sides of a volcano at speeds of 100 miles (160 kilometers) per hour. It can flow for great distances, sweeping up houses and cars, uprooting trees, and burying entire communities.

In May 1980, with the eruption of Mount St. Helens in southern Washington State, came one of the largest landslides in U.S. history. Part of the north face of the mountain blew out and the volcanic ash combined with water from lakes and rivers to form colossal mudflows. The mud blocked rivers and ruined bridges and roads. (Fortunately, the area had been evacuated

In 1981 a large sinkhole formed in Winter Park, Florida. As the ground gave way, a three-bedroom house and three cars were swallowed up. The formation of sinkholes is a growing problem in urban areas of central Florida, as the population grows and underground aquifers become depleted at an alarming rate.

Heavy rains from an El Niño-driven storm caused this 65 foot sinkhole in Balboa Avenue in San Diego, California.

in advance.) Mud even stopped up the Columbia River, a main thoroughfare to the Pacific Ocean, trapping thirty ocean-going ships downstream.

Lahars resulting from the 1985 eruption of the Nevado del Ruiz volcano in the Colombian Andes struck an area that had not been evacuated, despite warnings from geologists (scientists who study the origin, history, and structure of the Earth). The largest of the mudflows overtook the city of Armero, where it claimed at least twenty-three thousand lives and left another twenty thousand people homeless. In some places, the mud was 12 feet (3.7 meters) deep. About 15 square miles (39 square kilometers) of land, including rich farmlands where coffee and rice were grown, were covered by the lahar.

Where landslides occur Landslides occur throughout the world. They are serious problems in several nations, however, particularly in Italy and Japan. More than one thousand urban areas in Italy are in danger zones

Garage and contents damaged by a 1982 mud slide in California. ©JIM SUGAR/CORBIS.

for landslides. In Japan, thousands of homes are lost and more than one hundred people are killed by landslides each year.

In the United States, landslides take place in all fifty states. Across the country, they kill between twenty-five and fifty people and cause up to $2 billion in damage each year. Landslides are the most prevalent in the Appalachians and Rocky Mountains, as well as along the Pacific Coast. It is estimated that more than two million landslides have occurred in the Appalachians, and evidence of past landslides exists on more than 30 percent of the area of West Virginia. In Colorado that figure is 8 percent. More than six hundred landslides have been distinguished in Utah. Coastal slides are a constant menace in California; the San Gabriel Mountains frequently unleash debris flows that ruin homes in the northern Los Angeles area.

Consequences of landslides

Each year, landslides take hundreds of lives and cause billions of dollars in damage throughout the world. Landslides engulf villages and kill people and animals. Falling and sliding rock, soil, and debris flatten houses and cars and uproot trees. Material that spills onto a roadway or railroad tracks halts traffic and causes accidents and sometimes fatalities.

House damaged by a volcanic mud slide (lahar) in Japan. ©ROGER RUSSMEYER/ CORBIS.

When rocks fall into a lake from high above, they create waves that threaten coastal settlements.

When a large quantity of material falls, it forces a wall of air ahead of it. That wind may be strong enough to knock down trees and houses. When the material strikes the ground it sends up a cloud of dust that may darken the sky and spread over a large area. Landslides also knock down utility poles and wires, and the region loses power and communication with the outside world. Landslides also scar the face of a hill or mountain, stripping it of soil, trees, and other vegetation.

Rock or soil that flows into a valley often blocks the flow of rivers, thus disrupting ecosystems and shipping routes and sometimes contaminating drinking water. The natural dam may later give way, causing floods.

The human factor

Most of the destructive impacts of landslides are due, in some part, to human activity. Many landslides occur on slopes that have been altered by grading (leveling off) for road or building construction. When a portion of a mountainside is graded, material is cut out of the slope and removed. The slope directly above the graded area is made much steeper, reducing support for earth and rock higher up the slope. If the excavated material is

The Yosemite rockfall

On July 10, 1996, a tremendous rockfall shook the ground in Yosemite (pronounced yo-SEM-it-ee) National Park in California. Two slabs of an enormous boulder, balanced 2,600 feet (79 meters) above Yosemite Valley on a granite arch, suddenly broke loose. The rocks, weighing 68,000 tons (61,676 metric tons), slid down a steep slope for the first 500 feet (152 meters) and then took to the air and fell freely for the next 1,700 feet (518 meters) until smashing into a rocky slope near the base of the cliff. When the fragmented rocks struck the ground, they were traveling faster than 160 miles (257 kilometers) per hour.

On impact, the rockfall released a wind blast that knocked over hundreds of pine and oak trees and destroyed a nature center and snack bar nearby. The falling trees killed one park visitor and injured several others. The dust from the rockfall and blast of wind blotted out the sky and hung in the air for several hours before settling over an area of about 50 acres (20 hectares).

Rock slide in Yosemite National Park in California in 1983. ©JONATHAN BLAIR/CORBIS.

deposited beneath the graded area, it may overload the lower portion of the slope and cause a landslide.

Construction is especially dangerous on slopes that, due to their geologic composition, are unstable (prone to landslides) in their natural state.

Landslides in Southern California

The mountains of Southern California are prone to mudflows, placing communities on the slopes above and in the valleys below in the danger zone. The slopes are steep and unstable. Much of the soil is barren, since frequent wildfires remove vegetation. Some landslides are triggered by intense storms, which saturate the soil and start it moving downhill. Frequent earthquakes also set landslides in motion.

The deadliest landslide in the region's history occurred in February 1969. During the winter of 1968–69, about 44 inches (112 centimeters) of rain fell on the Los Angeles area over a forty-two-day period. As the record-setting rain (which came after forest fires had cleared the slopes of vegetation the previous summer) fell on the San Gabriel Mountains, it soaked layers of soil and gravel. That material eventually began traveling down the mountainsides, gathering debris as it went. The muddy torrent drowned or buried one hundred people and caused about $1 billion in damage. One of the hardest-hit places was the fashionable suburb of Glendora, where the mud slide damaged 160 homes and destroyed 5 others. Mud piled up on the major highway leading into Los Angeles and destroyed citrus groves as far north as the Ventura, Santa Barbara, and San Luis Obispo counties.

Another part of the Los Angeles area that has suffered from slides is Portuguese Bend on the Palos Verdes Peninsula. Portuguese Bend is an expensive clifftop housing development overlooking the Pacific Ocean. It was built despite warnings from geologists about the region's instability. The material on the top of the cliffs, on which the houses sit, is sandstone mixed with a clay material made of hardened volcanic ash—materials that readily absorb water. The layer of rock below is shale, which becomes slippery when wet. The bases of the cliffs are subject to erosion by waves.

In 1956, heavy rains caused the first movement of the cliff tops since the homes went up. From the 1960s through the 1980s the gradual slide was made worse by a series of earthquakes, plus the increased weight from additional homes. In 1969, houses on nearby Point Fermin went sliding into the ocean. By the end of the 1980s, the slide of the cliff top in Portuguese Bend had damaged or destroyed 150 homes for a total cost of $10 million. Thereafter, new development in Portuguese Bend was halted and a drainage system was put in place to keep the slide from slipping further and to protect the remaining houses.

For example, mountains or cliffs that have a layer of sandstone on the surface and a layer of shale beneath are geologically unstable. Water can seep into pores and cracks in the sandstone and collect on the shale. The shale surface then becomes slippery, allowing the sandstone layer to slide off.

Mining is another activity that weakens slopes and promotes landslides. The removal of coal, stone, or other natural resources from the ground makes the remaining slope unstable and vulnerable to collapse.

Another contribution people make to landslides is cutting down trees on slopes, for use as fuel and lumber or to clear the land for farming. Trees

World's deadliest landslide: Gansu, China

On December 16, 1920, the deadliest landslide in recorded history struck Gansu (formerly Kansu), China, resulting in 180,000 deaths. The cause of the landslide was an earthquake centered near the border with Tibet. The hills and cliffs in the region were treeless and covered with a layer of loess (pronounced LOW-ess or LUSS), a soft, loosely packed material formed from the yellowish dust of the Gobi Desert. The combination of the bare slopes and the fine dust made the soil highly susceptible to slides.

The shock of the earthquake caused the sides of 100-foot (30-meter) cliffs to collapse. Falling material barricaded the entrances of mountainside caves, in which many peasants made their homes. The landslide laid waste to ten cities and numerous villages in the valleys.

In one village, the only survivors were a farmer and his two sons. Their plot of land had broken loose from a mountaintop and slid down the slope intact, atop a stream of flowing debris. The day of the Gansu landslides is known in China as *Shan Tso-liao,* or "When the mountains walked."

protect slopes by trapping rain on their leaves and reducing the erosive impact of wind and water on the soil. The roots of trees and other forms of vegetation absorb rainwater like a sponge and release it slowly into the soil. Roots also act as anchors, holding the soil together. Soil with no vegetative cover erodes quickly. It glides more easily over the rocky subsurface than does compact, cohesive soil. Landslides on deforested slopes, once set in motion, have no natural barriers to slow or stop them. Foot traffic on mountains, from sightseers or hikers, also tramples vegetation and increases the slopes' vulnerability to landslides.

Technology connection

Technology is of limited usefulness in predicting and preventing landslides. Most large slides occur without warning and are more powerful than any barrier that can be erected. A California engineer, at a conference in 1980, likened landslide prevention to "trying to hold back the storm tides of the ocean." Nonetheless, numerous measures are used to lessen the impact of landslides, as well as to predict certain kinds of landslides.

Limiting landscape damage Many methods are used to protect populated areas from material that may fall or slide down a slope. For instance, water drainage systems are employed to keep water from saturating ground that is vulnerable to landslides. Wells are pumped in the potential slide area to keep the rain from overflowing aquifers and soaking the ground. (An aquifer is an underground layer of spongy rock, gravel, or sand in which water collects.)

Trees, shrubs, or grasses are planted on bare slopes to hold the soil in place and to stop material that begins to slide. Terraces (broad, steplike cuts) are constructed on steep slopes, so that falling material or water is only able to travel short distances before landing on a plateau and losing its energy. Loose material is removed from high elevations before it begins rolling down a slope. The bases of slopes on which bulges of material, called "toes," have formed due to slump are immobilized with walls of rock, concrete, or soil. Strong wire-mesh fences are secured to some cliff faces above roadways to prevent rocks from falling. Railroads can be protected by electric fences that detect rock falls and communicate the need to halt trains in that section of track.

Another measure undertaken to prevent landslides is the filling-in of cracks that develop in the faces of mountains or hills. An option for protecting structures in landslide-prone areas is to build retaining walls or earth buttresses along slope bottoms. In some valleys, basins are constructed to trap landslide material. In Southern California, for instance, a series of 120 football-stadium-sized basins have been excavated along the base of the San Gabriel Mountains to catch rocks and debris. They must be emptied frequently in order to continue catching the falling material.

In Japan, which is home to 10 percent of the world's active volcanoes, walls of steel and concrete—as well as drainage systems—have been constructed on mountainsides to protect valley-dwellers from lahars. Television cameras are employed on some slopes to detect the start of landslides and provide advance warning to people in the path of danger.

Predicting landslides While most landslides occur without warning, certain types can be predicted. The U.S. Geological Survey, together with the National Weather Service, provides advance warning for landslides that are caused by heavy rains. Both organizations monitor rainfall data

Beams and wire netting form a rock slide fence near Bolungarvik, Iceland. ©PATRICK BENNETT/CORBIS.

Housing development collapses in the Philippines

On August 3, 1999, following four days of heavy rains that caused widespread flooding throughout eastern Asia, a hillside collapsed in Antipolo City, a suburb of Manila. Thirty-one people were killed as the wall of earth crashed into a housing development; as many as forty others were missing and presumed dead. Twenty-five houses were buried by the landslide, and 378 others were damaged. During that same week in the central Philippines, sixty-one other people died in the flooding.

Filipino officials placed the blame for the landslide on a nearby rock and gravel quarry. They claimed that too much rock had been excavated from the slope too close to the houses, thereby allowing groundwater to reach the ground and soften it. The heavy rains proved to be the final straw that caused the earth to give way and collapse on the houses. Officials also noted that they had issued evacuation warnings when cracks appeared in houses and streets earlier that day, but most residents had ignored the warnings.

Rescuers move debris from collapsed houses in an attempt to rescue victims of a series of landslides in the Philippines in 1999. ©AFP/CORBIS.

and forecasts in areas prone to landslides and issue warnings when the ground is becoming saturated. Landslides that come in the wake of volcanic eruptions can also be predicted. Volcano early warning systems detect rumblings that precede eruptions and, quite likely, volcanic mudflows. People living in the vicinity of a volcano are given plenty of advance warning of the need to evacuate.

Assessing the danger of building When construction is proposed in hilly areas, an assessment is made of the hazards posed by landslides. To determine the stability of the slope and the suitability of the region for construction, researchers conduct geologic explorations to determine soil and rock properties and look at the history of landslides in the area. From that information they can predict the frequency with which landslides will occur, as well as the destructive potential of those landslides. Areas where landslides are likely to occur would then be placed off-limits to construction and possibly designated for parkland or other limited use.

[*See Also* **Avalanche; Drought; Earthquake; El Niño; Flood; Tsunami; Volcano; Weather: An Introduction**]

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La Niña

La Niña has traditionally received less attention than the more well-known El Niño. For example, during the years 1997 and 1998, El Niño (pronounced el NEE-nyo) was the weather phenomenon most in the news. However, from late 1998 through the first half of 2000 El Niño was succeeded by the less widely publicized La Niña (la NEE-nya) phenomenon. La Niña is the cold-water counterpart to El Niño. El Niño is a period of unusual warming in the Pacific near Peru and Ecuador, while La Niña is a period of abnormally cool water temperatures in the same region. La Niña sometimes follows in the wake of El Niño. La Niña's influence is typically felt in the form of colder-than-usual winters in the northern United States and warmer-than-usual winters in the southern United States. La Niña also promotes the formation of Atlantic Ocean hurricanes that can affect Caribbean islands and the U.S. East Coast.

The term "la niña" is Spanish for "little girl." It was named for its relation to El Niño. Two other terms that are sometimes used to describe this cold-water phenomenon are El Viejo (el vee-AY-hoe), which means "the old man"; and "cold-phase ENSO event" (in contrast to El Niño, the warm phase of the El Niño/Southern Oscillation). According to guidelines set forth by the Japanese Meteorological Association, a La Niña year is one in which average sea temperatures along the equator in the Pacific are more than 1°F (0.5°C) colder than usual, and the water remains cold for at least six months.

La Niña sometimes, but not always, follows El Niño. Since 1975 there have been half as many La Niñas as there have been El Niños. On average, La Niña is present one year in every four. Sometimes La Niñas occur as infrequently as once every ten years. La Niña conditions typically last from nine to twelve months, but may persist for up to two years.

WORDS TO KNOW

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

cold-phase ENSO (El Niño/Southern Oscillation): another name for La Niña; colder-than-normal eastern Pacific waters.

convective zone: the region of warm tropical water over which thunderstorms form; the ocean under the Intertropical Convergence Zone.

El Niño: a term that means "the Christ child" or "little boy" in Spanish. A period of unusual warming of the Pacific Ocean off the coast of Peru and Ecuador. It usually starts around Christmas, which is how it got its name.

El Niño/Southern Oscillation (ENSO): the simultaneous warming of the waters of the eastern Pacific and the accompanying shifts in air pressure over the eastern and western Pacific.

flooding: the inundation of water onto land that is normally dry.

gale-force wind: any wind whose sustained speed is between 39 and 54 mph (63 and 87 kph).

Intertropical Convergence Zone: a belt of warm, rising, unstable air formed from the inward-flowing trade winds from north and south of the equator.

jet stream: the world's fastest upper-air winds. Jet streams travel in a west-to-east direction, at speeds of 80 to 190 miles (130 to 300 kilometers) per hour, around 30,000 feet (9,150 meters) above the ground. Jet streams occur where the largest differences in air temperature and air pressure exist. In North America, jet streams are typically found over southern Canada and the northern United States, as well as over the southern United States and Mexico. The northern jet stream is called the polar jet stream, and the southern jet stream is called the subtropical jet stream.

La Niña: Spanish for "little girl," a period of cooler-than-normal water temperatures in the eastern Pacific near the coast of Peru and Ecuador. It often follows an El Niño.

monsoon: a name for seasonal winds that result in a rainy season during the summer on tropical continents, when the land becomes warmer than the sea beside it.

mud slide: a landslide of mostly mud mixed with debris, often caused by heavy rains on steep land with sparse vegetation.

polar jet stream: a North American jet stream, typically found over southern Canada or the northern United States.

precipitation: water in any form, such as rain, snow, ice pellets, or hail, that falls to Earth's surface.

pressure gradient: the difference in air pressure between a high and low pressure area relative to the distance separating them.

research buoy: a tethered or drifting buoy placed in the open ocean capable of recording atmospheric and ocean conditions and transmitting them to a satellite.

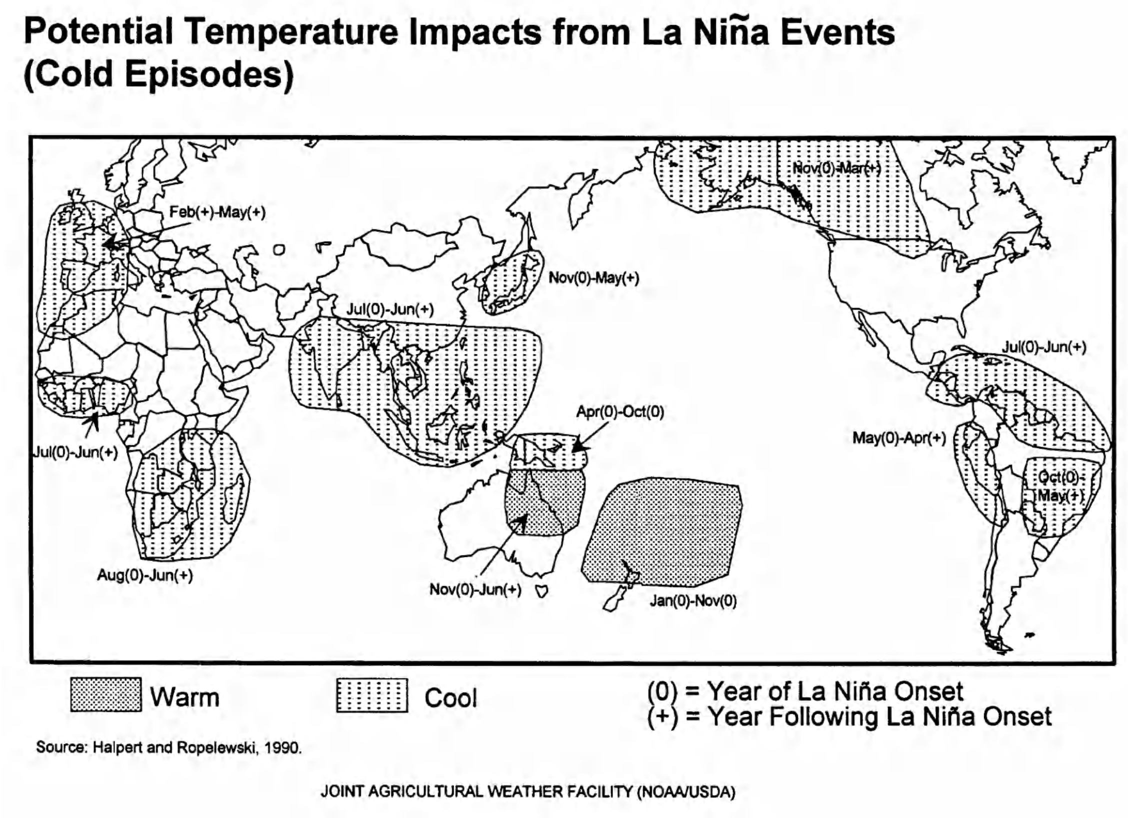
subtropical jet stream: a North American jet stream, typically found over the southern United States or northern Mexico.

thunderstorm: a storm resulting from strong rising air currents; characterized by heavy rain or hail along with thunder and lightning.

trade winds: an area near the equator of prevailing winds that blow from the northeast north of the equator and the southeast south of the equator.

upwelling: cold water flowing toward the surface, often caused by prevailing winds or pressure differences.

warm-phase ENSO (El Niño/Southern Oscillation): another name for El Niño; warmer-than-normal eastern Pacific waters.



Global map showing potential cold episodes caused by a La Niña.

A cooling of the waters

The main characteristic of La Niña is a cooling of the waters in the tropical Pacific, from the coast of South America to the central equatorial region. Normally, the Pacific Ocean temperature off the coast of South America is around 68°F (20°C). During El Niño years the water temperature may be 10°F (6°C) warmer than normal. In contrast, the temperature of coastal waters falls as much as 15°F (8°C) below normal during La Niña years.

La Niña's cold surface waters are produced by a strong upwelling—a churning up of cold water from below. The upwelling during La Niña is intensified by a strong easterly (from the east) trade wind, which is a prevailing wind near the equator. As the trade wind blows warm surface water westward across the ocean, cold water upwells to take its place.

La Niña, El Niño, or normal?

Defining the condition of the tropical Pacific Ocean is tricky business. While some meteorologists assert that the ocean undergoes periods of "normalcy," others argue that El Niño or La Niña is always present to some degree. Weather expert Kevin Trenberth of the National Center for Atmospheric Research stated that in the tropical Pacific for the years 1950–1997: conditions were normal 46 percent of the time; El Niño was present 31 percent of the time; and La Niña was present 23 percent of the time.

The El Niño/La Niña connection

Like El Niño, La Niña is produced by shifts in water temperature and air pressure (also called atmospheric pressure) between the eastern and western portions of the southern tropical Pacific Ocean. While the shift in El Niño is toward warmer water and lower air pressure in the eastern Pacific, however, the shift in La Niña is toward colder water and higher air pressure in the eastern Pacific.

La Niña and El Niño can be thought of as extremes in the range of conditions that may exist in the tropical Pacific Ocean, or as bookends of the El Niño/Southern Oscillation (ENSO). Whereas El Niño is considered a warm-phase ENSO, La Niña is considered a cold-phase ENSO.

In normal conditions, trade winds blow from the eastern Pacific (from the coast of South America), where pressure is higher, to the western Pacific, where pressure is lower. During El Niño, the pressure over the western Pacific rises and the pressure over the eastern Pacific drops, causing the trade winds to weaken or reverse course. During La Niña, the pressure gradient, or the difference between the high and low pressure areas related to the distance between them, tilts more steeply toward the west than usual. This is primarily because of the presence of very cold water in the eastern Pacific, which increases the air pressure there. This steepening of the pressure gradient causes trade winds to blow strongly toward the west.

Meteorologists' understanding of La Niña is not as great as that of El Niño. Less effort has been spent researching La Niña, in part, because La Niña is not as powerful or potentially destructive a force as El Niño. Whereas El Niño provokes unusual weather patterns, La Niña merely intensifies typical weather patterns.

Scientists were driven to learn more about El Niño by the reduction of Peruvian fisheries in the 1970s. La Niña has no such obvious consequence. It was only in the 1980s, when the far-reaching impacts of La Niña (called teleconnections) were discovered, that research into La Niña began in earnest.

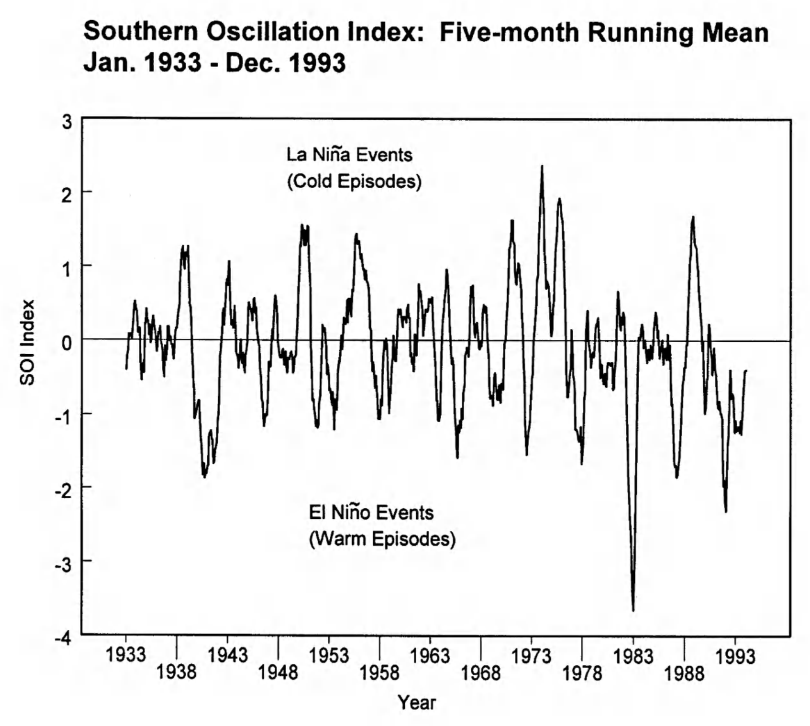


Chart of the Southern Oscillation Index: Five-month running mean (January 1933–December 1993).

La Niña and the jet stream

During La Niña, the "obstacles" that divert the jet stream during El Niño are removed. That is to say, the towering thunderstorms (storms caused by rising air currents) that form off the coast of South America during El Niño years shift to the western-central Pacific and weaken, due to cooler waters. With the displacement of the convective zone (the region of warm water over which thunderstorms form) comes a weakening of the subtropical jet stream found over the southern United States and northern Mexico.

Generally, during La Niña the subtropical jet stream occupies a region farther north than it does during El Niño. The area of strongest jet stream activity during La Niña is the central Rocky Mountains. It is there that the most severe weather can be expected. The jet stream also passes over the Great Lakes in the east. The polar jet stream, typically over the northern United States and southern Canada, is also weakened and pushed farther north, over Alaska and northern Canada.

Effects of La Niña

The effects of El Niño and La Niña are felt most intensely in the winter, when temperature contrasts between northern and southern states are greatest and the jet stream more directly influences the weather. The warming and cooling of the waters that characterize El Niño and La Niña also peak during the Northern Hemisphere winter.

In many ways, La Niña's effects on the weather are the opposite of El Niño's. For instance, La Niña brings cold winters to the northern Great Plains states, the Pacific Northwest, the Great Lakes states, and Canada, and warmer-than-usual winters to the Southeast. El Niño, in contrast, often spells warmer-than-usual winters for the northern United States. and colder-than-usual winters for the southern United States.

Whereas El Niño brings flooding (the inundation of normally dry land) to California, the Southwest, eastward across the states bordering the Gulf of Mexico, and Florida, La Niña brings drier-than-usual conditions to those locations. Also in contrast to El Niño, La Niña brings dry weather to the Central Plains states and the Southeast, and lots of precipitation to the Pacific Northwest. While El Niño brings unusually heavy rains to Peru and Ecuador, and drought to Southeast Asia and Australia, La Niña brings drought to the South American coast and flooding to the western Pacific region.

Another contrast between the two phenomena is that while El Niño hinders development of Atlantic hurricanes, La Niña seems to promote hurricane formation in the region. El Niño's westerly winds (from west to east) blow in the opposite direction of low-altitude winds in the Atlantic Ocean, lopping the tops off thunderclouds before they can come together into hurricanes. La Niña's winds, in contrast, which blow strongly from east to west, encourage the development of Atlantic hurricanes.

The effects of La Niña on weather patterns can be described as an exaggeration of normal conditions. For instance, while the northern United States typically has cold winters, La Niña makes them colder; and while coastal Peru and Ecuador are typically dry, La Niña makes them drier. Indonesia typically receives monsoon rains, caused by seasonal winds in the summer months, but La Niña makes the rains heavier.

However, it is it is misleading to label a specific rainstorm, hurricane, or other weather occurrence a "La Niña event" or an "El Niño event." La Niña and El Niño influence the position and intensity of weather patterns, but they are only two among many other factors that influence local weather.

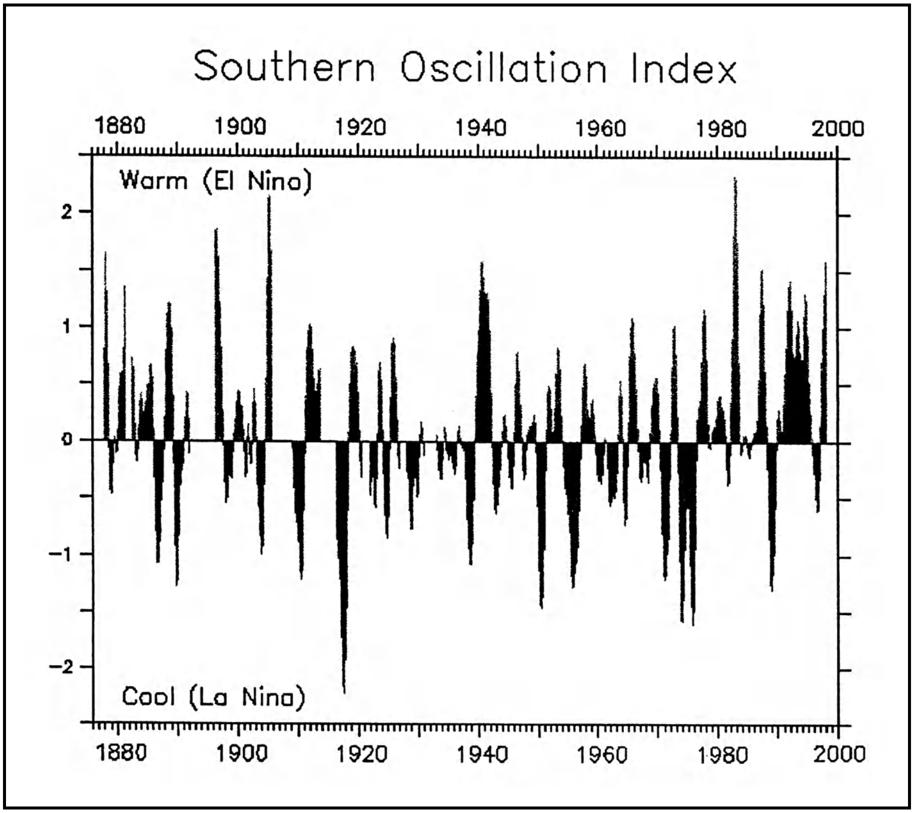


Chart of Southern Oscillation Index (1880–2000).

The 1998–2000 La Niña

In May 1998 a rapid cooling of the tropical Pacific waters began. This temperature drop signaled the end of El Niño and the start of La Niña. Over the next few months the cooling trend continued, after which temperatures varied. Ocean temperatures returned to normal at the end of June 1999, prompting some meteorologists to call a premature end to La Niña. The cooling resumed, however, leading to predictions that La Niña would continue through early 2000.

The first clue to the arrival of La Niña came in the fall of 1997. Scientists detected a drop in temperature of a large pool of ocean water in the western Pacific, 420 feet (128 meters) below the surface. Temperature readings over the next several months, taken by research buoys (floating devices containing weather instruments) indicated that the cool water was moving eastward and upward, toward the coast of South America.

A key reference to: The water cycle

The water cycle (also called the hydrologic cycle) is the continuous movement of water between the atmosphere and Earth's surface (oceans and landmasses). On one side of the equation is precipitation and on the other side is evaporation—the process by which liquid water at the surface converts to a gas and enters the atmosphere.

Eighty-five to ninety percent of the moisture that evaporates into the atmosphere comes from the oceans. The rest evaporates from the soil, lakes, and rivers that make up the continental landmasses. Plants lose water through tiny pores in the underside of their leaves in a process called transpiration.

Some of the moist air above oceans is carried over land by the wind. Clouds form and drop rain and snow on the ground. When precipitation hits the ground, it either sinks in or runs off, depending on the surface composition. On soft ground, most of the water sinks into the soil to be absorbed by plant roots or to seep down into underground aquifers, which are underground layers of spongy rock, gravel, or sand in which water collects. Some of it runs off into streams and rivers. If the water strikes a hard surface, like rock or pavement, most of it runs directly into streams or man-made drains. Eventually this water also flows into rivers.

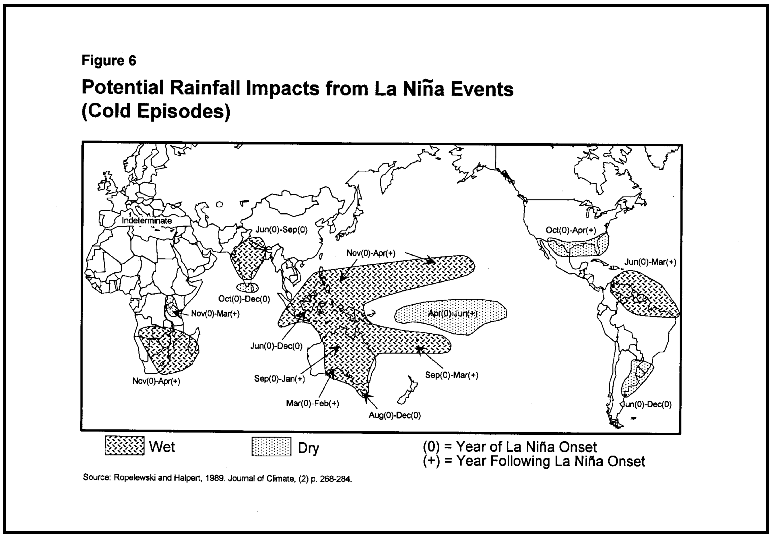
The oceans lose water in this portion of the cycle. More water evaporates from them than returns as precipitation. The oceans get this water back when the rivers empty their water back into the oceans. Thus the global water budget—the volume of water coming and going from the oceans, atmosphere, and continental landmasses—is kept in balance.

If the water cycle is kept in balance, that means that global precipitation levels remain fairly constant. So why do droughts occur? The answer is that rain and snow do not consistently fall in equal amounts in any given place. Moisture may evaporate from one place, travel through the atmosphere, and fall to the ground as rain in another. It is possible, then, for a given location to get lots of rainfall one year and almost no rainfall the next.

Throughout May and June 1998, temperatures along a 5,000-mile (8,000 kilometer) strip of coastal water dropped more than 15°F (8°C), to about 65°F (18.4°C).

Drought and wildfire La Niña, as expected, produced dry conditions in the summers of 1998 and 1999 for the Southwest, the Southeast, the central Plains states, and even the mid-Atlantic states. In addition to drought, some of these areas faced extended heat waves. In many places, non-essential uses of water (such as watering lawns and washing cars) were banned. Perhaps the greatest consequence of the hot, dry conditions was the outbreak of wildfires. Hundreds of thousands of acres burned during these two summers.

In Florida, more than 500,000 acres were consumed by fire in the summer of 1998. In the first half of 1999, more than 35,000 acres



Global map of potential rainfall impacts of La Niña events.

burned. Several homes were lost to the blaze. A state of emergency for the entire state was declared in April 1999 and the National Guard was brought in to assist firefighters.

In March 1999, fire blackened seventy-eight thousand acres of Nebraska prairie—an area the size of Rhode Island—and killed hundreds of cattle. That fire came one month after an unusual wintertime grass fire near North Platte, Nebraska, that burned fifteen thousand acres.

For the first half of 1999, the mid-Atlantic region (New Jersey, New York, Pennsylvania, Delaware, Maryland, and Washington, D.C.) had precious few drops of precipitation. That spring wildfires raged in Georgia, eastern Tennessee, and western North Carolina, prompting the evacuation of hundreds of residents.

The Southwest rebounded from its wet El Niño years with extraordinarily dry conditions in late 1998. The desert wildflowers that bloomed in abundance in the spring of 1998 were noticeably absent in 1999. Precipitation was so scarce in the mountains that Arizona ski resorts took the unusual step of closing for the 1998–1999 season. Even desert oases dried up in Arizona, prompting mountain lions and other desert-dwellers to enter populated areas and drink water out of chlorinated swimming pools.

In some parts of Texas the drought began as early as August 1998. By April 1999, a state of emergency had been announced for 170 of the state's 254 counties.

Torrential rains caused by La Niña triggered a landslide in Sao Paulo, Brazil, in 1999. ©MARIE HIPPENMEYER/ CORBIS.

The wet zone As predicted for La Niña, the Pacific Northwest received above average precipitation during the winter of 1998–99. In Washington State, Mount Baker logged more than 90 feet (27 meters) of snow, rivaling Mount Rainier's record for snowfall in a single season. Lowland communities in the Pacific Northwest and in the Sierra Nevada Mountains in California faced threats of flooding. Around Puget Sound, precipitation fell for ninety-one straight days during the first quarter of 1999.

In the early spring, the Midwest received heavy rains. The Midwest also experienced a series of tornadoes in early 1999; however, meteorologists are divided as to whether or not La Niña was responsible.

As predicted, India, China, Southeast Asia, and Australia experienced unusually heavy monsoon rains and flooding. In the summer of 1998 flood waters stood chest-high in parts of eastern India and Bangladesh. River flooding in China claimed the lives of 4,150 people.

In August 1999, several Asian countries were besieged by torrential downpours, and gale-force winds with speeds between 39 and 54 mph (63 and 87 kph). They also suffered from mud slides, landslides of mud caused by heavy rain, and flooding. Across South Korea, Thailand, the Philippines, and Vietnam tens of thousands of people were forced to evacuate their homes and at least fifty people perished in the floods.

Flooding in Thailand, 2005. PHOTODISC RED/GETTY IMAGES.

An active hurricane season A La Niña event began just in time for the 1998 hurricane season, which runs from June 1 through November 30. As predicted for a La Niña year, the Atlantic hurricane season was fast and furious. With a death toll of between twelve thousand and fifteen thousand, mostly in Central America and the Caribbean, 1998 was the deadliest Atlantic hurricane season 1780.

The year 1998 saw fourteen tropical storms, ten of which became hurricanes and three of which became major hurricanes. Seven of the 1998 storms made landfall in the United States (the third highest number on record), causing twenty-one deaths and more than 3.2 billion dollars in damage. The real story of the 1998 hurricane season was a pair of monster hurricanes, Georges and Mitch, that brought death and destruction to Central America.

A mild winter Predictions of an extra-cold winter of 1998–99 for the northern United States turned out to be wrong. The polar jet stream remained farther north than expected, trapping polar air north of the Canadian border. As a result, northerners enjoyed a relatively mild winter. The southern portion of the United States, south of the Rockies in the west and New York in the east, experienced spring-like conditions. Record high temperatures were set in many places.

The winter of 1999–2000 In July 1999, meteorologists at the National Centers for Environmental Prediction, the National Oceanic and Atmospheric Administration, and other agencies predicted a continuing, but weakened, La Niña for the winter of 1999–2000. Forecasts included wet conditions for the Pacific Northwest and dry conditions for the South. The predictions were at least partly accurate. The winter proved to be one of the warmest and driest on record. It was driest in the Southwest and Southeast with Louisiana recording abnormally dry conditions. The Northwest was average to wet, with Montana and Wyoming experiencing above-average precipitation.

Weather experts also predicted a lively hurricane season for autumn 1999, anticipating at least three major storms. This prediction proved accurate. There were twelve named storms, eight hurricanes, and five intense hurricanes during the season.

Predictions for winter of 2006–2007

Scientists continue to try and predict the effects of El Niño and La Niña. In the fall of 2006, the Climate Prediction Center/National Centers for Environmental Prediction (a branch of the National Weather Service) predicted El Niño conditions developing for the 2006–2007 winter season. These conditions included warmer-than-normal temperatures for western and central Canada, and the western and northern United States. Wetter-than-average conditions were predicted for portions of the U.S. Gulf Coast and Florida, while drier-than-average conditions were expected in the Ohio River Valley and the Pacific Northwest. As of February 2007 scientists saw a return to ENSO-neutral conditions with the possible development of La Niña conditions.

[*See Also* **Climate; El Niño; Flood; Forecasting; Hurricane; Weather: An Introduction**]

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Local Winds

Mesoscale winds are winds that blow across areas of the surface ranging from a few miles to a hundred miles in width. Mesoscale winds are better known as local winds or regional winds. A local wind can persist anywhere from several minutes to several days. Local winds can be driven by temperature and pressure differences or by variations in topography, the shape and height of Earth's surface features. Regardless of their cause, local winds have certain general characteristics. In addition, local winds have many interesting and descriptive names.

Sea and land breezes

Sea breezes and land breezes are two familiar categories of local winds that are driven by differences in temperature and in air pressure, which is the pressure exerted by air on a given area. A sea breeze blows from the water to the shore. It comes as a welcome relief to coastal inhabitants on a hot day. A land breeze, in contrast, blows from the shore toward the water. Land breezes occur in the evening.

Sea breezes form on hot days because the land warms more rapidly than does the water. As a result, a low-pressure area develops over warm ground and a high-pressure area over the cooler water. A mild wind blows across the pressure gradient, from the high-pressure area (over the water) to the low-pressure area (over the land). At night, the process is reversed as the land loses heat more quickly than does the water. The resultant land breeze flows from the high-pressure area, over the shore, out to the low-pressure area, over the water.

Sea breezes and land breezes are strongest at the shoreline, where temperature and pressure differences are most pronounced. They lose intensity as they travel inland or out to sea. The time of day when temperature and pressure differences are greatest, and therefore the breezes are strongest, is midafternoon, when land reaches its maximum

WORDS TO KNOW

adiabatic process: a process by which the temperature of a moving air parcel changes, even though no heat is exchanged between the air parcel and the surrounding air.

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

anabatic wind: winds caused by warm air close to Earth's surface. The air is less dense than the surrounding air and travels upward along a slope.

anemometer: an instrument that measures wind speed.

barchan dune: a sand dune that, when viewed from above, resembles a crescent moon, with the tips of the crescent pointing downwind. Also called barchane dune, barkhan dune, or crescentic dune.

chinook wall cloud: a solid bank of wispy, white clouds which appears over the eastern edge of the Rocky Mountains in advance of a chinook wind.

cold front: the leading edge of a moving mass of cold air.

compressional warming: an adiabatic process by which an air parcel warms as it descends. The descending parcel is compressed by the increasing pressure of the surrounding air, which adds kinetic energy to the molecules. Also called compressional heating.

conduction: the transfer of heat from a substance at a higher temperature to a substance at a lower temperature through the transfer of kinetic energy from a faster-moving molecule to a slower-moving molecule.

cumuliform: a puffy, heaped-up cloud formation.

cyclone: a weather system characterized by air that flows inward and circulates around a low-pressure area.

desert pavement: hard, flat, dry ground and gravel that remain after all sand and dust has been eroded from a surface.

downburst: an extremely strong, localized downdraft beneath a thunderstorm that spreads horizontally when it hits the ground, destroying objects in its path.

heat stroke: a life-threatening condition that sets in when heat exhaustion is left untreated and the body has spent all its efforts to cool itself. Also called sunstroke.

hurricane-force wind: sustained winds greater than 74 mph (119 kph).

katabatic wind: a strong wind that travels down a mountain under the force of gravity, and is stronger than a valley breeze.

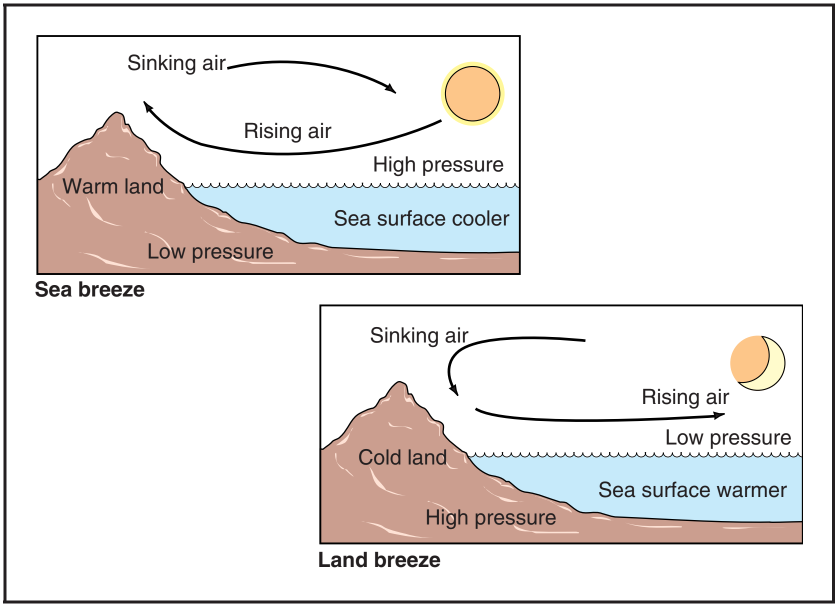
lake breeze: a wind similar to a sea breeze that can be felt at the edge of a large lake.

leeward slope: the slope of a mountain opposite to the direction of local or prevailing winds down which cold air descends, producing dry conditions.

lightning: a short-lived, bright flash of light during a thunderstorm that is produced by a 100-million-volt electrical discharge in the atmosphere.

local winds: winds that blow across surface areas ranging from a few miles to about 100 miles (about 160 kilometers) in width. Also known as mesoscale winds or regional winds.

mesoscale winds: winds that blow across surface areas ranging from a few miles to about 100 miles (about 160 kilometers) in width. Also known as local winds or regional winds.



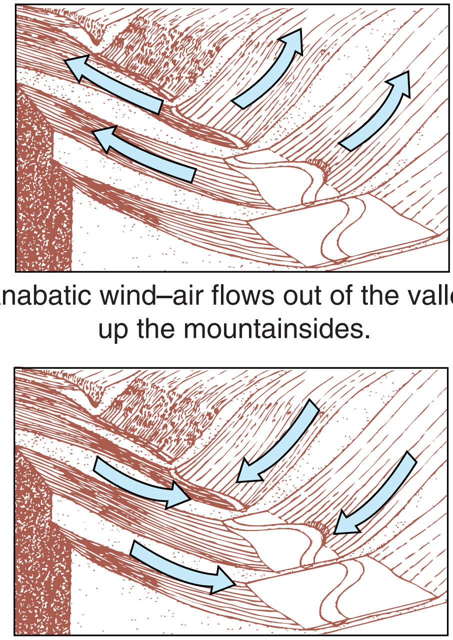
Sea and land breezes.

temperature. Sea breezes are generally stronger than land breezes, since temperature contrasts are greater during the day than at night.

While the strongest sea breezes blow in from over the ocean, sea breezes can also be felt on the edges of large lakes, such as the Great Lakes. They are called lake breezes. They form in the Northern Hemisphere, that is, north of the equator, between May and August on summer days when the land becomes warmer than the water. As a lake breeze or sea breeze travels over the land it acts like a cold front, or the leading edge of a moving cold air mass, thrusting the warm air above it. Vertical clouds, which are clouds developed upward to great heights, and rain showers are often produced over a stretch of land several miles (kilometers) inland.

Mountain and valley breezes

Mountain breezes and valley breezes arise from a mechanism similar to that of sea breezes and land breezes: different rates of surface heating and a resultant pressure differential. Valley breezes, also called anabatic (pronounced an-uh-BAT-ick; Greek for "climbing") winds are formed during the day. The sun warms air closest to the surface of a mountain most rapidly. Air that is farther from the surface, at the same altitude, warms more slowly. The warmer air hugging the surface, which is less dense than the surrounding



Anabatic and katabatic winds.

air, travels upward along the slope. This type of wind is called a "valley breeze" because the air is flowing upward, out of the valley.

A valley breeze typically begins shortly after sunrise. It is strongest on clear, sunny days, and first develops on slopes that face east, toward the rising sun. Since east-facing slopes are also the first ones during the day to end up in the shade, the valley wind there generally stops by late afternoon.

South-facing slopes receive the greatest amount of sunlight throughout the day. Hence it is on these slopes that the strongest valley winds are found. If a valley wind contains sufficient moisture, it will produce cumuliform clouds, which are puffy, piled-up formations, and possibly showers over the mountains in the early afternoon.

At night, the temperature gradient between the surface air and the layer of air above it is reversed, forming a mountain breeze that blows down the slope. Once the sun goes down, the mountain surface begins losing heat to the atmosphere by radiational cooling, which is the movement of heat from the ground upward. The layer of air just above the surface loses heat to the surface in a transfer process called conduction and also cools rapidly. This cold, dense surface air travels down the mountain and sinks into the valley. A mountain breeze is also called gravity wind or drainage wind.

Mountain breezes are usually stronger than valley winds, since at night the temperature difference is greatest between the layers of air next to and those farther away from the mountain. This is especially true in the winter, when the ground cools very quickly at night. A mountain breeze is one type of katabatic wind (pronounced kat-uh-BAT-ick; Greek for "going down"), a wind that blows downhill.

Katabatic winds

A katabatic wind is any wind that travels down a mountain under the force of gravity. However, the term is usually reserved for downhill winds which are considerably stronger than mountain breezes.

As a katabatic wind descends the mountainside, it is warmed by compressional warming. Compressional warming occurs as an air parcel descends and is compressed by the increasing pressure of the surrounding air. That compression leads to an increase in the kinetic energy of molecules and a resulting increase in the temperature of the air. In cases where the air is very cold when it begins its descent, it may still be colder than the surrounding air when it reaches the base of the mountain. However, where the air was somewhat less cold to start with, the wind that flows into the lowland may actually be warmer than the air mass it is replacing.

Katabatic winds range in strength from gentle to hurricane-force. Their speed depends largely on the terrain over which they travel. For instance, the wind accelerates when it travels down long, steep slopes or is squeezed through narrow canyons and valleys.

Cold katabatic winds Cold katabatic winds usually arise during winter or early spring on snow-capped mountains or high-elevation plateaus. The snow keeps the air above it exceedingly cold, forming a dome of high pressure just above the surface. The heavy, dense air descends along the mountainside and through the canyons. If a storm (a low-pressure system) moves into the area, the contrast in pressure between the cold surface air and the surrounding air increases, causing the wind to rush down the slopes even faster.

One of the most famous katabatic winds is the "mistral" of southern France. Its name comes from the Latin word *magistral*, which means "master wind." This cold, dry wind comes from the north or northwest in the winter. It originates in the snowy Alps and travels down to the Gulf of Lyons on the Mediterranean Sea.

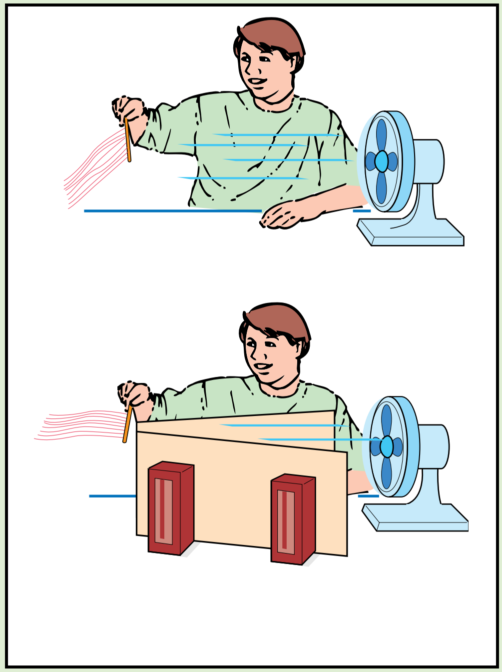
As the mistral descends through the Rhône River Valley, it is squeezed through narrow passages and picks up speed. The gusts of a mistral can exceed 100 mph (160 kph), bringing a blast of frigid air to the otherwise warm French Riviera. The mistral sometimes lowers temperatures so much that frost forms and endangers vineyards.

A cold winter wind that occurs in eastern Europe is called the "bora." The bora blows from the Dinaric Alps down to the Adriatic Coast. This blustery wind travels from the north or northeast, like the mistral, and can also reach speeds greater than 100 mph (160 kph).

A "papagayo" (pronounced pa-puh-GUY-oh) is a strong, northeasterly wind that affects the Pacific coast of Central America, from Guatemala to the Gulf of Papagayo in Costa Rica. The papagayo winds

Experiment: How canyons affect wind speed

This experiment simulates how the wind accelerates as it squeezes through narrowing canyons or valleys. The only equipment needed is an electric fan, two pieces of cardboard or other material that can serve as walls, a pencil, and some string or yarn.



First, tape several 1-foot-long (30-centimeter-long) pieces of string or yarn to one end of the pencil. Then place the fan on a table and turn it on the lowest setting. Hold the pencil (by the end without the strings) a couple of feet (less than 1 meter) in front of the fan. Note how high the breeze blows the strings.

Now it's time to create your canyon walls. To do this, stand your pieces of cardboard on the table. Prop them up with bricks, heavy books, or other sturdy objects, if necessary. In order to "funnel" the wind, the distance between the walls must be greater at the end nearest the fan and smaller at the end farthest from the fan.

Turn the fan on the lowest setting again. Hold the pencil so that the end with the strings is just beyond the small opening between the "walls." The pencil should be about the same distance from the fan as it was the first time. Observe how high the strings are blown. Notice any difference in the intensity of the unobstructed breeze and the funneled breeze.

are produced by a cold air mass that travels down through the Central American mountains. It brings weather that is cold and blustery, yet clear.

The "Columbia Gorge wind" is the only cold katabatic wind native to the United States. Residents of Portland, Oregon, are all too familiar with this strong wind and the cold spell it introduces. The origin of the wind is cold air that settles over the Columbia Plateau. As it sinks, the air follows the Columbia River Gorge westward through the Cascade Mountains. Upon reaching the coast, the cold Columbia Gorge wind replaces the mild coastal air.

The world's fiercest katabatic winds occur in Antarctica. There, the cold, dense air roars down the mountainsides and along the ice sheets constantly, for days and months on end. The wind averages 50 mph (80 kph) in many parts of the continent. It sometimes rages to 100 mph (160 kph), generating intolerable windchill equivalent temperatures below –100°F (–75°C).

Warm katabatic winds Warm katabatic winds are generally set in motion by a larger-scale circulation pattern, for example the movement of strong upper-air westerlies across a mountain range. (Westerlies are global mid-latitude surface winds.) When a trough of low pressure is created over the mountain's leeward (opposite from the prevailing and local winds) slopes, it strengthens the high pressure system at the mountaintop and forces air down the mountains. Warm katabatic winds can also be drawn downhill by a strong cyclone (low-pressure system) or anticyclone (high-pressure system) located to the east of the mountains.

Chinook The best known warm katabatic wind in North America is the chinook, a dry wind that blows down the eastern side of the Rocky Mountains, from New Mexico to Canada, in winter or early spring. Chinooks are also common on the eastern side of the Cascade Mountains in Washington.

Chinook winds originate as cool, dry air at the top of a high mountain. The air is dry because it has released most of its moisture, forming clouds, when it ascended the mountains' windward side, which is the side of the local or prevailing winds. As the air descends the leeward, or opposite side, slopes, it undergoes compressional warming at the dry adiabatic lapse rate. The dry adiabatic lapse rate is the rate that the temperature of a parcel of unsaturated air—air that has less than 100 percent humidity—changes as it ascends or descends. Specifically, the air warms by 5.5°F for every 1,000 feet (10°C per 300 meters) it descends. Given that air can travel 9,000 feet or more (5,000 meters or more) down the slopes of the Rockies, the warming may be considerable.

"Chinook" is an Arapaho Indian word meaning "snow eater." This name is appropriate for this wind because chinook winds bring a dramatic warming to winter-weary regions and melt snow in their path. Chinooks are dry; they may have less than 5 percent relative humidity, that is, 5 percent of the amount of water vapor possible relative to temperature, so they rapidly vaporize melted snow. A chinook can erase all signs of a foot-deep cover of snow in just a few hours.

Weather report: Chinooks to remember

- On January 22, 1943, in Spearfish, South Dakota, the temperature rose 49°F (29°C) in just two minutes. At 7:30 AM the thermometer read –4°F (–20°C) and at 7:32 AM. It read 45°F (7°C)!
- On January 27, 1962, in Pincher Creek, Alberta, Canada, the temperature rose by 57°F (14°C) within one hour. It was –20°F (–29°C) at midnight and 37°F (3°C) at 1 AM.
- On January 6, 1966, also in Pincher Creek, the temperature rose by 38°F (23°C) within four minutes.
- On January 7–8, 1969, outside of Boulder, Colorado, winds reached 130 mph (210 kph), with frequent gusts of more than 100 mph (160 kph). The greatest wind speed recorded within Boulder city limits was 97 mph (156 kph). That wind caused heavy property damage, including twenty-five roofs that were blown off.

Chinooks have been known to raise the temperature of an area by more than 35°F (20°C) in just one hour and by as much as 60°F (33°C) in a day. However, a chinook-induced warm spell does not mean that spring has come. The warm air can remain for several hours to days only to be displaced by cold winds from the west or the north. This can cause problems for plants that set buds or animals that start shedding winter coats too early.

While chinooks typically reach speeds of 25 to 50 mph (40 to 80 kph), they occasionally reach speeds greater than 100 mph (160 kph). The strongest chinook gust ever recorded was around 150 mph (230 kph) near Boulder, Colorado, on December 4, 1978. Violent chinooks can rip roofs off buildings and tear down trees and power lines. They whip up pebbles and debris, which can break windows and dent cars.

One warning sign of an approaching chinook is a chinook wall cloud. This solid bank of wispy, white clouds sometimes appears over the front range of the Rockies. A chinook wall cloud is formed as air rises along the windward slopes and moisture condenses. After this, air rapidly descends the leeward slopes.

Warm, dry winds similar to the chinook also occur in other parts of the world. Most notable is the foehn (or Fuhrn or fane), also spelled "föhn," that flows down from the Alps onto the plains of Austria and Germany. In Argentina this type of wind is called the zonda; in Romania it's called the austru; and in the Canterbury Plains of New Zealand it's called the nor'wester.

Santa Ana winds The Santa Ana winds are warm, dry, gusting katabatic winds from the east or northeast that create a major wildfire hazard in southern California. These winds occur between the months of October and February, peaking in intensity in December. In order to be classified as "Santa Anas" by the National Weather Service, the wind speed must be at least 30 mph (45 kph).

Smoke from massive forest fires in Southern California are fanned by dry Santa Ana winds. FMA, INC.

Santa Ana winds originate over the elevated plateau of the Mojave Desert and wind their way through the San Gabriel and San Bernardino mountains. They gain speed as they travel through the canyons and reach tremendous speeds in the Santa Ana Canyon, for which they are named. The winds then spill out into the foothills of the Los Angeles Basin and the San Fernando Valley.

The Santa Ana winds are generated by a high pressure system that sits above the Great Basin, the high-altitude plateau east of the Sierra Nevada Mountains and west of the Rockies. As this system turns clockwise, it pushes the air downward, over the edge of the high plateau, toward the lower pressure area at the coast.

Santa Ana winds blow with the force of about 40 mph (65 kph) on average, gusting to between 55 mph (90 kph) and 115 mph (185 kph). The strongest winds occur at night, in the absence of the sea breeze. The sea breeze blows in the opposite direction of the Santa Anas and acts as a counterforce.

As the air descends, it undergoes compressional warming in the same way as the chinooks. This air originates over the desert and, therefore, is dry from the start. Its relative humidity becomes even lower as it heats on descent. Santa Anas bring on heat waves throughout southern coastal California, with temperatures reaching 100°F (38°C) or higher.

Weather report: The losing battle against Mother Nature

Southern California's urban sprawl of recent decades has not stopped at the edge of wildfire- and mud slide–prone areas. Rather, homes have been and continue to be constructed in danger zones. Many foothill-dwellers have paid the price.

Since the start of southern California's building boom, Santa Ana wildfires and mud slides have caused billions of dollars in property damage and have claimed scores of lives. The following are some examples of Santa Ana–fueled disasters that have occurred in recent years:

- In October 1991, wildfire invaded Oakland and Berkeley. It burned down about 23,000 homes and killed 25 people.
- In October 1993, fifteen separate fires raged across the landscape from Ventura County to San Diego County. In all, the fires destroyed more than 1,200 buildings with damage totaling over $1 billion. One month later, fires fanned by 100 mph (160 kph) winds ravaged the outskirts of Malibu.
- In October 1996, fires in Malibu and Harmony Grove destroyed more than 150 homes and burned more than 41,000 acres.
- In 2003, California was beset by one of the worst wildfire seasons on record, prompting some to label it a "fire siege." Santa Ana–fueled fires raged across southern California, burned 750,000 acres, killed 24 people, and destroyed nearly 4,000 homes. Damage totaled $2 billion.

As the Santa Ana winds travel across the dry, scrubby southern California vegetation, they further dry it out and turn it into perfect brush-fire fuel. The Santa Anas create conditions such that a single spark can set off a fire. Once the fire begins, the winds fan the flames into an inferno. The Santa Anas are also known for changing direction rapidly, which spreads fire to new areas.

Mud slides are a secondary problem brought about by the Santa Ana winds. Mud slides often occur after wildfire has removed the vegetation and left the slopes bare. If heavy winter rains fall before seeds have germinated and new vegetation has taken hold, the top layer of soil and debris will be washed away. Mud slides occasionally inundate roadways and even destroy homes.

Desert winds

Deserts are windy places, primarily because of surface heating. The temperature of dry ground on a sunny day may be exceedingly hot, in some places over 130°F (55°C). Air rises from the hot surface in a powerful convection, which starts surface winds blowing. Wind speeds are greatest during the hottest part of the day and during the hottest time of year.

In addition to transporting scorching heat from one place to another, desert winds may produce sandstorms. As strong winds blow across a desert, they lift up and carry along sand and dust. Sandstorms may take the form of billowing walls or clouds, or spinning whirlwinds.

Sandstorms and dust storms One type of sandstorm that occurs frequently in the deserts of the Sudan region of north-central Africa and occasionally in the southwestern United States is the haboob. This word is taken from the Arabic word *habub,* which means "blowing furiously." A haboob is a tumbling, black wall of sand that has been stirred up by cold downdrafts along the leading edge of a thunderstorm or a cold front. These downdrafts strike the hot, dusty ground and force the surface air, as well as the top layer of sand and dust, upward. The sand wall may rise a mile or more above the ground, sometimes all the way to the base of the thunderstorm cloud. Haboobs sometimes travel across distances greater than 90 miles (145 kilometers), reducing visibility to near zero.

On the shelves: *Leaning on the Wind: Under the Spell of the Great Chinook*

Published in 1995, this widely acclaimed collection of essays by Canadian writer Sid Marty, a former park ranger, explores the folklore and realities surrounding the chinook winds. Marty takes readers on astonishing adventures through the retelling of his life in southwest Alberta, Canada.

A spinning vortex of sand and dust, called a dust devil, a whirlwind, or in Australia a willy-nilly, sometimes forms along the leading, cold air–warm air boundary of a haboob. More often, however, dust devils arise separately from haboobs, on clear, hot, relatively calm days. Fair-weather dust devils form over particularly warm areas, such as deserts, plowed fields, or flat expanses of dirt or pavement. Although dust devils bear a superficial resemblance to tornadoes, they form by different processes.

The first step in the formation of a dust devil is that hot air rises forcefully from the surface by convection, creating a low-pressure area at the surface. Next, surface winds converge to that point of low pressure. If there are horizontal layers of wind traveling at different speeds (a phenomenon called wind shear), rising air begins to spin around a vertical axis.

Dust devils are usually small and harmless, measuring less than 10 feet (3 meters) in diameter and less than 300 feet (90 meters) in height. They often last less than one minute. The largest dust devils reach a diameter of 100 feet (30 meters) and a height of 5,000 feet (1500 meters) and last for twenty minutes or more. The wind speed in dust devils may exceed 85 mph (135 kph).

While dust devils are generally harmless, they can sometimes cause significant damage, including overturning mobile homes and tearing roofs off buildings. A large and long-lived dust devil can toss over 50 tons (45 metric tons) of dust and debris into the sky.

Sand and dust storms are also common occurrences in western Africa, due to the "harmattan" (pronounced har-ma-TAHN). The harmattan—also

WORDS TO KNOW

monsoon: a name for shifting seasonal winds that result in a rainy season occurring in the summer on tropical continents, when the land becomes warmer than the sea beside it.

mountain breeze: a gentle downhill wind that forms at night as cold, dense, surface air travels down a mountainside and sinks into the valley. Also called gravity wind or drainage wind.

nor'easter: a strong northeasterly wind that brings cold air, often accompanied by heavy rain, snow, or sleet, to the coastal areas of New England and the mid-Atlantic states. Also called northeaster.

Northern Hemisphere: the half of the Earth that lies north of the equator.

precipitation: water in any form, such as rain, snow, ice pellets, or hail, that falls to Earth's surface.

pressure gradient: the difference in air pressure between a high and low pressure area relative to the distance separating them.

radiational cooling: the loss of heat from the ground upward into the atmosphere.

relative humidity: the amount of water vapor in an air mass relative to the amount of water in a saturated air mass of the same temperature.

sea breeze: the gentle wind that blows from over the sea to the shore during the day, due to differences in air pressure above each surface.

snow fence: a device placed in fields and along highways that slows the wind and reduces the blowing and drifting of snow.

squall line: a moving band of strong thunderstorms.

topography: the shape and height of Earth's surface features.

trade winds: an area of prevailing winds near the equator that blow from the northeast north of the equator and the southeast south of the equator.

transverse dune: a series of connected barchan dunes, which appear as tall, elongated crescents of sand running perpendicular to the prevailing wind.

tsunami: the largest type of water wave, generated by a submarine earthquake, landslide, or volcanic eruption.

unsaturated air: air that has less than 100 percent relative humidity.

valley breeze: an uphill wind that forms during the day as the valley air is heated and rises. Also called anabatic wind.

ventifact: a rock, boulder, or canyon wall that has been sculpted by wind and wind-blown sand.

vertical cloud: a cloud that develops upward to great heights. Vertical clouds are the products of sudden, forceful uplifts of small pockets of warm air.

westerlies: global mid-latitude surface winds that travel from the southwest to the northeast in the Northern Hemisphere, and from the northwest to the southeast in the Southern Hemisphere, between about 30 and 60 degrees latitude.

wind shear: a condition in which a vertical layer of air is sandwiched between two other vertical layers, each of which is traveling at a different speed and/or direction, causing the sandwiched air layer to roll.

windward: the slope of a mountain on the side of local or prevailing winds up which cooler air ascends producing moist, cloudy, or rainy conditions.

spelled "harmatan," "harmetan," or "hermitan"—is a mild, dry, and dusty wind. It is an easterly or northeasterly wind that originates over the Sahara during the cool winter months, from late November through mid-March. The harmattan blows across the continent to Africa's west coast, where, despite its dryness, it brings a welcome relief from the intense tropical heat and humidity.

The negative side of a harmattan is that it can create towering sand and dust storms, up to 20,000 feet (6,100 meters) high. Over 100 million tons (90 million metric tons) of dust are deposited into the Atlantic Ocean annually by harmattan dust storms.

Blowing sand and dust obscure a supermarket parking lot during a dust storm near Riverside, California. FMA, INC.

Winds of the Sahara In most cases, the winds that originate in the Sahara Desert in northern Africa are northerly winds, meaning they blow to the south. However, the presence of storm systems at certain locations may redirect these winds, turning them into southerly winds. In such cases, the winds blow across the Mediterranean Sea and into southern Europe or the Middle East. These patterns usually occur in spring or fall.

There are several names for the winds of the Sahara, depending on their point of origin and their destination.

The "leste" (pronounced LESS-tay) is a hot, dry wind that comes from Morocco or Algeria. When a storm system is present off the northwest tip of Africa, just southwest of Spain, this wind blows out over the Atlantic Ocean or the Mediterranean Sea. If the leste crosses the Mediterranean and blows onto southern Spanish shores, it is called the "leveche" (pronounced luh-VAY-chay). The leveche, like the leste, is hot and dry. The wind picks up only a very small amount of moisture during its short trip across the water.

The sirocco (pronounced suh-ROCK-oh), in contrast, has a longer journey across the Mediterranean. Hence, by the time this dry, dusty southeasterly wind out of North Africa reaches Sicily and southern Italy,

A dust devil—a spinning vortex of dust, dirt, and sand—in Kenya. JLM VISUALS.

it has become warm and humid. The sirocco is generated when a storm system is positioned to the southwest of Italy, over the Mediterranean.

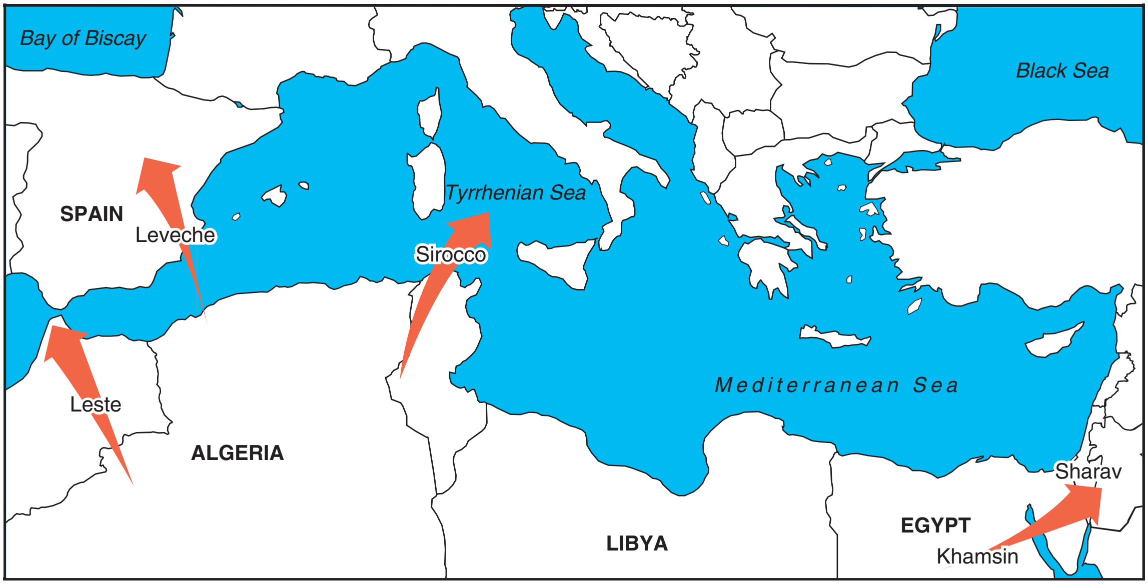
The word "sirocco" (often spelled "scirocco") comes from the Arabic word *suruk,* which means "rising of the sun." In the central Sahara region, this wind is called "shahali" (pronounced SHA-ha-lee); in Tunisia it is called "chili" (pronounced SHILL-ee); and in southern Algeria it is called "chichili" (pronounced CHEE-chi-lee).

Another hot, dry, southerly wind originating on the Sahara, this one in Libya and Egypt, is the "khamsin" (pronounced kahm-SENE). When a storm is present to the north-northeast, over Turkey, the khamsin blows over the northern tip of the Red Sea and into Saudi Arabia, Jordan, and Israel. The khamsin is a strong wind that produces large sand and dust storms. The name for this wind in Israel is the "sharav" (pronounced shahr-AHV).

The khamsin reappears regularly each year. Its name is the Arabic word for "fifty" because it blows for about fifty days continuously, starting in mid-March. The air carried by the khamsin has a temperature greater than 120°F (50°C) and a relative humidity of 10 percent.

The "simoom" (pronounced si-MOOM) is a dry, blustery, dust-laden wind that blows across the Sahara and the deserts of Israel, Syria, and the Arabian peninsula. It often reaches temperatures of more than 130°F (55°C), with a relative humidity less than 10 percent. The simoom, which can cause the life-threatening condition heat stroke, is nicknamed the "poison wind." The word "simoom" comes from the Arabic word *semum,* which means "poisoning."

"Gharbi" (pronounced GAHR-bee) is the name of a wind that originates over the Atlantic Ocean, sweeps across Morocco, and travels over the Mediterranean. This wind picks up dust as it crosses the desert and moisture as it crosses the water. It then



The migrating winds of the North African Sahara region.

deposits heavy rains on the lands of the north and east Mediterranean region. Due to the sand and dust, this precipitation is reddish and is called "red rain."

Other desert winds The "berg" wind originates in the interior of South Africa. It blows down the mountains and out to the coast. This wind is dry, dusty, and very hot. "Berg" is an Afrikaans word meaning "mountains."

The "brick fielder" is Australia's version of a dry, dusty, very hot wind. It comes from the central desert region in the summer months and blows heat, dust, and sand toward the southeastern coast.

The "shamal" (pronounced shah-MALL) is a northwesterly wind that blows throughout the Persian Gulf and the lower valley of the Tigris and Euphrates rivers in Iraq. This hot, dry, and dusty wind can begin to blow suddenly, at any time of year. It typically blows for forty days continuously in June and early July, in what is known as the "great shamal" or the "forty-day shamal." At all other times of year, it generally lasts from one to five days and becomes calm at night.

"Shamal" is the Arabic word for "left-hand" or "north." Another name for this wind is "barih" (pronounced BAR-ee).

Weather report: Daunting dust devils

One of the worst dust devils on record occurred in May 1995 near Minong, Wisconsin. It left a 300-yard-long (275-meter-long) path of destruction, including a damaged roof, a torn-up snow fence, and a downed power line that started a fire.

Another destructive dust devil rose up completely unannounced on a sunny day in March 1995 in upstate South Carolina. The whirlwind smashed the covered porch of a home and carried the wreckage hundreds of yards (meters) away.

In the spring of 1991, a dust devil passed right by the National Weather Service station at Albuquerque, New Mexico. The station's anemometer, a device that measures windspeed, measured the wind gusts at 70 mph (110 kph).

Cold winds

One of the more familiar examples of a regional cold wind is the "Texas norther." As its name implies, a Texas norther is a northerly wind that dips far south, bringing cold air into Texas. Texas northers (sometimes just called "northers") usually follow in the wake of an intense winter storm traveling eastward across the United States. A Texas norther can lower the temperature in Texas by dozens of degrees in just a few hours.

A Texas norther that causes a dramatic drop in temperature, possibly accompanied by sleet and snow, is called a "blue norther." A Texas norther that continues southward and brings cold air into Central America is called "el norte."

A nor'easter or "northeaster" is a strong, northeasterly wind that brings cold air to the coastal areas of New England and the mid-Atlantic states, occasionally as far south as Florida. Nor'easters are generated by extratropical cyclones in the Atlantic (cyclones that develop at high latitudes). These storms develop or intensify off the eastern seaboard of North America and move to the northeast along the coast. The gale-force wind that spins off the storm is often accompanied by heavy rain, snow, or sleet.

One of the most extreme cold winds is Australia's "southerly buster" (originally and properly called "southerly burster"). This violent, cold wind, which comes from the south, represents the leading edge of a strong cold front. A southerly buster can lower the temperature in southeastern Australia by as much as 36°F (20°C) in just a few minutes.

The strong cold wind of central Asia is called the "buran" (pronounced boo-RAN). This dreaded wind originates in Siberia and brings unbearably cold blasts into Russia and the central Asian republics. When the buran is accompanied by snow, which may be heavy, it is called "purga" (pronounced POOR-guh).

A cold, snowy wind similar to Russia's purga is Alaska's "burga" (pronounced BOOR-guh), also spelled "boorga." This wind comes from the northeast and may carry sleet as well as snow.

A cold, dry wind that comes from the north or northeast and invades southern Europe is called a "bise" (pronounced BEEZ, also spelled "bize"). This wind blows in the winter and early spring. It sometimes brings on frosts after the start of the growing season, thus endangering crops.

A "tehuantepecer" (pronounced te-WAHN-te-peck-er) is a cold, blustery, northerly wind that blows down from the Gulf of Mexico. This winter wind picks up speed as it crosses the mountains between Mexico and Guatemala. It then spills out into the Gulf of Tehuantepec, on the southern coast of Mexico, and can blow for 100 miles (160 kilometers) over the sea.

The "pampero" (pronounced pahm-PAIR-oh) is a South American wind. Similar to the Texas norther, the pampero descends from the plains and brings bitterly cold air to typically warm regions. This southwesterly wind originates in the Andes Mountains and blows across the grasslands (*pampas,* in Spanish) of Argentina and Uruguay and out to the Atlantic Coast of Brazil. The pampero is often accompanied by thunderstorms and brings about a rapid drop in temperature.

The coldest local wind of all is the "whirly." The whirly, sometimes classified as a storm, is a small, violent squall in Antarctica. It is a rapidly spinning wind that whips up snow across an area ranging from a few yards to hundreds of yards in diameter. This windstorm usually occurs during the transition periods between the light Antarctic summer and dark Antarctic winter.

Weather extremes: The Great Blue Norther of 11/11/11

On November 11, 1911, a weather event widely known as The Great Blue Norther of 11/11/11 produced the most dramatic temperature changes in U.S. history. The temperature in several places plunged over 60°F (30°C) in a few hours. By nightfall, several cities were dealing with single-digit temperatures. Kansas City, Missouri, had just established a record high temperature for the date of 76°F (25°C) in the late morning. By midnight, the temperature had dropped to 11°F (–12°C), setting a record low temperature for the same date.

Several cities broke high and low records that day. Springfield, Missouri, had set a record high of 80°F (27°C). Within two hours, the temperature had dropped to 40°F (4°C) and before midnight the temperature had plummeted to a record 13°F (–11°C). Oklahoma City also set record high and low temperatures on the same date, with a high of 83°F (28°C) and a low of 17°F (–8°C).

Other local winds

There are several other kinds of local winds that do not fall neatly into any of the categories listed above. They have been grouped together in this section.

Derechos A derecho (pronounced day-RAY-cho) is a destructive, hurricane-force wind that travels in a straight line. This wind was named in 1883 by

Weather extremes: Ravaging nor'easters

In February 1969, a storm with nor'easter winds dumped record-setting snowfalls throughout New England. In Rumford, Maine, snow accumulation totaled 70 inches (175 centimeters). There were 114 inches (290 centimeters) of snow in Mansfield, in the mountains of Vermont; and 164 inches (415 centimeters) at Pinkham Notch, in the mountains of New Hampshire.

In March 1984, a storm struck the Atlantic coast from Virginia to Maine. The shoreline was battered by waves that rose to heights of 20 feet (6 meters), along with 92 mph (148 kph) nor'easter winds. This storm destroyed beaches, homes, boardwalks, and seawalls. The damage totaled over $1 billion.

the director of the Iowa Weather Service, Gustavus Hinrichs. Hinrichs decided on the name "derecho," a Spanish word meaning "straight ahead," to underscore the difference between this wind and a tornado, which spins. "Tornado" is from the Spanish word *tornar* meaning "to return" or "to change."

To be defined as a derecho, the winds must travel faster than 58 mph (93 kph) and the path of the damage must be at least 280 miles (450 kilometers) long. Derecho winds sometimes exceed 100 mph (160 kph) and cause damage across a 150-mile-wide (240-kilometer-wide) area. Derechos are relatively long-lived. Some have swept across several states in a period of sixteen hours.

A derecho is caused by a series of intense downbursts, which are extremely strong, localized downdrafts, from a squall line, or cluster of thunderstorms. These thunderstorms collectively cover an area that is 75 to 300 miles (120 to 480 kilometers) wide. They act as a single storm with tremendous force. The downbursts

Damage to a stand of trees and a home from the passage of derecho winds in the Midwest.
FMA, INC.

Weather extremes: Destructive derechos

Derechos occur most often at night, in the late spring and summer. They usually occur in the central and northern Great Plains states and the Midwest, and sometimes as far east as New York.

In July 1995, a derecho blasted through New York State and southern New England in just three and a half hours. It ravaged rural upstate New York with wind gusts of up to 106 mph (170 kph), and was accompanied by thousands of lightning strikes, each of which is produced by a 100 million-volt electrical discharge. The wind storm knocked down tens of millions of trees across the nearly one-million-acre (four-hundred-thousand-hectare) Adirondack State Park, piling felled trees 10 to 20 feet (3 to 6 meters) high. Four people who were camping in the park were killed by the falling trees.

In 1999, an unusually long-lived derecho hit the border area between the United States and Canada. The so-called "Boundary Waters-Canadian Derecho" began on July 4 and lasted twenty-two hours, with winds gusting above 100 mph (160 kph). The system traveled 1,300 miles (2,092 kilometers) from northen North Dakota to New England, injuring dozens, killing two, and causing property damage in excess of $100 million.

In June 2004, a derecho tore through northern Louisiana, southern Arkansas, east Texas, and Oklahoma, killing one person, uprooting trees, and overturning cars and trucks.

St. Louis, Missouri, was hit by two derechos in three days: one on July 21 and one on July 23, 2006. The winds, topping 80 mph (129 kph), knocked out power for more than 600,000 people and cut a swath of damage 400 miles long and several miles wide.

of a derecho form when a line of thunderstorms passes over a layer of dry air that is several thousand feet above ground. As precipitation, or water in any form, falls into this dry air, moisture rapidly evaporates, thus cooling the air. The cool, heavy air that is formed, assisted by the downward motion of the raindrops, then surges toward the ground. These forceful downbursts together form a derecho. They often spawn tornadoes as well.

Monsoons A "monsoon" is a seasonal wind that occurs throughout southeast Asia, along the Atlantic coastal regions of northern South America, and on the coasts of central Africa. The name "monsoon" comes from the Arabic word *mausim,* meaning "season." This wind blows throughout the summer months, bringing heavy rains and flooding to a region that is dry for most of the winter.

Throughout the winter, the region affected by monsoons is tilted away from the sun. As a result, the sea is warmer than the land during that time.

Commuters in Manila, the Philippines, wade through flood waters caused by monsoon rains when the passenger bus they were riding stalled. ©REUTERS/CORBIS.

A land breeze forms, and hot, dry winds from far inland are blown out toward the sea.

When spring arrives, the monsoon area moves to a position almost directly beneath the sun and the winds shift direction. The land is heated intensely, which causes surface air to rise. This air is replaced by moist winds from over the ocean, similar to a sea breeze. The moisture from these winds forms clouds which yield heavy rains.

Levanters The "levanter" (pronounced li-VAN-ter, also spelled "levante") is the most pleasant wind in the Mediterranean region. The levanter is a fresh, mild easterly or northeasterly wind that blows across the southern coast of France, the eastern coast of Spain, and through the Straits of Gibraltar. It is named for Levant, a region along eastern shores of the Mediterranean Sea.

The levanter travels over the Mediterranean, which makes it humid. This often strong wind brings overcast skies and rain. It occurs most frequently in June through October.

Konas Hawaii is famous for its overall pleasant weather, which is largely influenced by the trade winds, which are the prevailing winds near the equator. The "kona" (pronounced KOH-nuh) winds, which usher in heavy rains and storms, stand in contrast to this trend. The konas are southwesterly winds that blow down leeward (the Hawaiian word for which is “kona”) slopes of Hawaii’s mountains, about five times each winter.

These warm, very humid winds are of moderate strength. They may produce intense storms with heavy rainfall or steady to light rainfall, lasting from several hours to several days.

The wind’s effect on surfaces

Local winds are like sculptors, etching away at surfaces and objects standing in their path. The winds blow the sand, snow, and water, and even shape rock walls and trees. The effect of the winds can be gradual and long term, such as where it shapes the buttes of the American West and the sand dunes of the Sahara Desert. The effect of the winds can also be much more immediate and short term, such as where it whips water into waves and blows snow into drifts.

Sand formations Even a moderate desert wind can set sand in motion. A wind of about 15 mph (24 kph) is strong enough to move very small grains of sand, with diameters of about .008 inches (.2 millimeters). At speeds of 30 mph (48 kph), the wind can move grains with diameters of about .08 inches (2 millimeters). However, the tiniest particles of dust and sand can not be moved directly by the wind. The reason is that a very shallow layer of calm air, extending only about .004 inches (.1 millimeters) above the ground, is unaffected by the wind. The tiny particles are stirred only when they are struck by moving particles.

When the wind blows, it sets in motion a process called saltation, the migration of particles along the ground and through the air. When sand particles are set in motion by the wind, they first slide along the surface. Once these particles overtake and strike other particles, some of the particles bounce into the air and are carried along by the wind. These particles, in turn, fall back to the ground and kick other particles up, into

Weather report: Hot winds and human health

Numerous local winds are thought to be responsible for temporary declines in the mental and physical health of a region’s inhabitants. While the health-wind connections in some cases are popularly accepted as fact, it remains a mystery as to whether or not scientific processes are involved. What follows are examples of winds and the alleged negative effects they have on human health.

- The chinooks are reported to cause irritability, depression, and illness.
- The sirocco winds are claimed to cause fatigue and mental weakness.
- The Santa Ana winds seem to make people nervous, anxious, and possibly even homicidal.
- The foehns are reported to increase the frequency of suicide attempts among people who have suicidal thoughts.

The statistical links between these various irritating winds and human psychological problems are weak and the effect, if any, is small. The frequency of suicide during a foehn event might increase by less than 10 percent. However, the alleged effect has been given the name “Föhnkrankheit” or “Föhn-sickness”, and researchers are searching for a cause-and-effect relationship.

Desert winds blow sand particles in a process called saltation. FMA, INC.

the wind. Eventually, through this process, sand can be blown across great distances.

As sand is continually carried away from a particular location, the surface level becomes lower and lower. Eventually, if all the sand and dust is removed, all that remains is hard, flat, dry ground and gravel. This type of surface is called desert pavement. The bare, dry floor of the Gobi Desert in Mongolia is an example of desert pavement. Desert pavements can also be formed outside of deserts. Agricultural fields, for instance, may turn to desert pavement when soil erosion is accompanied by prolonged drought.

The wind may also sculpt the sand into sand dunes. Sand dunes form when billions of sand grains accumulate in a given location. A sand dune is a mound of sand that is produced over time by a strong wind blowing in a fairly constant direction. Blowing sand comes to a halt behind obstacles, such as rocks or plants. When an accumulation of sand becomes large enough, the sand pile itself acts as an obstacle behind which blowing sand continues to gather.

The angle of a sand dune is more gradual on the windward side, where the wind blows strongest, and steeper on the leeward side, where the wind is calm by comparison. The difference in angle of incline from one side of the dune to the other results because the wind blows the sand

Weather extremes: The windiest places in the world

Declaring a particular spot the windiest place is a bit tricky. For one thing, recorded wind speeds are probably not the highest speed winds that have ever happened on Earth. Faster winds have probably occurred at other locations, but were not recorded. The windiest spot on Earth is even more difficult to establish because the place with the highest average wind speed is not necessarily the place with the highest recorded wind speed.

Commonwealth Bay, Antarctica, is home to the world's highest recorded average wind speeds, so it is considered by many to be the world's windiest place. It was so named in 1912 by an early Australian explorer, Douglas Mawson (1882–1958), who spent two winters there. This bay is situated on the coast of Eastern Adelie Land and West King George Land. It is on the Indian Ocean side of the continent, opposite Australia.

The wind at Commonwealth Bay was measured in 1951 by a team of French scientists who established a base there. They clocked the cold katabatic winds at 40 mph (65 kph) on average, for the year. The highest monthly average winds were 65 mph (105 kph), in March. The highest average winds in a twenty-four-hour period were 108 mph (174 kph), on March 21–22. The winds regularly gusted to over 200 mph (320 kph).

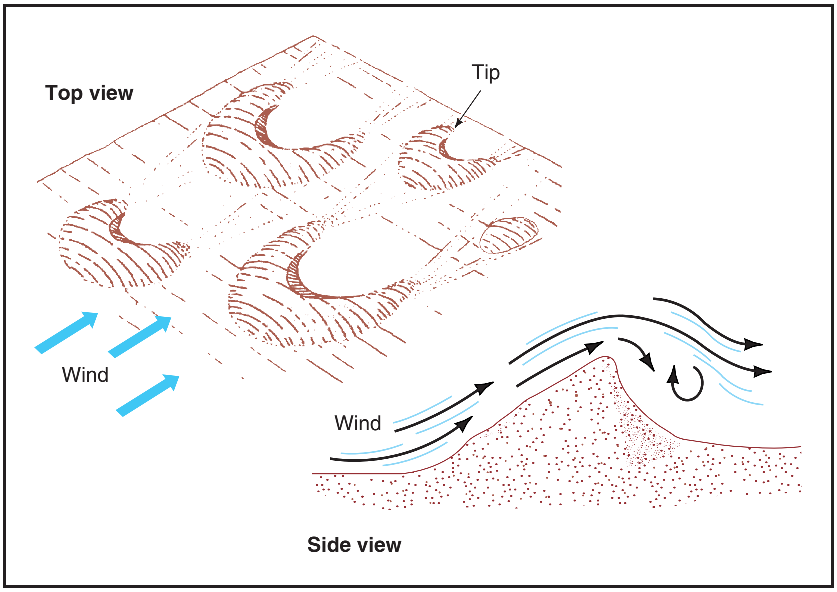
Another candidate for windiest place on Earth, and certainly the windiest place in the United States, is Mount Washington, New Hampshire. The Mount Washington Observatory, located at an altitude of 6,288 feet (1,915 meters), recorded a wind gust of 231 mph (371 kph) on April 12, 1934. Subsequently, there have been frequent gusts up to 220 mph (355 kph) recorded there. Mount Washington also holds the U.S. record for the highest average wind speed in a twenty-four-hour period. On April 12, 1932, the wind blew at an average speed of 130 mph (210 kph).

up the windward face to the top of the dune. On reaching the top of the dune, the sand merely drops to the other side. By examining the shape of a sand dune, it is possible to tell the direction of the prevailing winds at the time the dune was formed.

Entire dunes are also nudged along by the wind. Sand dunes move as much as 50 feet (15 meters) a year.

Barchan (pronounced bar-KHAN) dunes, also called barchane, barkhan, or crescentic dunes, are formed by winds blowing in a nearly constant direction and moderate speed, across relatively flat land with only a shallow layer of sand. When viewed from above, these dunes resemble crescent moons, with the tips of the crescent pointing downwind.

Where sand is more plentiful, a series of connected barchan dunes may form. This structure, called transverse dunes, appears as tall, elongated crescents of sand running perpendicular to the prevailing winds.



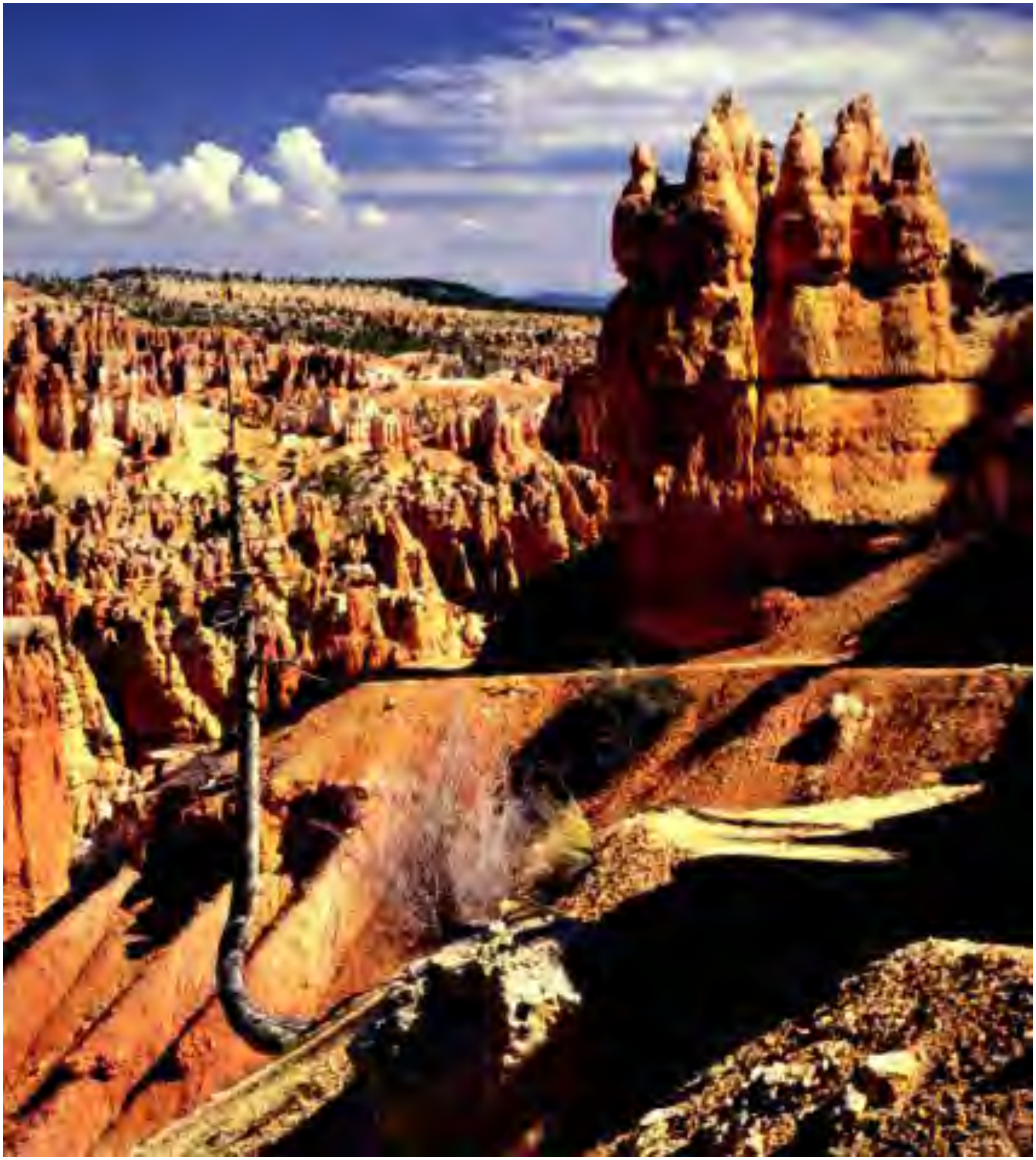
Barchan dunes.

Barchan dunes with very pronounced crescent shapes, that exist either singly or in connected lines, are called seif (pronounced safe) dunes. These dunes are very steep; the crest of a seif dune forms a sharp ridge.

"Seif" is an Arabic word meaning "sword." These dunes are so named because their shape resembles the curved blade of a sword. The seif dunes of Algeria and Iran reach up to 650 feet (197 meters) in height. When seifs exist in a series, they form a meandering pattern that is caused by shifting winds.

Sand ripples are wavy designs formed by the motion of sand along the surface of a sand dune. The ripples run in a direction perpendicular to the wind. Like the sand dune, sand ripples have a more gradual incline on the windward side of the dune and a steeper incline on the leeward side. The direction of the sand ripples changes whenever the wind changes direction.

Sculpted objects Another consequence of wind and wind-blown sand is the eroding and shaping of solid objects. Rocks that have been sculpted by these forces are called ventifacts. Ventifacts include not only rocks lying on the ground, but larger structures such as boulders and canyon walls. Surface rocks, however, constitute the bulk of ventifacts. The reason for this fact is that wind-borne sand generally travels close to the ground.



Ventifacts in Bryce Canyon National Park, Utah. FIELD MARK PUBLICATIONS.

Wind and blowing sand can also erode the bases of solid rock structures, such as boulders, canyons, and cliffs. The wind has the greatest effect on soft rock, such as sandstone. The windward side of a boulder may be rough and pitted, even notched, while its leeward side is relatively smooth. Sometimes wind-blown sand has the effect of polishing rocks. This effect occurs most often in areas prone to sandstorms, where billions of sand grains batter the rocky surfaces.

Ventifacts abound in Utah's Goblin Valley. The sandstone formations there, made of alternating hard and soft layers, have been sculpted into strange and beautiful shapes by the wind. One particular type of ventifact found in Goblin Valley is the "mushroom rock." Mushroom rocks form from boulders, the lower portions of which are made of soft sandstone and the upper portions of which are made of hard sandstone. The wind erodes the soft portion at a much faster rate than the hard portion. Thus, these rocks look like mushrooms, with large heads of hard sandstone sitting atop skinny stems of soft sandstone.

One of the world's largest and most magnificent collections of ventifacts is found in Bryce Canyon, Utah. There, the wind (as well as water) has battered the tops of tall, layered rock formations. The erosion of the outer layers has created a breathtaking array of stone spires.

Rock is not the only material to be shaped by wind-blown sand. Telephone poles, trees, and cars can also be sculpted in the desert. Because of the constant beating by wind-blown sand on lower portions of telephone poles, the poles become narrower at the base than they are higher up.

Snow formations Another medium sculpted by the wind is snow. Snow can be blown into large drifts called snow dunes that are similar to sand dunes. Snow dunes form when a strong wind comes along after snow has fallen on a flat landscape. The wind carries the snow until it meets a barrier, where it deposits the snow. In the Great Plains states, when snow falls on fields and is blown away, the first obstacles it meets are typically in populated areas. For this reason, snow accumulation may be negligible in the countryside at the same time that there are several inches (centimeters) in town.

Gentler winds form ripples in the snow, rather than blowing it away. Snow ripples, similar to sand ripples, are long wavelike patterns that run perpendicular to the direction of the wind.

Snow ripples in Antarctica and other very cold places are called sastrugi (pronounced SASS-truh-ghee). These patterns form when the wind blows from the same direction for several days. Sastrugi freeze solid and can

Did you know? Snow fences

Snow fences are devices that slow down winds and reduce the blowing and drifting of snow. They are erected in two areas: in fields and along highways. The purpose of snow fences in fields is to prevent the wind from stripping the ground of snow. A blanket of snow protects the soil by insulating it against bitter cold temperatures. The snow also provides much needed moisture when it melts.

The purpose of snow fences along a highway is to reduce the amount of snow that blows across or piles up on the road. As the wind whips across a clearing, it picks up snow. When this snow-laden wind hits a snow fence, its speed is reduced. A slower wind will deposit its snow, and at the same time will pick up very little new snow. The snow that's deposited forms a gradual drift on the other (downwind) side of the snow fence.

A snow fence must be placed far enough from the road so that most of the snow gets deposited between the fence and the road, with as little snow as possible reaching the road. The rule of thumb is that snow will accumulate downwind of the fence for a distance approximately ten times the height of the fence. Thus, if a fence is 10 feet (3 meters) high, it should be placed at least 100 feet (30 meters) from the road.

remain for a long time. The singular form of "sastrugi" is "sastruga," which comes from the Russian word *zastruga,* meaning "wind-made furrow."

Water formations In addition to sand and snow, the surface of water is also shaped by the winds. However, only one pattern can be created on the water's surface: waves. Wind-driven waves are technically known as wind waves. While the wind is the most common cause of surface waves, it is not the only cause. Some other forces that give rise to waves include: tides, volcanic activity, and earthquakes beneath the ocean floor.

Wave height is directly proportional to wind speed. To calculate the height of waves precisely, however, requires knowledge of the length of time the wind has been blowing, as well as the distance over water, or fetch, the wind is blowing. The longer the time and distance over which the wind blows, the taller the waves will be.

It stands to reason that the largest wind waves are generated by large, stationary storm systems. The tallest wind wave ever recorded was 112 feet (34 meters) high. This wave occurred during a storm on the Pacific Ocean, with winds of nearly 70 mph (112 kph), on February 7, 1933. This wave was not the tallest of all waves, however. That title is reserved for another class of waves called tsunamis, which are generated by submarine earthquakes.

[*See Also* **Climate; Monsoon; Tsunami; Weather: An Introduction**]

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Monsoon

A typical monsoon climate (climate is the weather experienced by a given location, averaged over several decades) is warm year-round with very rainy summers and relatively dry winters. The change from dry season to rainy season is abrupt, and the rainy season is marked by heavy rainfall. For many people, the monsoon represents only the anxiously awaited rains of summer, which provide a break from the oppressive heat and mark the beginning of the growing season.

While most people associate the term monsoon with seasonal rains, meteorologists (scientists who study weather and climate) use the term specifically to refer to a relatively abrupt seasonal wind shift: the wind blows from land to sea during the winter and from sea to land during the summer. The term "monsoon" comes from the Arabic word *mausim,* meaning "season."

The monsoon climate is most pronounced in India and in parts of Southeast Asia. Monsoon climates also exist along the Atlantic coastal regions of northern South America, on the coasts of central Africa, and in other warm regions of the world where large landmasses meet ocean basins.

Monsoon rains can mean salvation or disaster to the areas where they fall. Half the world's population relies on the seasonal rains to water their crops (principally rice, which requires very wet conditions) and support livestock, as well as to bring relief from the hot, dry winter and spring. If there isn't enough rain, crops will die and people may face food shortages and famine. Too much rainfall, on the other hand, may bring flooding, destruction, and death.

Bangladesh's monsoon floods of 1998

In the summer of 1998, monsoon rains in the south Asian republic of Bangladesh caused the worst flooding in that nation's history. While in an

WORDS TO KNOW

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface.

climate: the weather experienced by a given location, averaged over several decades.

deforestation: the removal of all or most of the trees from a region.

drought: an extended period during which the amount of rain or snow that falls on an area is much lower than usual.

El Niño: Spanish for "the Christ child"; an extraordinarily strong episode (occurring every two to seven years) of the annual warming of the Pacific waters off the coast of Peru and Ecuador.

erosion: the wearing away of a surface by the action of wind, water, or ice.

flood: the overflow of water onto normally dry land.

meteorologist: a scientist who studies weather and climate.

monsoon: seasonal wind that blows from land to sea during the winter and from sea to land during the summer; also, more commonly, a seasonal period of heavy rainfall.

monsoon climate: a climate that is warm year-round with very rainy (flood-prone) summers and relatively dry winters. It encompasses much of southern and southeastern Asia, the Philippines, coastal regions of northern South America, and slices of central Africa.

orographic uplift: the forcing of air upward, caused bythe movement of air masses over mountains.

pressure gradient: the rate at which air pressure decreases with horizontal distance.

Southern Oscillation: shifting patterns of air pressure at sea level, between the eastern and western edges of the Pacific Ocean.

average rainy season Bangladesh has one-third of its land submerged, the rains of 1998 covered three-fourths of the country. While the flooding typically lasts one or two weeks, in 1998 it lasted two months (three times longer than the next longest flood in Bangladeshi history). The flooding began in late July, when the Ganges and other rivers overflowed their banks. The rivers continued to rise until mid-September, only starting to recede at the end of that month.

More than fifteen hundred people lost their lives in the floods, and about twenty-five million were left homeless. In many villages, residents spent two months living on the tin roofs of their homes. There was widespread loss of livestock and crops in this primarily agricultural nation. Countless roads, bridges, and power lines were damaged or destroyed, and half of the nation's rice seedlings, waiting to be planted, were washed away.

Families pass over a flooded highway in Kalaroa, Bangladesh, during the monsoon flood season. AP IMAGES.

Background on Bangladesh Bangladesh is a small, flood-prone country situated just east of India on the Bay of Bengal. It is the size of the state of Wisconsin, but holds more than 125 million people (about half the population of the United States), making it the most densely populated nation in the world. It is also one of the poorest nations in the world; its citizens earn an average of only $200 a year.

Bangladesh is in the path of waters that flow down the slopes of the Himalayas. Those waters course through India before entering Bangladesh. Since Bangladesh sits at a lower elevation than India, it receives the runoff from India's floods.

Most of the land of Bangladesh is in the flat, low-lying Plain of Bengal. Roughly 80 percent of Bangladesh is less than 30 feet (10 meters) in elevation. Near the coast, the land is practically at sea level with an elevation less than 3 feet (1 meter).

Bangladesh is crisscrossed by a complex and interconnected system of rivers and tributaries. The situation is further confused because the same river is known by different names in different portions of its course. The four major rivers are the Ganges, the Jamuna (also known as the Brahmaputra where it crosses India), the Padma, and the Meghna. These rivers also have hundreds of tributaries. The Ganges, Jamuna, and Padma combine to form the Meghna which enters the Bay of Bengal in a wide delta system. During the rainy season, the multiple channels of the Meghna merge to form a vast river of water and silt.

Much of the land exists as islands, called "chars" locally, that are constantly appearing and disappearing as the rivers change course. The chars' soil is made extremely fertile by the silt deposited by the rivers. Individual chars, however, rarely exist for more than ten years. Most homes in this fertile region are built on stilts to keep them above the flood waters.

Bangladesh has an extremely rainy climate, and flooding is common during the monsoon season. That flooding becomes disastrous if some or all of the major rivers flood, and worse yet if it coincides with high tides in the Bay of Bengal. The flooding can put nearly all of the country under water if a tropical cyclone strikes at the same time. The floodwaters run swiftly, sweeping away many homes—even those built on stilts. As dry ground disappears and villagers can no longer find safety from the floodwaters, the number of deaths from drowning increases. In the worst years, tens of thousands of people in Bangladesh have died, and millions have been made homeless.

Women trapped in flood waters, Bangladesh, 2000. ©AFP/CORBIS.

Another consequence of flooding in Bangladesh is the spread of disease. Disease is common because of the mixing of sewage with drinking water and the increase of illness-spreading insects. In a country that has only one medical doctor for every forty-five hundred people, there is little chance that sick people will receive the necessary treatment.

Torrential rains swell rivers The primary source of Bangladesh's 1998 floods was torrential rains that pelted the nation every day for a month. Adding to the rising floods was runoff from rain in the Himalayas and India. Floodwaters took at least one thousand lives in India before continuing into Bangladesh. Bangladeshi rivers overflowed their banks and spread out over the land. In early September the Ganges River reached its highest level in recorded history.

Typically, Bangladesh's rivers empty into the Bay of Bengal. In the late summer of 1998, however, high sea levels blocked the seaward-flowing rivers. The high sea levels were believed to be the result of numerous minor undersea earthquakes in the region as well as runoff from melting glaciers in the Himalayas.

More than 10,000 miles (16,000 kilometers) of roads, fourteen thousand schools, and millions of homes were partially or totally submerged. Flooding was made worse by faulty levees (high walls built along the banks of a river to prevent flooding) that had been put in place in a failed attempt to tame the river. That effort, which was coordinated by

Flood victims line up outside a refugee camp in Bangladesh, 2000. © REUTERS/CORBIS.

the World Bank at a cost of $150 million and called the Flood Action Plan, was declared a failure in 1996.

"I can trace the orange clay lines of major roads, which are built on artificially raised ground . . . then, again and again, I see these roads disappear under water," wrote journalist Mark Levine in a November 1998 article in *Outside Magazine,* while surveying Bangladesh from an airplane. "I see floating clusters of trees and houses, isolated from one another like islands. I see the tips of power lines poking through the surface of the floodwater, and small herds of cattle—four or five heads apiece—huddling on tiny dots of land."

Crops destroyed by flooding More than 2 million tons (1.8 million metric tons) of rice crops were destroyed by the floods, reducing rice production in the nation by about 75 percent. Replanting of rice was impossible while the floods persisted and had to wait until the next year's growing season. In the winter months, some people were able to plant wheat, spices, and other dry-weather crops.

Some 80 percent of Bangladeshis make their living by farming. "I don't know how God will save us," stated Mohammad Harunuddin Sheik, a villager from Chor Shibola who was camped out on the roof of his shack with his wife and daughters, in a September 7, 1998, *New York Times* article. "All my crops were destroyed. Where will I get seeds to plant next year?"

Causes of death At the end of November 1998, the Bangladeshi death toll was estimated to be more than fifteen hundred people. The main causes of death were drowning, diarrhea, cobra bites, and being crushed by collapsing houses. Disease and hunger posed grave threats in a nation where two-thirds of children are seriously malnourished even in the best of times.

Sickness spread through the foul floodwaters, which served as both garbage dump and toilet in a nation where indoor plumbing is a rarity, and the landfills were now underwater. People living in slums had no choice but to use the thick, black water around them for cleaning, cooking, and in some cases for drinking.

By mid-October, more than one million people were suffering from diarrhea. While the government had ample supplies of anti-diarrheal medication, it was difficult to deliver the medicine to sufferers.

As the floods receded, they left in their wake a thick layer of black sludge. The sludge, like the floodwaters, contained contaminants that spread disease and provided a breeding ground for malaria-carrying mosquitoes.

Difficulties faced by relief missions The floods and resulting food shortages left Bangladeshis, especially those without grain reserves from the previous year's harvest, in desperate need of international aid. The United Nations responded to the crisis by raising about $200 million from international donors. The distribution of food was difficult, however, given that millions of hungry people were distributed on numerous strips of land that stood out in the rising water. Dropping supplies from airplanes was not feasible, since packages would likely fall into the water. Some aid agencies chartered boats to traverse the floodwaters, however many crews refused to work because they feared capsizing in the dangerously fast currents. As floodwaters receded, relief agencies faced new obstacles to food delivery: water was too shallow for boats yet the roads were too muddy for cars.

There were also political obstacles to aid distribution. Some residents of Dhaka, the capital of Bangladesh, accused the government of withholding food from people in regions known to be opposition-party strongholds.

As the fall wore on, food distribution became more reliable. According to the program set up by the government, each family in need received 31 pounds (14 kilograms) of rice and wheat every month. That quantity

Experiencing the monsoon: An eyewitness account

The following passages are from a book titled *Chasing the Monsoon* by English journalist Alexander Frater. Frater, who was in Trivandrum, India (at the country's southern tip), when the rains came, described the scene as he joined a group of Indians gathered on the seashore. His account demonstrates how quickly the monsoon season can start, and how its arrival is anxiously awaited by many people.

> A line of spectators had formed behind the Kovalam beach road. They were dressed with surprising formality, many of the men wearing ties and the women fine saris. . . . Their excitement was shared and sharply focused, like that of a committee preparing to greet a celebrated spiritual leader. . . . As I joined them they greeted me with smiles. . . . The sky was black, the sea white. Foaming like champagne it surged over the road to within a few feet of where we stood. . . .
>
> More holiday-makers were joining the line. The imbroglio of inky cloud swirling overhead contained nimbostratus, cumulonimbus and Lord knows what else. . . . Thunder boomed. Lightning went zapping into the sea. . . . Then . . . we saw a broad, ragged ban of luminous indigo heading slowly inshore. Lesser clouds suspended beneath it like flapping curtains reached right down to the sea.
>
> 'The rains!' everyone sang.
>
> The wind struck us with a force that made our line bend and waver. . . .
>
> The deluge began. . . .
>
> The rain hissed on the sea and fell on us with a buzzing, swarming noise. . . .
>
> Water sheeted off the hillside, a rippling red tide carrying the summer's dust down to the sea. . . .

was said to be adequate for at least one meal a day. Programs were also initiated that paid Bangladeshis to rebuild roads, schools, and hospitals. In that way people were given the opportunity to buy their food rather than relying on handouts.

Moneylenders make it worse Many Bangladeshis, desperate to make ends meet, sold their farm animals for discouragingly low prices. Such a move meant they would have no animals with which to till their land the following year. Many were also left with no choice but to sell their chickens and milk cows—for about half of the pre-flood prices.

Even after selling their possessions, cash-strapped Bangladeshis had difficulty meeting their basic needs. Moneylenders took advantage of the situation. These businessmen lent villagers small amounts of money

Family returns home as floodwaters recede in Bangladesh, 2004. AP IMAGES.

(about $125 maximum per loan) at interest rates as high as 100 percent. For some borrowers, such an equation would leave them in debt the rest of their lives. "I borrowed 1,000 taka ($21.00) at 100 taka ($2.10) interest per month," stated one villager in a 1998 CNN report. "They (private lenders) squeeze us to the bones to get their money back."

Money matters were made worse by the financial crisis that struck Asia at the same time as Bangladesh's floods. Many Bangladeshis who had been working in other countries in Southeast Asia were sent home. Prior to the flooding, money sent to Bangladeshis by family members working abroad totaled almost $1.5 billion per year. That was second only to exports for the nation's largest source of foreign income.

Bangladesh floods in 2002 and 2004 Bangladesh suffered devastating floods again during the monsoon rains of 2002. While not as severe as the 1998 floods, 2.3 million people were left stranded or homeless from floodwaters and two hundred thousand homes were submerged. Fortunately, the death toll was relatively low. Official accounts place the toll at nineteen people dead, sixteen of them from waterborne diseases. Other news accounts place the death toll at around 157 people. Hundreds of homes and farms were destroyed.

Flood problems were worse in 2004 due to flooding caused by monsoon rains and high tides in the Bay of Bengal. Millions of people were left without adequate food or clean water as the floods submerged

A young street vendor is caught in a monsoon downpour in New Delhi, India, 2000. ©AFP/CORBIS.

two-thirds of the country. According to some news reports, the death toll was as high as one thousand persons. Annual floods during the monsoon rains are likely to continue to plague Bangladesh for years to come, especially when combined with high tides and tropical cyclones.

Dangerous science: Monsoon

A monsoon is a huge, natural weather event that exchanges heat and moisture between land and sea. It is driven by the temperature differences between the two environments.

The monsoon climate is most pronounced in the Indian subcontinent and southeast Asia—home to a full 50 percent of the world's population. The monsoon zone includes India, the Indus Valley of Pakistan, portions of Nepal, Bhutan, Bangladesh, Burma, Malaysia, Vietnam, Thailand, Laos, and the Philippines, and the southeast tip of China. Some Atlantic coastal regions of northern South America also experience monsoon climate, as do slices of central Africa. Recently monsoon winds have been shown to exist in the southwestern United States, Japan, and portions of southern Europe.

The monsoon-driven rainy season typically lasts for four months, from June through September. India, for instance, gets 80 percent of its yearly rainfall during that period. The start and end dates of the monsoon

Monsoon clouds over Nepal. ©GALEN ROWELL/CORBIS.

rains vary from place to place and from year to year, as do the rainfall amounts.

A seasonal wind pattern Throughout the winter, the region affected by the monsoon is tilted away from the sun. During that time the land is cooler than the ocean. (Land heats up and cools down more quickly than water. Water heats up more slowly than land in the summer—which is why we go swimming to cool off—but water retains its heat longer than land.) The cooler air, which is denser, sinks. As the air sinks, the moisture within it evaporates and prevents the formation of clouds. At the same time, the relatively warm air above the ocean expands and rises, because it is less dense. The air over the sea is replaced by cooler air from far inland, due to the difference in air pressure (the different pressures exerted by the weight of the air). The air travels from a region of higher air pressure, over land, to a region of lower air pressure, over sea.

When spring arrives, the monsoon-prone area moves to a position almost directly beneath the sun and the winds shift direction. The land heats up, becoming warmer than the ocean. The surface air over land expands and rises, thus lowering the air pressure. Relatively cool air from over the ocean, made moist by evaporated ocean water, flows in and equalizes the pressure. Once the ocean air is heated over the land, it also rises. As it rises, the moisture within it condenses and forms clouds. Those clouds yield heavy rains throughout the summer months. When

Experiment: Convection currents in the atmosphere

A monsoon is driven by solar energy working through convection. When air is heated, it becomes less dense and rises. Cooler air flows in to take its place. Likewise, cooler air is more dense and sinks, displacing warmer air.

For this experiment you will need a large clear, plastic box. A plastic shoe box works well. You will also need a cup full of ice cubes, a small candle in a candle holder (such as a tea-light), and some black or dark-colored construction paper. Ask a teacher or parent to help you with the lit candle.

First, attach black paper to the back side of the plastic box, so the convection currents will be visible. Next, place the cup of ice in one end of the shoe box. Then have your parent or a teacher carefully light the candle and place it at the opposite end of the shoe box. Allow the candle to sit for a few moments. Then gently blow out the candle and place the lid on the shoe box. The smoke from the candle will follow the convection current inside the box.

This experiment reproduces the circumstances under which monsoon winds are formed. Earth's surface is warmed by sunlight and the less dense air rises. Cooler, denser air from over the ocean flows in to take the place of the warmer, rising air. The cooler, denser air brings moisture from the ocean to the land and the rains come.

temperatures on land in the summer are exceptionally hot, the rains are very strong and cause widespread flooding.

The monsoon climate In the monsoon climate, the year is divided into dry and rainy seasons. While monsoon regions generally receive as much total annual rainfall as do rain forests, the precipitation is concentrated in the summer months. It is typical for around 120 inches (300 centimeters) of rain to fall during the rainy season, causing destructive flooding. Rainfall in the spring and fall is moderate while the months of December, January, and February are dry. The official designation of a monsoon climate is one in which monthly precipitation drops below 2.3 inches (6 centimeters) for one or two months of the year.

The total annual rainfall in monsoon regions is generally sufficient to sustain forests, even through the dry period. In some areas this forest resembles a rain forest while in others it is less dense and merges into scrublands. The land is primarily cultivated with rice, a crop that thrives on flooding.

Monsoon in India The cycle of life in India is closely related to the seasonal rain pattern. In India, the shape of the land intensifies the monsoon; it strengthens the flow of the wind out to sea, as well as back to land. India is shaped like a huge triangle. It is surrounded by ocean on two sides and very tall mountains on the third. The Bay of Bengal lies to the east of India, the Arabian Sea lies to the west, and the Himalayan Mountains are situated to the north.

In the winter months, the land is at its coolest and the sea is warmer than the land. The relatively cool air sinks down from the mountains,

People caught in the monsoon rains, Simla, India. © BEN SPENCER; EYE UBIQUITOUS/ CORBIS.

pulled by the force of gravity, and moves across the land. It then moves out over the water. Precipitation during the winter months is scarce.

In the spring the land heats up. In May and June, daytime air temperatures are typically more than 104°F (40°C). By June the land becomes warmer than the sea and the wind reverses direction. Cool, moist air flows onto land from both the Indian Ocean and the Bay of Bengal, forming eastern and western arms of the monsoon. That humid air abruptly triggers torrential rainfalls. The air is forced upward, in a process called orographic uplift, by the hills that occupy the center of the Indian peninsula. This contributes to the rainfall along the coasts. In a typical year, most of India has rain every day in June.

The rainfall is particularly heavy in the foothills of the Himalayas. When the moist air reaches the mountains, it is forced upward sharply. That motion causes the formation of towering storm clouds that produce abundant rain. One of the wettest places on Earth is the town of Cherrapunji. This town sits on the slopes of the Himalayas, just north of the Bay of Bengal. Cherrapunji receives more than 400 inches (1,100 centimeters) of rain per year.

Consequences of monsoons

Monsoons are complex phenomena that, unlike tornadoes or avalanches, are not always disastrous. Yes, some monsoons, those that bring far too

The Arizona monsoon

In recent decades, meteorologists have recognized that the late summer thunderstorms that occur over the mountains of the southwestern United States are a monsoon, at least marginally. While the wind does seasonally shift from the west and northwest in winter to the south and southeast in late summer, the shift is not as strong or abrupt as that experienced in India and Southeast Asia.

The mechanics that drive the southwestern monsoon are similar to those that drive other monsoons. During the winter months the air pressure is higher over land than it is over bodies of water to the south. In the spring, as the air warms considerably and the pressure over land lowers, moist air from over the Pacific Ocean, the Sea of Cortez (the water separating the Baja Peninsula from the Mexican mainland), and the Gulf of Mexico flows northward. As a result, in mid-to-late summer and early fall the deserts and dry plateaus of Arizona and New Mexico experience numerous thunderstorms. The thunderstorms that accompany the monsoon are caused by a combination of orographic uplift, daytime heating from the sun, and weak upper-level disturbances moving across the region.

The summer rains supply a significant portion of the region's annual precipitation. Arizona, for instance, receives only 6 percent of its annual rainfall in April, May, and June. In July, August, and September—the period considered the wet monsoon—the state gets 32 percent of its annual rainfall.

A summer monsoon breaks over the desert sky in Tucson, Arizona. ©ANDREW BROWN; ECOSCENE/CORBIS.

A Sri Lankan farmer guides his oxen through a muddy rice paddy. ©TIM PAGE/CORBIS.

much or far too little rain, fit the definition of "natural disaster." In general however, monsoons are a seasonal rhythm. The billion people who live in monsoon climates have adapted their lives to the seasonal changes.

Flooding Many parts of India, Bangladesh, and certain Southeast Asian nations become flooded every rainy season. The poor generally feel the effects of the flooding the most, as their homes are built on land most prone to floods, especially in shantytowns surrounding major cities. Some people have standing water in their houses for weeks at a time every year. Particularly large floods cause drownings and carry away people's meager possessions—and sometimes even entire homes. Floodwaters often mix with sewage and other refuse, creating health hazards for people reliant on river water for drinking, cooking, and washing.

The collapse of the Manchu River Dam

On August 11, 1979, excessively heavy monsoon rains caused the collapse of the Manchu River Dam near Morvi, India. Morvi is located 300 miles (480 kilometers) northwest of Mumbai (formerly Bombay). Before the dambreak, Morvi was a thriving industrial town of seventy thousand people. The collapse of the dam unleashed a 20-foot (6-meter) wall of water that killed some fifteen thousand of Morvi's citizens, as well as countless others from thirty small villages between Morvi and the dam.

The Manchu River Dam, built in 1972, had been designed to withstand an average yearly rainfall of 22 inches (56 centimeters). The 197-foot-high (60-meter-high) dam protected Morvi and other downstream settlements from flooding. The heavy monsoon rains of the summer of 1979 had already been placing stress on the dam when a severe storm dumped 28 inches (71 centimeters) of rain on the region in just twenty-four hours. Engineers tried to open the sluice gates to allow more water to flow out of the dam and relieve the pressure, but they found the gates had been rusted shut. When water levels behind the dam had risen to 20 feet (6 meters) above normal, the dam gave way.

The concrete structure of the Manchu River Dam in Morvi, India. AP IMAGES.

The water rushed forward, destroying everything in its path within fifteen minutes. In Morvi, people were knocked over and drowned, and mud homes were washed away. The floodwaters reached the second stories of tall buildings. After the flood passed, bodies were strewn everywhere, and a thick layer of mud covered everything.

Drought For regions dependent on the monsoon rains for their livelihood, when a monsoon does not come it can be deadly as well. An example of this tragedy can be found in the African Sahel—the strip of semi-arid land south of the Sahara Desert. The Sahel depends on annual seasonal rains to support grasslands for grazing livestock and to grow crops. The monsoon was weak or virtually nonexistent in the Sahel from

Edmund Halley studies monsoons

English astronomer Edmund Halley (1656–1742) is best known for his calculations involving a comet that passed close to Earth in 1682, and which he (correctly) predicted would return again in 1758. Today, we know it as Halley's comet, and it crosses our skies about every seventy-five years. Halley was a friend of English physicist Isaac Newton (1642–1727), and it was Halley who provided the money to publish Newton's famous *Principia Mathematica* in 1687, which many people feel is the most important document in the history of science.

Edmund Halley.

What most people do not know is that Halley also made one of the first studies of monsoon wind patterns. He conducted his observations while at sea and during a two-year stay on the island of St. Helena in the Atlantic Ocean off the western coast of Africa. He combined his observations with information obtained from sailors who had traveled throughout the world. As a result of these studies, Halley established that the difference between the temperatures of the air over land and over the adjacent ocean produced different air densities, which were the driving force behind seasonal monsoon winds. He published his findings in 1686 along with one of the first meteorological maps, which showed wind patterns on the world's oceans.

1968 through 1973, and again during several periods throughout the 1970s, 1980s, and early 1990s. This caused extensive drought (pronounced DROWT), an extended period during which the amount of precipitation is much lower than usual. Due to the lack of rainfall, large portions of the Sahel have been turning to desert.

Positive aspects of monsoons Monsoon rains nourish crops and support people and livestock. For instance rice, the number-one crop in monsoon regions, requires very wet conditions to grow. There are even

The effect of El Niño on India's monsoons

In recent years, scientists have discovered a link between El Niño and the failure of India's monsoon. El Niño is an extraordinarily strong episode (occurring every two to seven years) of the annual warming of the Pacific waters off the coast of Peru and Ecuador. In 1982–1983, in conjunction with one of history's strongest El Niños, India's monsoon rains never came.

Scientists linked El Niño and the monsoon by discovering that at the same time the waters grow warm off the coast of Peru, a warming also occurs in the Indian Ocean. That warming causes a reversal of the pressure gradient in the Indian Ocean. The surface winds that usually blow to the northwest, toward the coast of Africa and India, change direction. They blow toward the southeast, where temperatures are warmer and pressure is lower, bringing warmth and moisture to western Australia. At the same time they leave India and southern Africa drier than normal.

positive aspects of floods caused by the monsoon. The floodwaters deposit a layer of nutrient-rich soil on farmland, increasing its fertility. In some areas, along with the floodwaters come fish and other edible aquatic life. Fish provide a needed source of protein when crops are submerged and other food is scarce.

The human factor

The level of flooding caused by monsoon rains in India and Bangladesh is made worse by erosion (wearing away) of the Himalayan mountainsides. Massive deforestation, the removal of most or all of the trees, on the slopes, has left the soil exposed and vulnerable to being washed away by heavy rains. The sediments get swept downstream and are deposited in riverbeds and in the Bay of Bengal. The sediments raise the levels of the riverbeds, leaving less room for water and contributing to the incidence and severity of flooding.

Deforestation also contributes to the severity of drought when rainfall is scarce. The lack of plants reduces the soil's ability to retain moisture. Erosion creates hard-packed ground that is unable to absorb any rain that does fall.

Another way that human activity magnifies the negative effects of monsoons is through the concentration of settlements in monsoon regions. Indeed, the locations affected by monsoons have the highest population density in the world. This fact means that when natural disasters do occur there, large numbers of people suffer the consequences.

Another human factor when talking about monsoons is that aid meant for victims of floods or drought is often mishandled. Distribution of food, water and supplies may be hampered by inefficiency on the part of government officials or may be deliberately withheld from certain areas because of political considerations, such as support for an opposition political movement.

Technology connection

The behavior of monsoons has been the subject of intense study by meteorologists for the last century. Nonetheless, monsoons, and especially what causes them to vary from year to year, are not entirely understood. This lack of knowledge makes monsoon prediction very difficult.

Efforts at predicting the arrival dates of monsoons are largely based on readings of the Southern Oscillation—changes in patterns of air pressure at sea level between the eastern and western edges of the Pacific Ocean. The rising and falling of the pressure gradient (the rate at which air pressure changes with horizontal distance) across the ocean may foretell changing wind patterns and the arrival of monsoon rains. Attempts at predicting rainfall amounts for specific locations involve the imperfect method of searching for patterns in past rainfall records.

"Though the monsoon winds constitute one of the greatest weather systems on earth, and an enormous amount of research has been carried out . . . , many questions remain shrouded in mystery," stated Julius Joseph, Monsoon Officer of the Indian Meteorological Center, in the book *Chasing the Monsoon*. "It's like the human brain. We know it but we don't know it."

[*See Also* **Climate; Drought; El Niño; Flood; Weather: An Introduction**]

For More Information

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Optical Effects

The interaction between sunlight and the atmosphere produces a wide array of patterns and colors of light in the sky, and even optical illusions on the ground. The amount and types of particles (including water and ice) in the air, as well as the position of the Sun in the sky, influence the quality of the light perceived by our eyes.

Sunlight can appear as white light, as a single color of light, or as the entire spectrum of colors of light. The Sun itself may appear as a ringed image or as multiple images. Sunlight can also be distorted to create mirages, such as apparently wet roadways or towering mountains on the horizon.

These and other atmospheric optical phenomena are produced under specific and often unique conditions. Most of these phenomena take place during the day although some, caused by the interaction of moonlight and the atmosphere, occur at night. The visual displays that take place in the outermost reaches of Earth's atmosphere, the aurora borealis and aurora australis (also called the northern and southern lights), are caused by charged particles from the Sun rather than sunlight itself.

The color of light

About 45 percent of the solar radiation that reaches Earth's atmosphere is in the form of visible light. The electromagnetic spectrum includes the entire array of electromagnetic radiation, and visible light is that portion of the electromagnetic spectrum that we can see. Visible light includes the wavelengths of every color, from that with the longest wavelength, red, to that with the shortest wavelength, violet. The order of wavelengths of colors, from longest to shortest, can be remembered by using the mnemonic ROY G. BIV: R=red, O=orange, Y=yellow, G=green, B=blue, I=indigo, and V=violet. It is important to remember that violet, as used by physicists and astronomers, is not the same color as a violet crayon or the color of the flowers called violets. It is instead an extremely dark blue color, almost black in appearance.

WORDS TO KNOW

aurora: a bright, colorful display of light in the night sky, produced when charged particles from the Sun enter Earth's atmosphere.

cirriform: a wispy, feathery fair-weather cloud formation that exists at high levels of the troposphere.

conduction: the transfer of heat by collisions between moving molecules or atoms.

corona: a circle of light centered on the Moon or Sun that is usually bounded by a colorful ring or set of rings.

crepuscular rays: bright beams of light that radiate from the Sun and cross the sky.

critical angle: the angle at which sunlight must strike the back of the raindrop in order to be reflected back to the front of the drop.

diffraction: the slight bending of sunlight or moonlight around water droplets or other tiny particles.

dispersion: the selective refraction, or bending, of light that results in the separation of light into the spectrum of colors.

electromagnetic spectrum: the array of electromagnetic radiation, which includes radio waves, infrared radiation, visible light, ultraviolet radiation, X rays, and gamma rays.

Fata Morgana: a special type of superior mirage that takes the form of spectacular castles, buildings, or cliffs rising above cold land or water.

frontal system: a weather pattern that accompanies an advancing front.

glory: a set of colored rings that appears on the top surface of a cloud, directly beneath the observer. A glory is formed by the interaction of sunlight with tiny cloud droplets and is most often viewed from an airplane.

green flash: a very brief flash of green light that appears near the top edge of a rising or setting Sun.

halo: a thin ring of light that appears around the Sun or Moon, caused by the refraction of light by ice crystals.

inferior mirage: a mirage that appears as an inverted, lowered image of a distant object. It typically forms in hot weather.

iridescence: an irregular patch of colored light on a cloud.

middle latitudes: the regions of the world that lie between the latitudes of 30° and 60° north and south. Also called temperate regions.

mirage: an optical illusion in which an object appears in a position that differs from its true position, or a nonexistent object (such as a body of water) appears.

reflection: the process by which light both strikes a surface, and bounces off that surface, at the same angle.

refraction: the bending of light as it is transmitted between two transparent media of different densities.

scattering: multidirectional reflection of light by minute particles in the air.

superior mirage: a cold-weather mirage that appears as a taller and closer, and sometimes inverted, image of a distant object.

troposphere: the lowest atmospheric layer, where clouds exist and virtually all weather occurs.

Visible light is separated into its spectrum of colors when it passes through a glass prism or another medium, such as an ice crystal or raindrop. The prism bends each component of white light to a different degree, depending on that component's wavelength. For instance, red light, which has the longest wavelength, is bent the least. Violet light, which has the shortest wavelength, is bent the most. As a result, the entire rainbow of colors exits the prism, with red and violet on opposite ends.

Sunlight is white because it contains all visible wavelengths of light. The color of objects is caused by the fact that they absorb some wavelengths of light and reflect others. Reflection means that light bounces off a surface at the same angle that it strikes a surface. This definition will become important later in this chapter, when we compare reflection to refraction, which is the bending of light.

A white shirt, for example, does not absorb any wavelengths of visible light. The shirt reflects all wavelengths of visible light, which causes it to appear white. On the other hand, the skin of a red apple absorbs all wavelengths of radiation except red. Red light is reflected by the apple skin, which is the reason it appears red. An object that absorbs all wavelengths and reflects none appears black.

The scattering of light

When sunlight encounters minute particles in the atmosphere, such as air or water molecules, or small particles of dust, it reflects off them in every direction. Sunlight is, in effect, bounced around like a pinball by these particles. This multidirectional reflection is called scattering.

Blue skies The scattering of sunlight by air molecules is what causes the sky to appear blue. However, it is a *selective scattering,* meaning that not all wavelengths of visible light are scattered equally. Air molecules scatter primarily violet, indigo, blue, and green light, the colors at the short-wavelength end of the visible spectrum.

The small size of air molecules is responsible for the selective scattering of sunlight. The diameter of an air molecule is even smaller than the average wavelength of visible light. Air molecules are therefore better able to scatter shorter wavelengths of visible light than longer wavelengths.

When you look at the sky, your eye is bombarded from all directions by violet, indigo, and blue light. However, the structure of the human eye is such that the eye is much more sensitive to blue light than the other colors. Thus, when violet, indigo, and blue light are present at once, what the eye perceives is blue.

If there were no air molecules or other particles in the air, and therefore no scattering, the sky would appear black.

The scattering of light by clouds A cloud droplet has a far greater diameter than that of an individual air molecule. A cloud droplet, then, is capable of scattering all wavelengths of visible light to a fairly equal extent. In addition, a cloud droplet is a poor absorber of light. As described above, an object that reflects the entire spectrum of visible light appears white.

The amount of sunlight that penetrates a cloud depends on the thickness of the cloud. Some of the sunlight that strikes a small cloud will pass through the cloud, while the rest is reflected by the droplets it encounters. The sunlight that makes it through the cloud is scattered by droplets near the base, which is what makes the base of small clouds appear white.

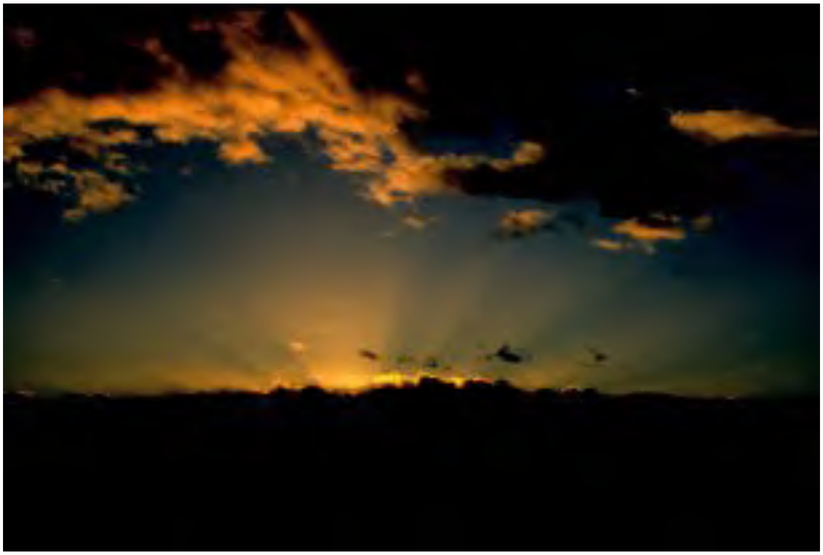
However, very little sunlight will reach the base of a tall cloud with a thickness of 3,300 feet (1,000 meters) or greater. That is the reason that the base of a cloud with vertical development appears dark. The base of a cloud also darkens as its droplets become larger. The reason for this is that larger droplets of water are better at absorbing light than are smaller units. Therefore, the darkness of the base of a cloud is also an indication of the likelihood of rain.

Haze Haze is the term used to describe a sky that has a uniform, milky white appearance. Haze is produced by high humidity in combination with a large number of particles in the air. Water vapor condenses around the suspended particles. These "haze particles," as they are called, scatter all wavelengths of visible light in all directions, just as cloud droplets do. The greater number of particles in the air, the whiter the sky appears.

The concentration of particles is often an indicator of air pollution, since the particles come mainly from emissions from smokestacks or automobile tailpipes. Haze may also be created by naturally occurring particles in the air, such as pollen and dust.

Haze occurs close to the surface. If you climb to the top of a tall mountain on a hazy day, you may see haze below and blue skies above.

Crepuscular rays Crepuscular rays are bright beams of light that appear to radiate from the Sun and cross the sky. They are most often visible at sunset



Crepuscular rays are sometimes referred to as "twilight rays," or alternating light and dark bands that appear to diverge in a fan-like array from the Sun. FMA, INC.

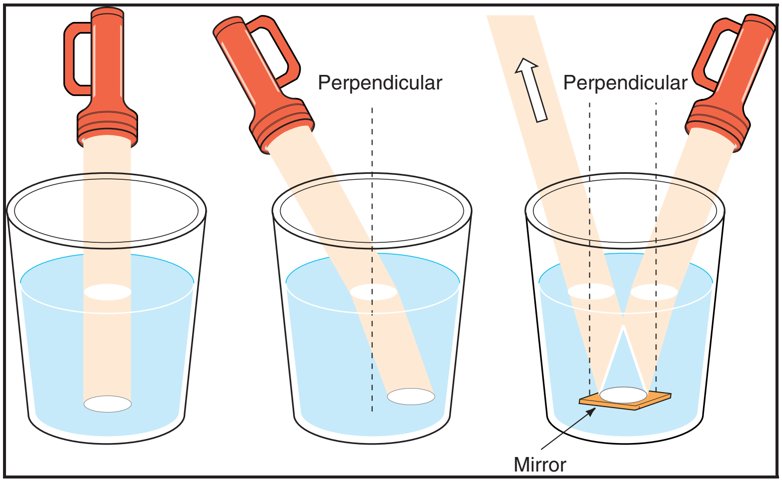
or when the Sun shines through a break in the clouds. The beams are made visible by the scattering of sunlight by dust, water droplets, or haze particles.

A similar effect is created when a bright light shines through a small opening, into a dusty room. This effect can be seen in a darkened movie theater where the intense beam of light leaves the projection booth. The beam is visible because it is being scattered by dust in the air.

Despite their appearance of fanning outward from the Sun, crepuscular rays run parallel to one another. The fan shape is only an illusion, caused by perspective. This illusion is similar to that of a road, railroad track, or any other long straight path that appears to narrow to a single point in the distance.

Colors at sunrise and sunset Why does the Sun appear red, yellow, or orange when it is on the horizon? The answer has to do with the angle at which sunlight strikes a given location. In the middle of the day sunlight strikes the ground most directly, and at the beginning and end of the day sunlight strikes the ground at the steepest angle. The angle at which sunlight strikes the ground is indicative of the amount of atmosphere through which the sunlight must pass.

At sunrise and sunset, the sunlight must pass through the greatest distance of atmosphere. In fact, sunlight passes through about twelve more miles (nineteen more kilometers) of atmosphere when the Sun is just over the horizon than it does when directly overhead. As the light of



The refraction of light as it enters and exits water.

the setting or rising Sun travels through all that atmosphere, its shorter wavelengths become scattered by the air molecules it encounters. The only wavelengths to make it all the way to Earth's surface are the longest wavelengths: red, orange, and yellow.

When the air is relatively clean, a setting or rising Sun appears to be orange-yellow. An orange-red Sun, however, indicates that the air contains a high concentration of particles. Particles that have diameters slightly larger than air particles scatter yellow wavelengths, leaving only light with the longest wavelengths—orange and red—to shine through. When the concentration of particles in the air is *very* high, such as after a volcanic eruption, only red light remains. All other colors are scattered and the Sun appears completely red.

The refraction of light

When light passes from one medium into a second medium, its speed changes. For example, when light travels from a less dense medium, like air, into a more dense medium, like water, the light slows down. If the light enters the denser medium at any angle other than from straight above, it will bend. The bending of light, as it passes through two transparent media (plural form of *medium*) of different densities is called refraction. The degree to which light bends depends on both the densities of the two substances and the angle at which light enters the second substance. When light is transmitted from a less dense substance to a more dense substance, it bends towards the perpendicular to the boundary between the two.

Positions of the Sun, Moon, and stars The light from the Sun, Moon, and stars travels from a less dense medium, space, to more dense medium, Earth's atmosphere. Thus, all starlight, sunlight, and moonlight, except that emitted when the Sun, Moon, or star is directly overhead, is refracted. As a result, our perception of the positions of the Sun, Moon, and stars is distorted.

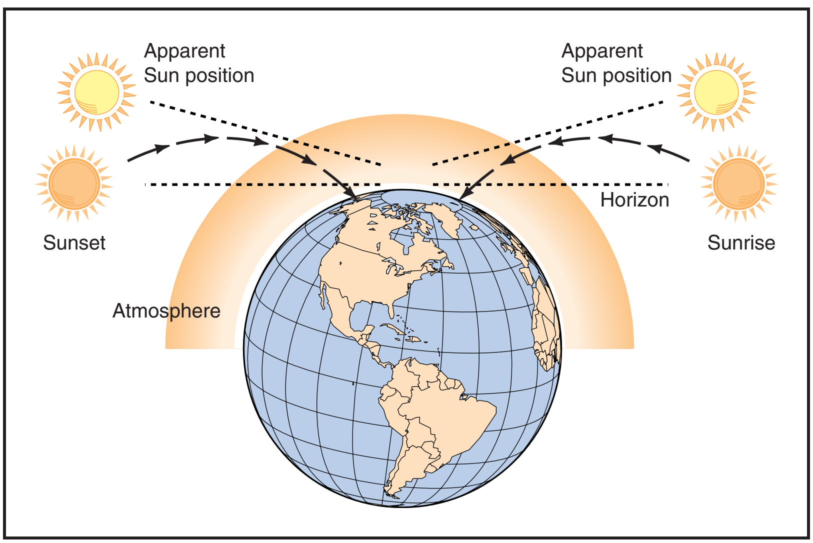
When we look at a star in the sky, we are actually seeing the light from that star which has been bent upon entering our atmosphere. Our eyes cannot perceive that the light has been bent, hence they cannot trace the path of light back to the actual position of the star. Therefore, the star appears to be higher in the sky than it actually is.

Experiment: The refraction of light by water

The best way to understand refraction is to try the following simple experiment: Fill a large glass beaker with water. Add a pinch of paprika or other ground spice. The spice causes a scattering effect, which makes the light beam easier to see. Then turn off the lights and shine a small flashlight into the water, from straight above. You will see the beam of light continue straight through to the bottom of the glass. Now tilt the flashlight so that the light enters the water at an angle. You will notice that the beam of light bends slightly toward the perpendicular.

When a star is near the horizon, its light must pass through the greatest amount of atmosphere, and undergo the greatest amount of refraction before it reaches an observer on the surface, of any position in the sky. Thus, when a star is near the horizon, the star's image appears farthest from its true position.

Refraction also causes an observer to see the rising of the Sun or Moon about two minutes before it actually occurs, and the setting of the Sun or



Refraction of sunlight as it travels though the atmosphere makes the Sun appear to rise earlier, and set later, than it actually does.

Moon about two minutes after it actually occurs. This situation is similar to what happens with starlight on the horizon. Because the light of the Sun and Moon must shine through so much atmosphere, it is refracted in such a way that they appear higher in the sky than they really are.

The refraction of light near the horizon is also responsible for the subtle "flattening" of a setting or rising Sun or Moon. Specifically, when the Sun or Moon is directly on the horizon, the light from the lower portion of the object is refracted to a greater degree than the light from the upper portion of the object. This causes the object to appear to be wider at the base than at the top.

Experiment: Create your own green flash

To learn how a green flash is created, perform this simple experiment. You will need a prism, a lamp (minus the shade), and a piece of dark paper. Hold the prism so it is between yourself and the light. Turn the prism until the entire spectrum of colors can be seen, with red on the bottom and blue on the top. The prism simulates Earth's atmosphere refracting the sunlight.

Then take the piece of dark paper and move it up between the prism and the bulb until only the thinnest bit of the light bulb is showing above the paper. This simulates the Sun about to go completely below the horizon. Move your head up and down until the thin strip of bulb appears green. This simulates the angle at which the green flash would occur.

Green flashes A green flash is a very brief and difficult-to-see optical effect that accompanies a rising or setting Sun. The green flash is a flash of green light that appears near the top edge of the Sun. The green flash is due to both refraction and scattering of light in the atmosphere.

A green flash occurs because all wavelengths of light from a setting or rising Sun are not refracted equally. Rather, the shorter wavelengths, purple and blue, are bent to the greatest degree, while the longer wavelengths, red and orange, are bent to the smallest degree. Thus, we would expect that the color of the very tip of the Sun as it first peeks over the horizon, or just sinks below the horizon, would be purple-blue. This would be true except that air molecules and tiny dust particles selectively scatter blue and purple wavelengths. The next longest wavelength, green, is what we see instead, unless there is a high concentration of particles in the air. In that case, green light will be scattered as well.

One reason that the green flash is so elusive is that in most cases, the green light is too faint to be seen by the human eye. The green flash is brightest, and noted most often, over the ocean where the air is relatively clean. It is also more common at high latitudes, where the Sun rises and sets more slowly. At the end of the long polar winter, the sunrise is so gradual that a green flash may persist for several minutes.

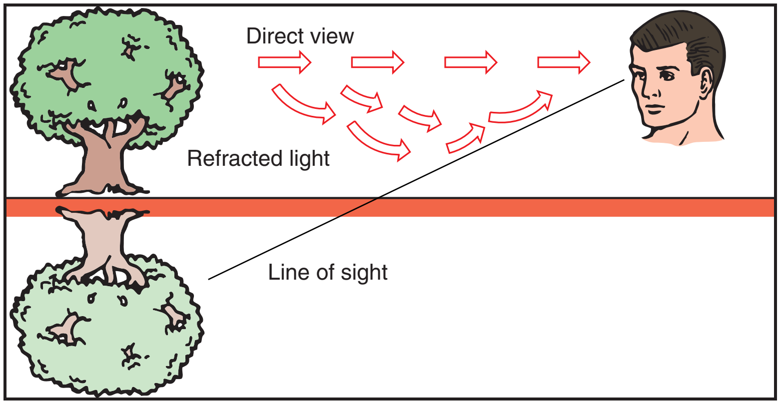
Mirages Another product of the refraction of light in the atmosphere is the mirage. A mirage is an optical illusion such that an object appears in a position different from its true position. Alternatively, a nonexistent object, such as a body of water, may appear. In some mirages, distant objects appear to be inverted or higher or lower than their true positions.

Mirages are caused by the refraction of light as it passes through layers of air with different densities. The differences in density are created by differences in temperature. The sharper the contrast in temperature between two air layers, the more pronounced the refraction of light.

Perhaps the best-known type of mirage is the appearance of "water" commonly seen on a roadway or in the desert. This type of mirage forms on hot days, when the pavement or sand becomes very hot. Heat is transferred from the surface to the air immediately above it by conduction (the transfer of heat by collisions between moving molecules or atoms). In contrast, the air just a few yards above the surface is cooler and denser.

A mirage of water on a road or desert surface is formed by the refraction of blue light from the sky. Rays of blue light from the sky near the horizon travel toward the surface. Near the surface, they encounter a thin layer of superheated air just above the ground. The rays bend upward away from the surface as they are refracted by the less dense hot air. Our eyes thus perceive the blue sky light as coming from just above the surface, in the distance. As we move toward the location where we saw the

In this mirage seen from Savoonga, Alaska, Siberian mountains are refracted to appear much closer than they really are. JLM VISUALS.



Inferior mirage of a tree over a hot surface.

mirage, the mirage disappears because the angle of light from the sky becomes too steep. The mirage reappears ahead, moving with us and always remaining in the distance.

Water mirages are even more convincing when they appear to "shimmer," as does water when struck by sunlight. The shimmering of a water mirage is caused by small shifts in the degree to which light is refracted. The reason why the angle of refraction changes is that near the surface hot air is constantly rising and cool air is constantly sinking. This variation causes a continual change in density of air layers which, in turn, causes the continual shift in the amount by which light is refracted.

Inferior mirages On a hot day, when you look at an object in the distance, you may see an upside-down version of the object directly beneath it. Yet, when you get right up to the object, the inverted image disappears. The upside-down image is an optical illusion called an inferior mirage. Inferior mirages are similar to water mirages. They form when the surface air is hotter and less dense than air at higher elevations.

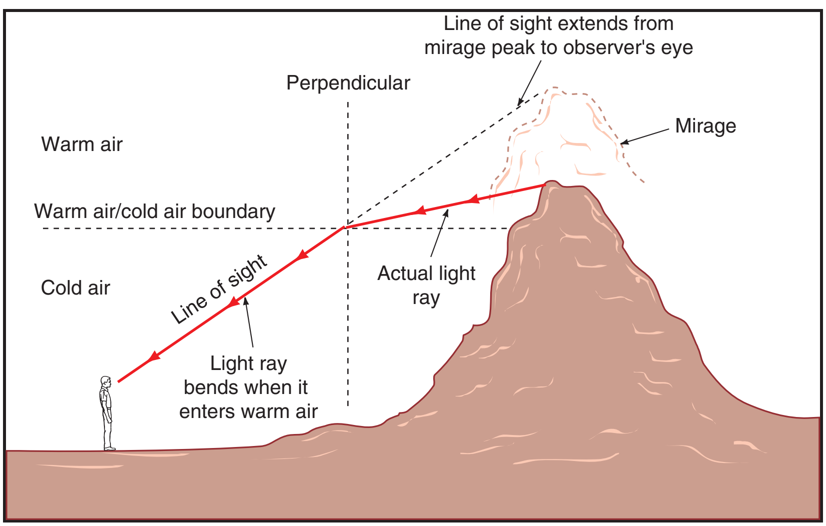
Light is reflected outward from a distant object, like a tree, in all directions. Some of the light from the treetop travels a straight horizontal path, never dipping into the warmer surface air. When that light reaches your eye, you get an accurate image of the tree. The light from the lower portions of the tree is not refracted because it remains within a medium of a single density, between the tree and your eye.

However, some of the light from the treetop travels at a gentle slope downward and eventually crosses the boundary between air layers. When it does so, it bends upward. When the refracted light reaches your eye, your eye follows the path of the light, at its refracted angle, back over the distance to the tree. Thus, the image appears lower to the ground than it actually is.

The light from the top of the tree is bent upward to the greatest degree, making it appear to come from the lowest position. For this reason, the lowered image of the tree is also upside-down.

Superior mirages Superior mirages are created under conditions that are opposite of those that create inferior mirages. They form in cold weather when the surface air is colder, and thus denser, than the air above. In a superior mirage, a distant object appears to be taller and closer to the observer than it really is. Sometimes it appears upside down. Superior mirages are most common in polar regions, where the air over a snow-covered surface is colder than the air several feet (about a meter) above.

For example, a mountain in the distance might appear taller and nearer than it actually is. The light from the mountaintop is reflected in all directions. Some of that light follows a gently sloping path downward. When that light enters the layer of colder air, it is bent toward the perpendicular; in this case, into a steeper downward path. When this refracted light reaches your eye, your eye follows the path of the light, at its refracted angle, back over the distance to the mountain. The image thus appears higher above the ground than it normally would.



Superior mirage of a distant mountain.

Did you know? The origin of Fata Morgana

The name "Fata Morgana" is Italian for "fairy Morgan." According to mythology, Morgan, or Morgan le Fay, was the fairy half-sister of King Arthur. She lived in an underwater crystal palace and was capable of creating magical castles out of thin air. In the fifteenth century, Italian poets from the town of Reggio viewed a fantastic, castle-like mirage near the Strait of Messina (the waterway between Italy and Sicily). Unable to explain what they saw, they called it a "Fata Morgana," and the name stuck.

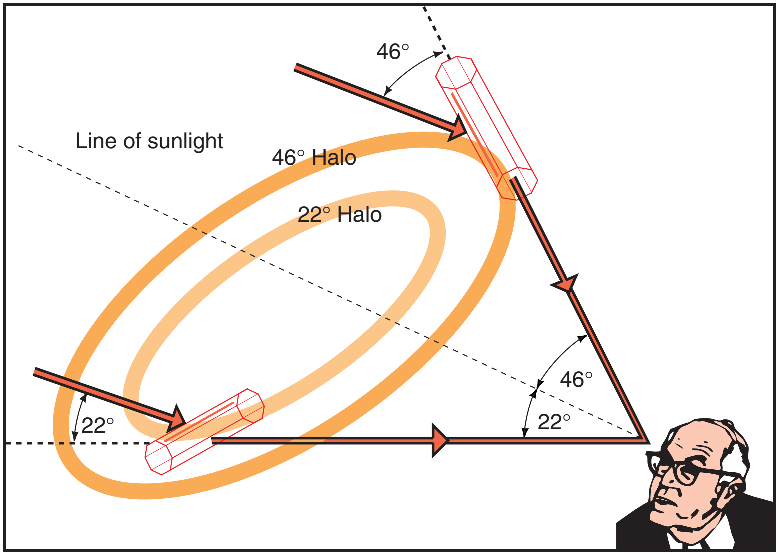
A special type of superior mirage is called a Fata Morgana. A Fata Morgana takes the form of spectacular castles, buildings, or cliffs rising above cold land or water, particularly in polar regions. This type of mirage is produced by light that is refracted as it passes through air layers of various temperatures. A Fata Morgana requires that the air temperature over a cold surface increase with height. Specifically, the temperature rises slowly throughout the surface layer of air, then several feet above the surface the air temperature rises more quickly. In the next layer of air, the temperature rises slowly again.

Halos A halo is a thin ring of light that appears around the Sun or the Moon. Halos are caused by the refraction of light by ice crystals. These ice crystals are either free-falling or within upper-level clouds called cirriform clouds. Cirriform clouds are the only type that are both high enough to contain ice crystals and thin enough to allow the image of the Sun to shine through.

There are two main types of halo: the 22° halo and the 46° halo. The 22° halo is smaller, encircles the Sun more tightly, and is more common than the 46° halo. There are several other sizes of halo but they appear very infrequently.

The size of a halo (22° or 46°) refers to the angle by which light is refracted through ice crystals and, consequently, the radius of the halo. For instance, if light is refracted by ice crystals at an angle of 22°, it will form a circle of light with a radius of 22°. To better understand this, draw a picture of a person on the ground and a Moon with a halo, above. Draw two lines: one between the person and the Moon, and the other between the person and a point on the far left or far right side of the halo. The angle formed by the two lines, which in reality would either be 22° or 46°, indicates whether the halo has a radius of 22° or 46°.

Both 22° and 46° types of halo are formed when light strikes small, pencil-shaped, hexagonal ice crystals that are around 0.0008 inches (20 micrometers) in diameter. The ice crystals that form a 46° halo may be as small as 0.0006 inches (15 micrometers) or as large as 0.001 inches (25



22° and 46° halos are formed by the refraction of sunlight (or moonlight) by ice crystals at different orientations.

micrometers), while the ice crystals that form a 22° halo are more uniformly 0.0008 inchs (20 micrometers).

A 22° halo is the result of refraction by randomly oriented ice crystals. The light enters one of the six sides and exits through another of the six sides. In the process, the light is bent by an angle of 22°.

The ice crystals that produce a 46° halo are oriented in such a way that sunlight strikes one of the six sides and exits through one of the two ends. This arrangement causes the sunlight to be refracted at an angle of 46°.

Halos may form at the leading edge of a frontal system, which is the weather pattern that accompanies an advancing front. Thus, they are often looked upon as a sign of rain. A halo is certainly not a foolproof forecasting tool, however, because the front may change direction or gently pass through without producing rain.

Sun dogs Sun dogs are also called mock suns or perihelia, Greek for "beside the Sun." They consist of one or two patches of light that appear on either or both sides of the Sun. Sun dogs make it appear that there are two or three suns in the sky. When two sun dogs occur, one may be brighter than the other, or higher than the other. They may appear white or colored. Sun dogs often appear just outside the circumference of a 22° halo.

Occasionally these patches of light are seen around a very bright, full moon. In that case, they are called moon dogs.

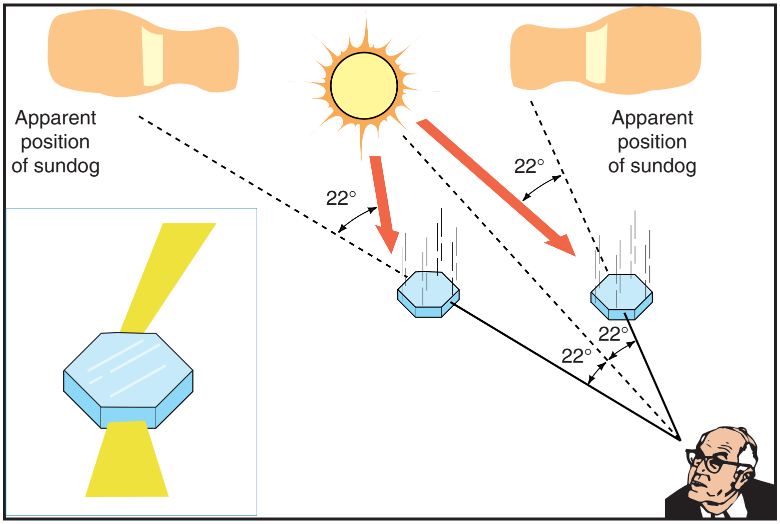
Sun dogs formed by high level ice crystal clouds. FMA, INC.

Sun dogs are produced by the refraction of sunlight that shines through plate-like ice crystals with diameters around 50 micrometers (.0019 inch) or larger. Aerodynamic drag causes the plate-like ice crystals to fall slowly through the air much like leaves falling from a tree. When the ice crystals are positioned horizontally, with large, flat ends parallel to the ground, they will refract sunlight at an angle of 22° and produce the sun dogs. When the ice crystals are randomly oriented, a 22° halo is produced. It takes millions of falling ice crystals, all oriented so that they refract sunlight at 22°, to produce sun dogs.

Where these falling ice crystals are relatively large and plentiful, the sun dogs will be colorful. This color is produced by the *selective refraction* of light, also called dispersion. In the process of dispersion, each ice crystal acts like a tiny prism, separating sunlight into the spectrum of colors.

The amount by which each color is refracted by an ice crystal varies slightly. Red light has the longest wavelength and is slowed the least as it passes through the ice crystal. Hence, red is bent the least. On the other extreme, violet light has the shortest wavelength and is slowed the most as it passes through the ice crystal. Hence, violet is bent the most.

The result is that red light appears on the edge of the sun dog closest to the Sun and blue appears on the edge farthest from the Sun. The reason



Sun dogs are produced by the refraction of sunlight through falling, plate-like crystals.

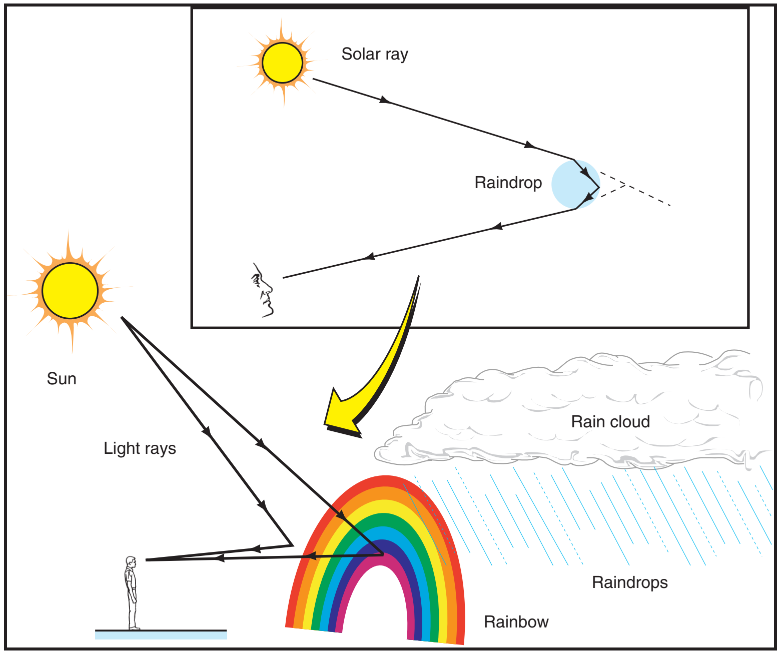
why blue, and not violet, appears is that the human eye is better able to perceive blue than violet.

Occasionally a halo will also be colorful, rather than its characteristic white. This dispersion of sunlight into bands of color, by the process just described, occurs when the ice crystals are relatively large and of uniform size and shape.

Rainbows A rainbow is an arc of light, separated into its different colors, that stretches across the sky. Rainbows are products of both reflection and refraction of sunlight by raindrops. A rainbow is, in effect, sunlight that has undergone dispersion and is reflected back to your eye. To observe a rainbow, the sun must be at your back and the falling rain must be in front of you.

A rainbow is formed by a rather complex process. As sunlight enters a raindrop, it is dispersed into its constituent colors, meaning that each color of the spectrum is refracted to a different degree. Most of this dispersed sunlight passes right through the raindrop. However, when sunlight strikes the back of the raindrop at a certain angle, called the critical angle, the sunlight is reflected back to the front of the drop. To achieve this critical angle, the Sun can be no higher than 42° above the horizon.

As a result of dispersion, once the sunlight enters the raindrop, each color strikes the back of the raindrop at a slightly different angle. Thus,



The formation and location of a rainbow.

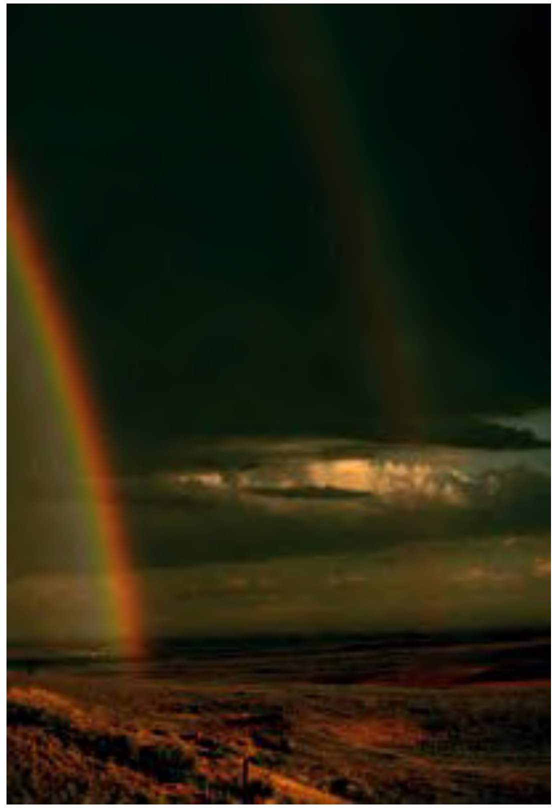
each color reflects off the back of the raindrop and emerges from the front of the raindrop at a slightly different angle.

Only one color exits from each raindrop at the exact angle necessary to reach your eye. This means that you see only one color at a time reflecting from each raindrop. For this reason, it takes millions of raindrops to create a rainbow.

Due to its angle of refraction, red light is reflected to your eye from the highest raindrops. Therefore, red is the color at the top edge of the rainbow. Violet light, which is reflected from the lowest raindrops, forms the bottom edge of the rainbow. The rest of the spectrum—orange, yellow, green, blue, and indigo—fills in the middle portion of the rainbow.

Each time you move, the rainbow you observe is being reflected from a whole different set of raindrops. Each raindrop produces only one ray of light at the appropriate angle to intercept your eye. By the same token, no two people can observe exactly the same rainbow!

Sometimes two rainbows appear in the sky at once. The brighter rainbow, formed by the process just described, is the *primary rainbow.* The fainter rainbow is called the *secondary rainbow.* A secondary rainbow is formed when sunlight strikes the raindrops at such an angle that the light is reflected twice within each drop. This double reflection causes violet light to be reflected to the eye from higher raindrops and red light, from lower raindrops. Therefore, in the secondary rainbow, the order of colors is reversed, with violet on top and red on the bottom. Some light is lost in the double-reflection process, which is the reason the secondary rainbow is dimmer than the primary one.



A double rainbow. FMA, INC.

The diffraction of light

Diffraction is the slight bending of sunlight or moonlight around water droplets or other tiny particles that it encounters. The diffraction of sunlight or moonlight produces patches of white and colored light in the sky.

Coronas A corona (Latin for "crown") is a circle of light centered on the Moon or Sun that is usually bounded by a colorful ring or set of rings. Coronas are difficult to observe around the Sun because of the Sun's brightness. Moonlight coronas are more easily observed.

A corona is the product of the diffraction of sunlight or moonlight around tiny, spherical cloud droplets. A corona can form only when the Sun or Moon is visible through a thin layer of clouds.

The smaller the cloud droplets, the greater the angle of diffraction, and the larger the corona. The largest coronas are produced by a newly formed cloud of uniform thickness. Coronas are much smaller than halos, however, because the angle of diffraction that produces a corona is only a few degrees.

Sometimes alternating light and dark bands are visible in the middle portion of a corona. Light and dark bands are formed when light waves, which have bent around a water droplet, come back together and recombine.

Light waves are similar to water waves in that they also have crests and troughs. When the crest of one wave meets the crest of another wave, the two are added together and become one large wave. This phenomena is

Experiment: Make your own rainbow

You can create your own rainbow using a clear glass bowl of water, a flashlight, and a small, flat mirror. The water acts as a refractor and the mirror acts as a reflector.

Simply place the mirror in the bowl of water, so that it rests against the side of the bowl at about a 45° angle. Then shine a flashlight straight down at the mirror. A rainbow will appear on the wall opposite the mirror.

called *constructive interference.* In light waves, constructive interference produces a bright band.

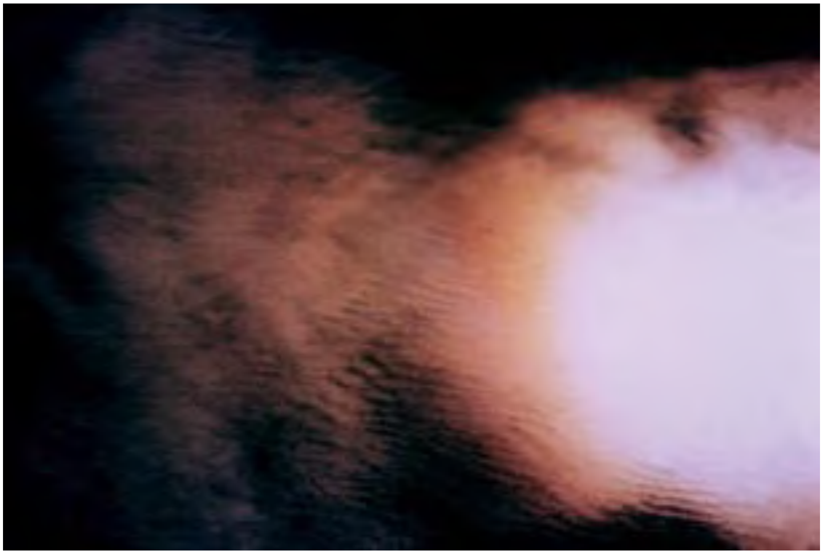
The opposite of constructive interference is *destructive interference.* Destructive interference occurs when the crest of one wave meets the trough of another and they cancel each other out. When destructive interference occurs in water waves, a calm spot is produced. When it occurs in light waves, a dark band is produced.

The colored rings on the edges of a corona are produced by diffraction of moonlight around cloud droplets of uniform size. If the droplets are different sizes, the color will appear in an irregular, and not a circular, pattern.

In a process similar to that of dispersion, diffraction causes the differential bending of light, according to wavelength. When white light is bent, its longest-wavelength component, red, bends the least and its shortest-wavelength component, violet, bends the most. In this way the light is separated into its constituent colors.

Red appears on the side of the ring farthest from the Moon and violet appears on the side of the ring closest to the Moon. The corona may have several rings, which become fainter with distance from the Moon.

A rare solar corona, caused by ice crystals from thin cirrostratus clouds ringing the Sun. FMA, INC.



Iridescent clouds. FMA, INC.

Iridescence Iridescence is the term used to describe irregular patches of colored light on clouds. This effect is most often seen within 20° of the Sun or Moon. Iridescence often appears as pastel shades of blue, pink, or green. The brightness of the colors is proportional to the number of droplets within the cloud and the uniformity of size of those droplets.

Iridescence forms in the same way as a corona and is, essentially, an irregular corona. One difference between the two phenomena has to do with the size of the cloud droplets. Iridescence is formed when sunlight is diffracted by cloud droplets of different sizes, while coronas require cloud droplets of a uniform size.

Sometimes iridescence appears as an arc, or a portion of a corona. This is the case when a cloud partially obscures the Sun or Moon, but does not cover the entire region in which a corona would form. Iridescence may also form on a cloud that is near, but not covering, the Sun or Moon.

Glories A glory is a set of colored rings that appears on the top surface of a cloud, directly opposite the Sun from an observer. Although it is possible to view a glory by climbing a mountain until you're above the clouds, it is much easier to view one from an airplane window. Because they are most

The Brocken Spectre

A Brocken Spectre (specter or ghost) is the apparently huge and distorted shadow cast by an observer on the tops of clouds that are below the mountain on which the observer stands. The name comes from the Brocken, the tallest peak of the Harz mountain range in Germany. The peak of the Brocken is often above the cloud level and the area is usually misty, so the conditions are often favorable to see a shadow cast onto a cloud layer. These shadows seem to move by themselves because the shape of the cloud layer constantly changes.

The same conditions that can produce a specter are also favorable for the observation of a glory. The appearance of giant shadows that seemed to move by themselves and which were surrounded by optical glories are possibly what gave the Harz mountains the reputation as a refuge for witches and evil spirits. In Johann Wolfgana Goethe's *Faust*, a famous play about a man who makes a bargain with the devil, the Brocken is called the Blocksberg and is the site of the Witches' Sabbath on Walpurgis Night, which is the night before May Day (May 1).

often viewed from airplanes, glories are generally thought of as the rings of color that surround the shadow of an airplane.

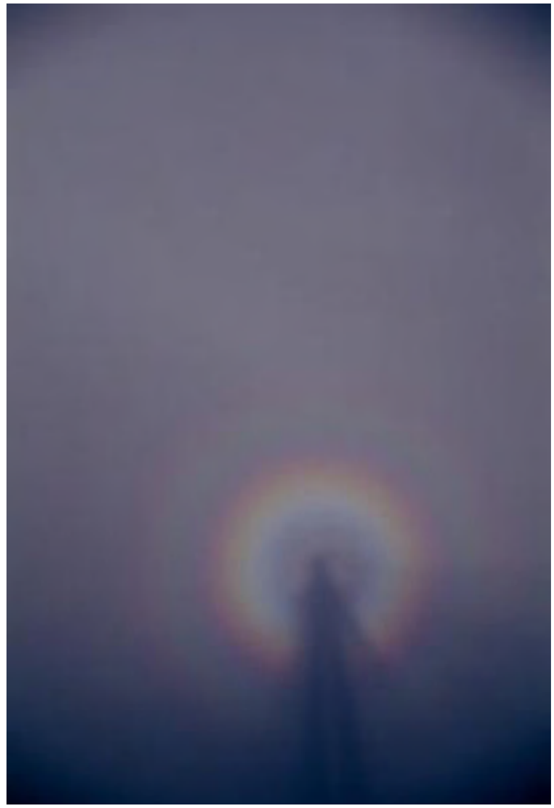
A glory is formed by a complex process similar to the formation of a rainbow. The main difference between the two phenomena, however, is that rainbows are formed by the interaction of sunlight with raindrops while glories are formed by the interaction of sunlight with tiny cloud droplets. The cloud droplets are less than 50 micrometers (about 0.002 inch) in diameter. In contrast, the droplets that form rainbows are around 0.04 to 0.24 inches (0.1 to 0.6 centimeters) in diameter.

In a glory, sunlight undergoes refraction, reflection, and diffraction within cloud droplets before being returned to your eye. First, sunlight that strikes the surface of a cloud droplet is refracted within the droplet. This refracted light then reflects off the back of the droplet. Some of this reflected light skims the opposite surface of the droplet and bends slightly, or is diffracted, around the droplet. The light then exits the droplet on a path that is parallel to its entry path.

The process of diffraction is also what separates the light of a glory into its constituent colors. As the light is diffracted by cloud droplets, red is bent the least and violet, the most. Hence, as with a rainbow, each droplet reflects light of only one color. The innermost ring of the glory appears purple and the outermost ring appears red, with the rest of the spectrum lying in between.

A glory is always positioned directly beneath the observer or opposite from the Sun. Like a rainbow, a glory moves with the observer. Thus, if you were on one airplane and another airplane was flying beside you, you would be able see the glory around your own plane's shadow, but not the glory around the other plane's shadow.

Auroras



A Brocken bow, or specter, is the apparently huge and distorted shadow cast by an observer on the tops of clouds that are below a mountain on which the observer stands. ©GALEN ROWELL/ CORBIS.

Unlike the other optical phenomena described in this chapter, auroras are not produced by sunlight or moonlight but by radiation from the Sun. Auroras are bright, colorful displays of light in the night sky. They come in two forms, aurora borealis and aurora australis, better known as the northern and southern lights. Auroras are most prominent near the North and South poles, but can be seen occasionally in the regions of the world that lie between the latitudes of 30° and 60° north and south, called the middle latitudes.

A display of northern or southern lights can be as fascinating as fireworks. They vary in color from whitish-green to deep red and take on shapes such as streamers, arcs, curtains, and shells.

Auroras are produced when charged particles from the Sun enter Earth's atmosphere. As this stream of particles approaches Earth, it is trapped for a time in the outermost parts of the Earth's magnetic field. Eventually the particles are drawn down toward the north and south magnetic poles. Along the way, they ionize (create an electric charge within) oxygen and nitrogen gas in the atmosphere. This causes the atmosphere to glow.

[*See Also* **Climate; Clouds; Human Influences on Weather and Climate; Weather: An Introduction**]

For More Information

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Thunderstorm

Thunderstorms are relatively small, but intense, storm systems. An average thunderstorm is only 15 miles (24 kilometers) in diameter and lasts about thirty minutes. During that time, it produces strong winds, heavy rain, and lightning. Lightning is a short-lived, bright flash of light that is produced by a 100 million-volt electrical discharge in the atmosphere. Only 10 percent of thunderstorms are considered "severe," meaning they produce some combination of high winds, hail, flash floods, and tornadoes. Only about 1 percent of all thunderstorms are the source of tornadoes, whose violently rotating winds reach the ground and can cause great damage.

Severe thunderstorms and their related phenomena produce significant human injuries and fatalities, as well as property damage, each year. Hailstorms, for instance, storms which bring frozen precipitation called hailstones that range in size from peas to softballs, are responsible for nearly $1 billion a year in crop damage. Tornadoes also cause about eighty deaths and fifteen hundred injuries annually. While straight-line winds called derechos occur less frequently and result in fewer fatalities, a single derecho can cause millions of dollars in damage.

Lightning, which occurs with all thunderstorms, sets off about ten thousand forest fires each year in the United States alone, causing several hundred million dollars in property damage. Furthermore, in the United States lightning causes between 75 and 100 deaths and about 550 injuries annually. It is the second biggest weather killer in the country, topped only by flash floods. Flash floods, which are sudden, intense, localized floods caused by heavy rainfall, kill an average of 140 people yearly.

Thunderstorms are produced by cumulonimbus clouds, which are tall, dark, and ominous—and they are giant storehouses of energy. A typical thunderstorm unleashes 125 million gallons (568 liters) of water and enough electricity to provide power to the entire United States for twenty minutes.

At any given time, there are about two thousand thunderstorms underway around the world. About forty thousand thunderstorms occur worldwide each day, and fourteen million thunderstorms happen each year. Earth is struck by lightning from these storms one hundred times every second.

Watching a thunderstorm approach can be quite an exhilarating experience. Imagine standing on your front porch on a hot, humid afternoon. The morning's haze, when the sky appeared milky, has given way to a line of tall cotton-ball-like cumulus clouds. On the horizon there are enormous thunderstorm clouds, with their whitish tops and dark undersides. As these clouds approach, the sky darkens, almost blocking out the sunlight. Then comes a calm period in which the air feels still, hot, and very muggy. Next the wind picks up and the rain begins to fall in large drops. Soon the rain intensifies to a downpour and the wind turns cold and blows wildly. Lightning brightens the sky here and there. Then it strikes nearby and is followed by a thunderclap so loud it jolts you to your feet. Half an hour later the storm is over. The storm clouds move away, the sun comes out, and the air is cooler and less humid. Before long, however, the heat returns.

Evolution of thunderstorms

Two atmospheric conditions are required for the development of a thunderstorm. The first is that the surface air must be warm and humid. The other is that the atmosphere must be unstable. "Unstable" means that the surrounding air is colder than a rising air parcel. As long as the atmosphere remains unstable, an air parcel will continue to rise. When the air parcel reaches a height at which the atmosphere is stable, meaning that the surrounding air is warmer than the air parcel, it will rise no further.

Thunderstorms occur when warm, moist air rises quickly through an unstable atmosphere. On reaching the dew point, the temperature at which the air is saturated, the moisture within the air condenses, forming a cloud. If the atmospheric instability is great enough, this air will rise to great heights, and the cloud will develop vertically (upwardly) into a towering cumulus cloud. In conditions of great instability, the cloud will develop into a full-fledged cumulonimbus, or thunderstorm, cloud.

A number of factors may trigger the uplift of warm air. For example: an air mass (a large quantity of air throughout which temperature and moisture is constant) rides up, along a mountainside. Or air is forced

WORDS TO KNOW

air mass: a large quantity of air throughout which temperature and moisture content is fairly constant.

anvil: the flattened formation at the top of a mature cumulonimbus cloud.

cirrus: clouds at high levels of the troposphere, created by wind-blown ice crystals, that are so thin as to be nearly transparent.

cold front: the line behind which a cold air mass is advancing, and in front of which a warm air mass is retreating.

condensation: the process by which water changes from a gas to a liquid.

convective cell: a unit within a thunderstorm cloud that contains updrafts and downdrafts.

convergence: the movement of air inward, toward a central point.

cumulonimbus: tall, dark, ominous-looking clouds that produce thunderstorms. Also called thunderstorm clouds.

cumulus: clouds that look like white or light-gray cotton balls of various shapes.

dart leaders: the series of dim lightning strokes that occur immediately after the original lightning stroke, that serve to discharge the remaining buildup of electrons near the base of the cloud.

derecho: a destructive, straight-line wind, which travels faster than 58 mph (93 kph) and has a path of damage at least 280 miles (450 kilometers) long. Also called plow wind.

dew point: the temperature at which a given parcel of air reaches its saturation point and can no longer hold water in the vapor state.

divergence: the movement of air outward, away from a central point.

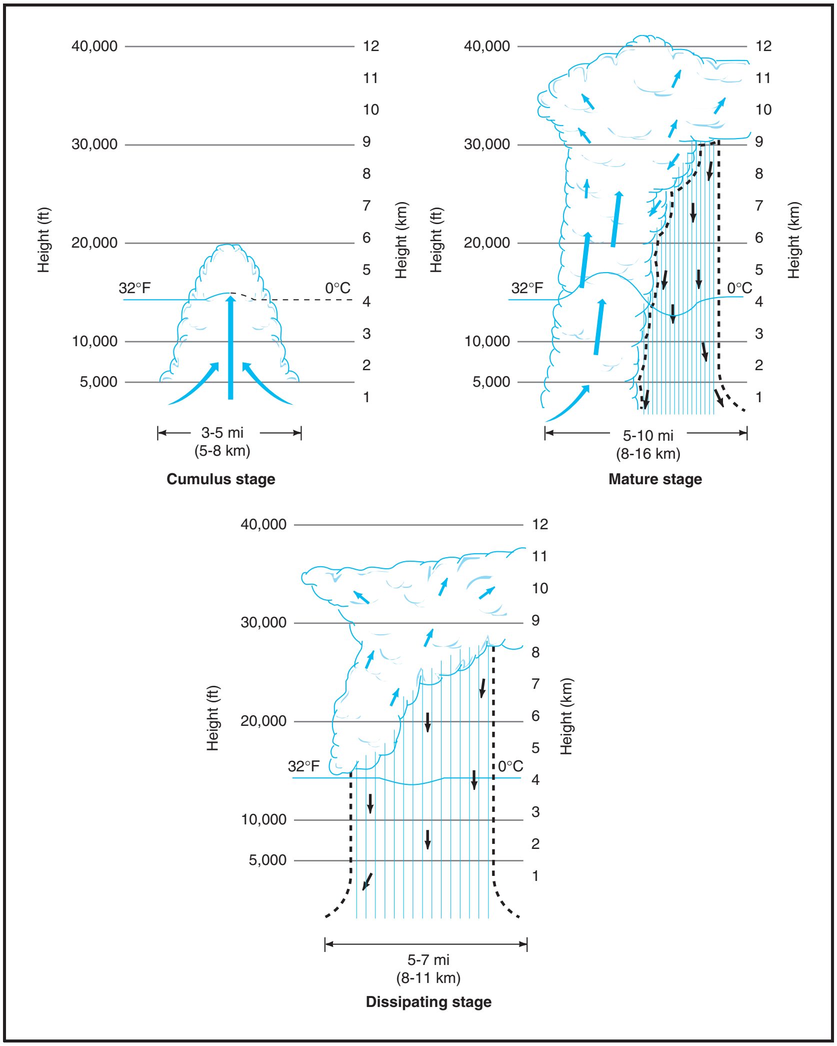
downburst: an extremely strong, localized downdraft beneath a thunderstorm that spreads horizontally when it hits the ground, destroying objects in its path.

downdraft: a downward blast of air from a thunderstorm cloud, felt at the surface as a cool wind gust.

dry adiabatic lapse rate: the constant rate at which the temperature of an unsaturated air parcel changes as it ascends or descends through the atmosphere. Specifically, air cools by 5.5°F for every 1,000 feet (1.0°C for every 100 meters) it ascends and warms by 5.5°F for every 1,000 feet (1.0°C for every 100 meters) it descends.

upward by an advancing cold front, the forward boundary of a cold air mass and/or thermal (a pocket of rising warm air). At the same time, there must be a divergence (movement outward) of winds aloft. This divergence causes surface winds to converge beneath, and rise to the point of divergence.

The life cycle of a thunderstorm can be broken down into three stages that trace its development from inception to dispersion. These stages are called: the cumulus stage, the mature stage, and the dissipating stage.



The life cycle of a thunderstorm.

Cumulus stage A thunderstorm begins its development in the cumulus stage, also known as the developing stage. A thunderstorm usually begins forming late in the afternoon or early in the evening. It follows a period in which cumulus clouds have been forming, then evaporating into the dry air, only to form again at higher altitudes. Each time the clouds evaporate, they raise the humidity of the air. This fact is important because as long as the air is dry, any moisture that condenses within rising warm air will quickly evaporate. Only when the air is humid will moisture condense into a cloud that remains in the air. As the air is humidified at increasingly higher levels, the conditions are right for the development of towering cumulus clouds.

In the cumulus stage, which takes only fifteen minutes or so, cumulus clouds undergo dramatic vertical growth. The cloud tops rise to a height of about 30,000 feet (9,000 meters). At the same time, the clouds spread horizontally and merge into a line up to about 9 miles (15 kilometers) across. When air rises it cools by the dry adiabatic lapse rate (5.5°F per 1,000 feet, or 9.8°C for every 1,000 meters). Once the air has cooled to the dew point, it becomes saturated and the moisture within it condenses (becomes liquid). Latent heat, which is the heat that must be removed from water vapor to cause it to turn into a liquid, or that must be added to a liquid water to cause it to turn into a vapor, is released into the cloud through condensation. This heat increases the temperature contrast between the cloud and the surrounding air, fueling the upward growth of the cloud as long as warm air continues rising into it.

Once air enters a cloud and becomes saturated, it cools by the moist adiabatic lapse rate (2.7°F per 1,000 feet, or 4.9°C for every 1,000 meters). Thus, it cools more slowly than it did at the dry adiabatic lapse rate, when it was unsaturated (had less than 100 percent relative humidity). This change enables the air to rise to even greater heights before reaching a stable layer of atmosphere. Air will continue rising as long as it is warmer, and less dense, than the surrounding air. The greater the instability of the air (the more rapidly the air cools with height, the higher the air parcel will ascend. As air rises beyond the top of the cloud and into the dry air, the cycle is repeated. The moisture evaporates and increases the humidity of the dry air, enabling condensation to take place at ever-greater altitudes. In this way, a cumulus cloud develops upward, into a cumulonimbus cloud.

Precipitation rarely occurs during the cumulus stage, because water droplets or ice crystals are blown upward by rising air, into the tops of the clouds. Within the cloud, the speed of updrafts, columns of air blowing upward, may exceed 30 feet per second (10 meters per second). Lightning and thunder are produced only occasionally during the cumulus stage.

Experiment: Lightning in your mouth

Experimenting with lightning or electricity is too dangerous for ordinary people. But you can experiment with mild electric charges that operate on the same principle as lightning. Here's one fun way to do it: get a wintergreen-flavored Life Savers candy and go into a completely dark room that has a mirror. Let your eyes adjust for a few minutes. Then, crunch down on the candy with your teeth, keeping your mouth open. As it breaks, you should see little sparks or flashes of light. This happens because the breaking of the sugar inside the candy releases electrical charges into the air which attract oppositely charged nitrogen in the air. When the opposite charges meet, they produce "lightning."

WORDS TO KNOW

entrainment: the process by which cool, unsaturated air next to a thunderstorm cloud gets pulled into the cloud during the mature stage of a thunderstorm.

evaporation: the process by which water changes from a liquid to a gas.

flash flood: a sudden, intense, localized flooding caused by persistent heavy rainfall or the failure of a levee or dam.

front: the boundary between two air masses.

frontal system: a weather pattern that accompanies an advancing front.

gust front: the dividing line between cold downdrafts and warm air at the surface, characterized by strong, cold, shifting winds.

hail: precipitation comprised of hailstones.

hailstone: frozen precipitation that is either round or has a jagged surface, is either totally or partially transparent, and ranges in size from that of a pea to that of a softball.

haze: the uniform, milky-white appearance of the sky that results when humidity is high and there are a large number of particles in the air.

hurricane: the most intense form of tropical cyclone. A hurricane is a storm made up of a series of tightly coiled bands of thunderstorm clouds, with a well-defined pattern of rotating winds and maximum sustained winds greater than 74 mph (119 kph).

induction: the process by which excess electrical charges in one object causes the accumulation by displacement of electrical charges with opposite charge in another nearby object.

insulator: a substance through which electricity does not readily flow.

inversion: a stable reversal of the normal pattern of atmospheric temperature, formed when a warm air mass sits over a cold air mass near the surface.

ion: an atom that has lost or gained an electron, thereby acquiring a positive or negative electrical charge.

jet stream: a fast-flowing, relatively narrow air stream found at an altitude of approximately 36,000 feet (11,000 meters).

latent heat: the heat that must be removed from a quantity of water vapor to cause it to turn into a liquid, or that must be added to a quantity of liquid water to cause it to turn into a vapor; called latent because the temperature of the quantity of water or water vapor does not change.

lightning: a short-lived, bright flash of light during a thunderstorm that is produced by a 100 million-volt electrical discharge in the atmosphere.

Mature stage The mature stage of a thunderstorm begins when the first drops of rain reach the ground. It is during the mature stage that one sees heavy rain, strong winds, lightning, and sometimes hail and tornadoes. If the thunderstorm is severe, the sky may appear black or dark green. A thunderstorm generally remains in the mature stage for ten to thirty minutes, occasionally longer.

Throughout the mature stage, the cumulonimbus cloud continues building. Eventually it builds to the tropopause, the boundary between the troposphere and the stratosphere which is between 5 and 7 miles (8 to 11 kilometers) above Earth's surface. The cumulonimbus cloud may even overshoot the tropopause. Above the tropopause, the temperature of the atmosphere increases with altitude. Thus the rising air becomes cooler than the surrounding air, so it ceases to rise and starts to spread out laterally in the anvil shape that characterizes the top of mature thunderstorm clouds. The base of the cloud, meanwhile, grows to several miles across. Precipitation begins to fall from the thunderstorm cloud when ice crystals or water drops within the cloud reach a critical mass. That is, they become large enough to overcome the updrafts that have previously confined them to the tops of the clouds. As the precipitation falls, it pulls air with it. These downward blasts of air, felt at the surface as cool gusts, are called downdrafts.

The updrafts of air continue to bring warm, humid air into the thunderstorm throughout the mature stage. These updrafts create a situation in which there are columns of rising air adjacent to columns of descending air. The rising air builds up the storm cloud while the descending air returns the cloud's moisture to Earth.

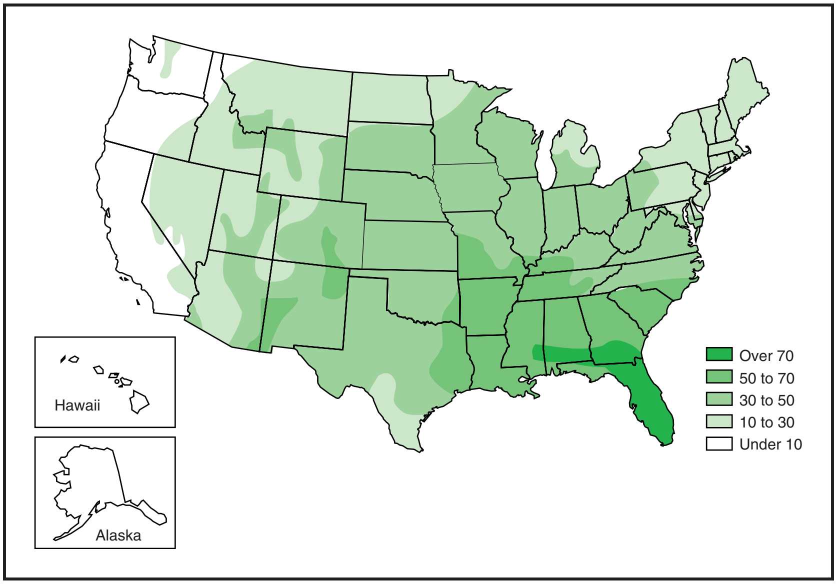
As the storm progresses, the updrafts weaken and downdrafts strengthen by entrainment. Entrainment is the process by which cool, unsaturated air next to a cloud gets pulled into the cloud. As this dry air mixes with air in the cloud, the relative humidity (amount of water vapor in the air mass) in the cloud is lowered. Some of the water droplets evaporate, a process that absorbs latent heat from the cloud as water changes from liquid to gas. This has the opposite effect that condensation had in the cumulus

Weather report: Where thunderstorms occur

More than fourteen million thunderstorms take place throughout the world each year. For the most part, they occur in warm, humid areas. The world's greatest concentrations of thunderstorms are in Brazil's Amazon Basin, the Congo Basin of equatorial Africa, and in the islands of Indonesia. In each of these areas, thunderstorms occur on more than one hundred days each year.

Thunderstorms occur, with varying frequency, all throughout the United States. Central Florida's Gulf Coast has thunderstorms more often than any other U.S. location. Thunderstorms occur there on 130 days per year, on average. On the other extreme is the Pacific Coast, which sees thunderstorms on only five to ten days per year, and Alaska, which only has one thunderstorm every three to five years.

In between those two extremes are the following annual averages: 1) Florida's Gulf Coast, plus the Gulf Coasts of Alabama and Mississippi, have thunderstorms on 80–100 days; 2) the rest of the southeastern United States has thunderstorms on 60–80 days; 3) the central portion of the Rockies has thunderstorms on 50–70 days; 4) the Corn Belt (Iowa, Indiana, and Illinois) and Great Plains states (states just east of the Rockies) have thunderstorms on about 50 days; 5) the portion of the Midwest that lies east of Iowa, as well as the mid-Atlantic states and New England, have thunderstorms on 20–40 days; 6) the desert Southwest also generally has thunderstorms on 20–40 days but the rate is terrain-dependent; 7) the far West, has the fewest thunderstorms with 0–20 days.



Average number of days on which thunderstorms occur each year in the United States.

stage. Specifically, evaporation cools the rising air and slows its ascent. It also cools the downdrafts. Since cold air is denser and heavier than warm air, this cooling causes the downdrafts to fall faster.

The thunderstorm peaks in intensity at the end of the mature stage. As downdrafts begin to dominate updrafts, the thunderstorm yields the heaviest rain, the most frequent lightning, and the strongest winds. If the thunderstorm produces hail or tornadoes, they will occur at the end of the mature stage.

Dissipating stage In the dissipating stage of a thunderstorm, precipitation falls from the entire cloud base. Downdrafts overtake updrafts, preventing warm, moist air from rising up into the cloud. In effect, the downdrafts cut off the thunderstorm's fuel supply. Without a constant influx of moisture from below, the cloud begins to evaporate. During the dissipating stage, rain becomes light and winds become weak. An hour or so after the cumulus stage began, the storm cloud dissipates, leaving only wispy traces high in the sky. The traces are of cirrus clouds, at high levels of the troposphere. These clouds are so thin as to be nearly transparent. The cool, refreshing air brought by downdrafts during the mature stage subsides. The rain evaporates, which increases the humidity of the air. The heat and humidity following the thunderstorm may create even more oppressive conditions than those that existed before the thunderstorm.

The preceding explanation of a thunderstorm's life cycle applies to a single convective cell of a thunderstorm. A convective cell is a unit within a thunderstorm cloud that contains updrafts and downdrafts. While some thunderstorms are of the single cell variety, most thunderstorms contain several convective cells and are called multicell thunderstorms. In the case of a multicell thunderstorm, convective cells are simultaneously in various stages of development. Old cells die and new cells form as the storm moves over the ground and encounters fresh sources of warm, moist air. The life cycle of each convective cell lasts thirty minutes to sixty minutes. A multicell thunderstorm may last several hours.

Types of thunderstorms

Thunderstorms are classified by a number of criteria. The first criterion is the mechanism that triggers its formation. Another criterion is whether the thunderstorm is isolated or part of a cluster of thunderstorms. Finally, thunderstorms are classified on the basis of their severity. These groupings often overlap. For instance, a thunderstorm that forms along a cold front may be weak or severe, and may occur singly or in a line of thunderstorms.

Air mass thunderstorms An air mass thunderstorm, the most common type of thunderstorm, is one that forms within a single mass of warm, humid air. Air mass thunderstorms are relatively weak, meaning they don't produce hail or strong winds, and die out quickly. They do, however, produce lightning and sometimes destructive downward gusts of wind called downbursts. Air mass thunderstorms most often form in the late afternoon, at the warmest time of day. In regions outside of the tropics, they form only in summer.

For any thunderstorm to develop, air must be lifted to the level at which it is saturated, meaning the moisture within it condenses and forms a cloud. The air does not rise to its condensation level automatically. Rather, it requires a lifting mechanism. In air mass thunderstorms, that lifting mechanism is the intense heating of small areas on the surface, which produces rising pockets of air called thermals. This heating is most often accompanied by a convergence, or movement inward, of surface winds and a resultant uplift of air. The air ascends to a point where there is a divergence of winds aloft.

An air mass thunderstorm occurs in isolation from other thunderstorms. It may be composed of a single convective cell. More often, however, it contains multiple cells.

Air mass thunderstorms are common in the central and eastern United States in spring and summer. They are initiated by the northward flow of humid, tropical air masses from the Gulf of Mexico, the Caribbean, and the Atlantic Ocean near Bermuda. On an average, these thunderstorms occur one afternoon out of every three on the Gulf Coast of Florida.

Orographic thunderstorms An orographic thunderstorm, also called a mountain thunderstorm, is a type of air mass thunderstorm that is initiated by the flow of warm air up along a mountainside. Such storms occur most commonly on slopes with greatest exposure to the Sun.

As a slope is heated, the air next to it is also heated. That warm air rises and cools and the moisture within it condenses to form cumulus clouds. Given a constant influx of warm, moist air and an unstable atmosphere, these clouds will develop into cumulonimbus clouds.

Orographic thunderstorms are also relatively weak. They are common in the Rocky Mountains, as afternoon breezes lift warm air up the mountainsides. Because of this lifting mechanism, mountainous regions in the United States are hit with more thunderstorms than any region outside southeastern states.

Frontal thunderstorms Frontal thunderstorms form along the edge of a front. They occur most often when a cold front is displacing a maritime tropical (warm and moist) air mass that has remained stationary for several days. An advancing cold front wedges underneath an existing warm air mass, thrusting the warm air upward.

Less frequently, a frontal thunderstorm is initiated by an advancing warm front, the leading edge of a warm air mass. Such storms occur only if advancing warm air, which glides up and over the residing cold air mass, is entering a particularly unstable air layer.

Frontal thunderstorms may occur any time of day or night and at any time of year, except for very cold winter days. They are most likely to form in warm weather, when convection is enhanced by the heating of the ground. Frontal thunderstorms that occur in the winter may yield snow and are generally far weaker than their summertime counterparts.

Though they often have stronger winds and heavier rain than air mass thunderstorms, frontal thunderstorms are relatively weak systems. Under certain conditions, thunderstorms produced along a front are severe. This is the case when a series of thunderstorms, called a squall line, arises in a band running parallel to the front.

Frontal thunderstorms are most common in the Great Plains states and the Midwest, where cold fronts from Canada overtake warm, moist air from the Gulf of Mexico. More than half the world's tornadoes occur in this region.

Mesoscale convective complexes A mesoscale convective complex (MCC) is a group of thunderstorms that forms a nearly circular pattern over an area that is about one thousand times the size of an individual thunderstorm. An MCC may cover an area greater than 50,000 square miles (130,000 square kilometers), or the size of a small state.

The combined effect of the individual thunderstorms of the MCC is to produce an airflow that favors the formation of new thunderstorms. MCCs most often arise in warm weather and at night. More than fifty MCCs per year form over the central and eastern United States.

Thunderstorms continually form and dissipate within an MCC. The overall pattern persists for up to twenty-four hours and moves very slowly, usually less than 20 mph (30 kph). MCCs yield significant amounts of rainfall. In the Great Plains states and the Midwest, MCCs produce around 80 percent of the rainfall during the growing season. Around half of all MCCs are severe, spawning some combination of tornadoes, flash floods, hailstorms, and high winds.

Severe thunderstorms The National Weather Service defines a thunderstorm as "severe" if it has one or more of the following elements: wind gusts of at least 58 mph (93 kph); hailstones at least 3/4 inch (2 centimeters) in diameter; or tornadoes or funnel clouds. Severe thunderstorms may also be accompanied by flash floods.

Severe thunderstorms are formed in the same way as more moderate thunderstorms: by the rising of moist air into an unstable atmosphere. A strong cold front is frequently the force that provides the vigorous uplift of warm air required to produce a severe thunderstorm. At the same time, the moist surface air is pulled upward when a divergence, or flow away from a central point, occurs in the winds aloft. This divergence triggers the convergence, or coming together, of surface winds beneath that point. The surface winds then rise to the area of divergence above.

One condition that gives rise to some of the largest and most severe thunderstorms is that an inversion is present for much of the day. An inversion is the increase of air temperature with height, through some portion of the atmosphere. The presence of a warm air layer aloft acts as a lid that prevents warm, humid surface air from rising. In other words, an inversion produces a stable atmosphere. As a result, only shallow cumulus clouds can form.

Sometimes on a summer day when an inversion has occurred, surface air will become heated to the point at which it is warmer than the warm air aloft. Pockets of warm air will then burst through the upper warm layer, creating towering cumulonimbus clouds. Once the warm air has burst through the inversion layer, the clouds rapidly develop into severe thunderstorms.

An important factor in the formation of a severe thunderstorm is that updrafts are not weakened by falling precipitation. Such updrafts are produced in one of two ways. First, the updrafts are so strong that they keep all precipitation suspended in the cloud top for a long time, while the thunderstorm builds. Second, the updrafts are tilted so that precipitation falls alongside them, rather than into them. The updrafts become tilted by strong upper-level winds. When the updrafts are tilted, precipitation falls into dry air alongside the updrafts, rather than directly into the updrafts.

Updrafts that are not weakened by falling precipitation are able to continue building the cloud top upward to greater and greater heights. Meanwhile, the precipitation falls into dry air adjacent to the updrafts and partially or completely evaporates. The dry air becomes cooler and denser and plunges downward.

The updrafts in a severe thunderstorm travel at speeds of 50 mph (80 kph) or greater. They remain strong for far longer than they do in a weaker thunderstorm. Sometimes the updrafts are so powerful that they rise above the troposphere, the lowest atmospheric layer, and penetrate the stratosphere, the layer above. This condition is called overshooting.

One effect of the strong updrafts in a severe thunderstorm is to keep hailstones suspended in the cloud for longer than usual. During that time the hailstones receive several coatings of ice and become quite large. When they become so heavy that they can not be supported by updrafts, the large hailstones either descend with a downdraft or are tossed through the side of the cloud by an updraft.

The downdrafts in a severe thunderstorm are also very strong. When strong, cool downdrafts reach the ground they further intensify the storm by displacing the warm, moist air and forcing it back up into the cloud. In this way, the storm is continually rejuvenated and can persist for several hours. Sometimes the warm, moist air that is forced upward has the effect of producing new thunderstorms. When strong downdrafts occur in the spreading "anvil" at the top of the fully developed cloud, they may produce pouchlike mammatus projections on the anvil's underside.

The dividing line between cold downdrafts and warm air at the surface is called the gust front. Similar to a cold front, an advancing gust front is characterized by winds that are strong, shifting, and cold. The winds along a gust front can reach speeds of 55 mph (88 kph) or greater. In dry, dusty areas they carry debris along with them and create dust storms or sandstorms.

In some cases, a gust front can be clearly identified by the roll cloud that follows directly behind it. A roll cloud looks like a giant, elongated cylinder lying on its side that, as its name implies, is rolling forward. This cloud occupies a narrow vertical layer of air. The top of the cloud is prevented from developing upward by stable air at the base of the thunderstorm.

Another type of cloud associated with a gust front is a shelf cloud. A shelf cloud is fan-shaped with a flat base. It forms along the edge of the gust front as warm, humid air is thrust upward and encounters the stable air layer, the layer through which an air parcel cannot rise or descend. In contrast to a roll cloud, which is a distinct formation, a shelf cloud is attached to the underside of the cumulonimbus cloud. Particularly violent winds blow on the surface beneath a shelf cloud.

Squall lines Most thunderstorms that are classified as "severe" exist in a band of thunderstorms called a squall line. A squall line may form either along a cold front or up to 200 miles (320 kilometers) in front of it. A squall line is particularly ominous in appearance. It looks like a churning, solid bank of fast-moving, low, dark clouds. A squall line may stretch for hundreds of miles (hundreds of kilometers). It moves along at speeds approaching 50 mph (80 kph).

Thunderstorms may form along a cold front when the cold front wedges beneath a warm, moist air mass. If the air mass being displaced is sufficiently moist, this upward thrust can cause vertical cloud development and thunderstorms.

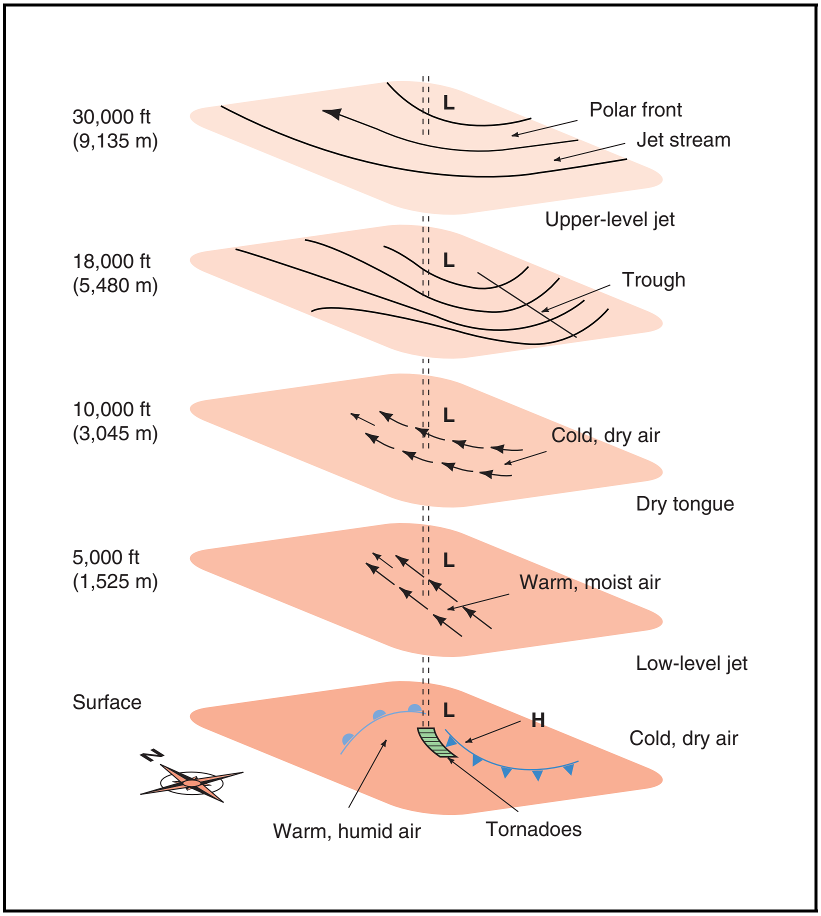
Supercell thunderstorms on the prowl in Nebraska. FMA, INC.

When the squall line is ahead of the cold front, it is known as a pre-frontal squall line. Two processes may lead to the formation of a pre-frontal squall line. One process involves the lifting of warm, moist air by upper-level winds. When upper-level winds encounter a cold front, they flow over it. Once they have crossed the cold front, the upper-level winds then dip downward again. This sets in motion a wave pattern of upper-level air flow. As the wave again flows upward, some 100 to 200 miles (160 to 320 kilometers) ahead of the cold front, it promotes the uplift of the warm, moist surface air.

A pre-frontal squall line may also form if the cold front is preceded by two air masses: a warm, dry air mass and a warm, moist air mass. In this case, thunderstorms don't form directly along the cold front, since the cold front is advancing on a dry air mass. However, the dry air mass is being pushed forward into the moist air mass, lifting the moist air upward. In that case, the squall line forms many miles ahead of the cold front.

Supercell storms Supercell storms are the most destructive and long-lasting of all severe thunderstorms. They may continue for several hours and produce one strong tornado after another, as well as heavy rain and hail the size of golf balls. A supercell storm blazes a trail of destruction stretching 200 miles (329 kilometers) or more. For these reasons, the supercell has earned the title "The King of Thunderstorms."

A supercell storm arises from a single, powerful convective cell. It forms along a cold front that is pushing its way through a mass of very

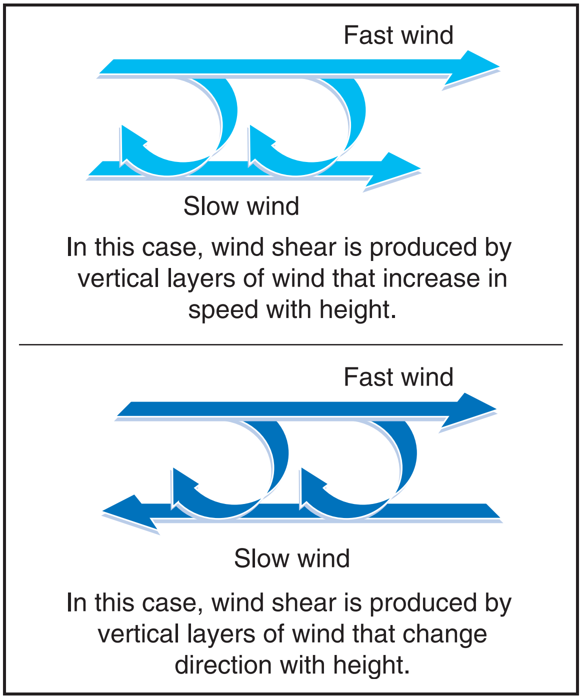


Arrangement of vertical air layers necessary for the formation of a supercell thunderstorm.

warm, humid air. A supercell storm may form in isolation or at the end of a squall line. Most supercell storms occur in spring and early summer, when temperature contrasts between warm and cold air masses is greatest.

The formation of a supercell thunderstorm requires a very specific vertical arrangement of air layers. At the surface, the cold and warm air masses are rotating around a central area of low pressure. At an altitude of about 5,000 feet (1,500 meters), above the surface low, there must be a layer of warm, moist air blowing towards the north. Above that, at about 10,000 feet (3,000 meters), is a layer of cold, dry air moving across from the southwest. This layer is called the dry tongue.

Located at the next highest layer, at about 18,000 feet (5,500 meters), are the upper-air westerlies. These winds aloft progress from west-to-east in a



Wind shear.

wave-like pattern of ridges and troughs. A ridge is a northward crest wherein exists a high-pressure area, and a trough is a southward dip wherein exists a low-pressure area. In this layer of air, the low-pressure center of a trough must be located just to the west of the warm surface air. Finally, at about 30,000 feet (9,000 meters) the jet stream produces an area of maximum speed where winds diverge (spread apart). At this level, surface air converges (comes together) and begins to rise.

A supercell storm reaches immense proportions due to strong winds aloft. The motion of the upper-level winds tilts the storm so that updrafts remain free from falling precipitation. The precipitation falls downward into the dry air, creating downdrafts that force additional warm, moist air upward. The updrafts, in turn, continue adding fuel to the storm, causing the thunderstorm cloud to surge to tremendous heights.

Another necessary ingredient in the formation of a supercell is wind shear. Wind shear describes a condition in which layers of wind increase in speed, and change direction, with height. When a layer of air is sandwiched between two other layers, each traveling at a different speed and direction, the sandwiched layer starts to roll.

The sandwiched air layer becomes a rotating horizontal roll, like a rolling pin. That rotating roll is then turned upright, like a barber pole, by powerful updrafts. As updrafts continue to blow through the now vertical, spinning column, the updrafts themselves begin to rotate. Wind shear creates a region of rotating updrafts within a supercell, called a mesocyclone. Mesocyclones are, on average, 10 miles (16 kilometers) in diameter although the diameters of the largest may reach 250 miles (400 kilometers). In addition to providing power to the thunderstorm, a mesocyclone is a necessary component in the formation of tornadoes.

Thunderstorm-associated phenomena

A number of destructive and potentially deadly elements are associated with thunderstorms. Lightning is the most common, but hail, flash

Weather report: Lightning safety

If you hear thunder, you are in the vicinity of lightning. Thunder should be considered a signal to seek shelter immediately. The best way to remain safe from lightning strikes is go inside a sturdy building. A shed or flimsy structure will not protect you from lightning. Once indoors, until the storm has passed do not do the following: talk on the telephone (cordless and cellular phones are safe); take a bath or shower; handle electrical appliances, computers, or plumbing fixtures. It's safest to unplug all electrical appliances except a radio, so you can be alerted to severe weather.

If you are not near a building when lightning threatens, the next safest option is to get into your car (as long as it's not a convertible!) and keep the windows rolled up. Do not touch the metal sides of the car.

If you are outdoors, far from buildings and vehicles, go to the lowest spot in the area and crouch down. However, do not crouch in or touch standing water. Keep away from trees, fences, and poles. If you are in the woods, stay away from the tallest trees.

If you are outdoors and feel your skin tingle, feel your hair stand on end, or hear clicking sounds, lightning may be about to strike. In that case, the safest position is to crouch down on the balls of your feet. Place your hands on your knees and your head down between your hands. If possible, pick up one foot and balance on the other. Do not lie down—the idea is to remain low while minimizing your body contact with the ground.

Once you have reached the safest possible spot, remain there until the storm has passed. If lightning strikes nearby, it does not mean the danger is over. Lightning may strike the same spot more than once during a storm. In fact, the Empire State Building in New York City was struck by lightning fifteen times during one thunderstorm.

The worst place to be in a thunderstorm is in the water. If you are boating or swimming, hurry back to land and seek shelter. Other dangerous places to be when lightning strikes include: under a tree; on an athletic field or golf course; on a bicycle, tractor, or riding lawnmower; or on a mountain.

If you witness someone being struck by lightning, immediately call for emergency medical assistance. Attend to the person right away. It is not true that someone struck by lightning carries an electrical charge. Check for breathing and a pulse. In many cases it will be necessary to administer cardiopulmonary resuscitation (CPR).

floods, tornadoes, and strong downdrafts of wind (including macrobursts, microbursts, and derechos) are also familiar to people who live in thunderstorm-prone areas. Lightning, flash floods, and downdrafts are discussed in this section. To learn about hail and hailstorms, see "Precipitation." For an explanation of derechos, see "Local Winds." Because of the complexity of tornadoes, they are discussed in their own chapter.

Lightning and thunder In order to qualify as a "thunderstorm," a rain shower or snow shower must be accompanied by lightning and thunder.

Who's who: Benjamin Franklin

Benjamin Franklin was born in 1706 in Boston, Massachusetts, that at that time was a British colony. Franklin was the fifteenth child out of a total of seventeen. Because his family was poor, the young Franklin had only two years of formal education. Franklin made up for this by educating himself. He went on to become a scientist, diplomat, author, publisher, and inventor.

Franklin was a pioneer in the study of electricity. He first conducted experiments using a Leyden jar, which is a glass jar filled with water and plugged with a rubber stopper. It contains a metal rod inserted through the stopper, one end of which extends into the water. The other end of the rod is connected to a machine that generates an electric charge. Using the Leyden jar, Franklin studied the nature of static electricity in water and the glass that enclosed the water.

The crackling noise made by electricity in the Leyden jar reminded Franklin of the crackling of thunder. This observation led him to wonder if lightning was also a form of electrical discharge. Late in 1752, in Philadelphia, Pennsylvania, Franklin conducted his famous kite-flying experiment to test this hypothesis.

He fashioned a kite from two wooden sticks and a large silk handkerchief. He attached a metal key to the kite string, just above the point where he held the string, and set the kite flying during a thunderstorm. The storm-generated electricity traveled down the rain-drenched string, to the key. When Franklin touched the key, he felt a shock.

Fortunately, Franklin had the foresight to run a wire from the key to the ground, so the electric charge would run into the ground. If he had not grounded his experiment in this way, the electrical discharge might have killed him. Franklin was also fortunate that lightning did not strike his kite directly. If that had happened, the grounding wire would probably have not protected him from a lethal electric shock.

Three years prior to his famous experiment, Franklin had invented lightning rods as a way to protect tall structures from lightning strikes. A lightning rod is a metal pole that is attached to the tallest point of a building and connected, by an insulated conducting cable, to a metal rod buried in the ground. Franklin's invention caught on quickly. Most tall structures, to this day, are topped with lightning rods.

Lightning is a short-lived, bright flash of light that heats the air through which it travels to about 50,000°F (28,000°C). Compare this to the surface of the sun, which is about 11,000°F (6,000°C)! Thunder is the sound wave that results when the intense heating causes the air to expand explosively.

At any given moment, approximately one hundred lightning flashes are occurring worldwide. Lightning kills between 75 and 100 people in

Franklin's weather observations went far beyond the topic of lightning. In 1743, Franklin was the first to conclude that a local storm was not an isolated event, but rather was due to the large-scale circulation of air masses. He made this discovery 175 years before meteorologists in Scandinavia discovered that rotating fronts produce large, organized storm systems. Franklin noticed that a storm had followed a path from Philadelphia to Boston—that is, from the southwest to the northeast. During the storm, however, the surface winds were blowing from the northeast. Franklin concluded that since the local storm had arrived from a direction counter to that of the local winds, it must not be local in nature, but part of a larger storm system.

Franklin's Experiment, June 1752, ***published by Currier & Ives.*** © ***Museum of the City of New York/Corbis.***

the United States each year and causes about 550 injuries. This is a greater number of deaths than those resulting from hurricanes or tornadoes. Lightning also is responsible for around ten thousand brushfires and forest fires annually, particularly in the western United States, western Canada, and Alaska. In addition, tens of millions of dollars in damage is caused to electrical utility equipment. The total property damage due to lightning in the United States alone is several hundred million dollars per year.

WORDS TO KNOW

mammatus: round, pouchlike cloud formations that appear in clusters and hang from the underside of a larger cloud.

moist adiabatic lapse rate: the variable rate at which the temperature of a saturated air parcel changes as it ascends or descends through the atmosphere.

multicell thunderstorm: a thunderstorm system that contains several convective cells.

orographic thunderstorm: a type of air mass thunderstorm that's initiated by the flow of warm air up a mountainside. Also called mountain thunderstorm.

precipitation: water in any form, such as rain, snow, ice pellets, or hail, that falls to Earth's surface

radar: an instrument that detects the location, movement, and intensity of precipitation, and gives indications about the type of precipitation. It operates by emitting microwaves, which are reflected by precipitation.

relative humidity: the amount of water vapor in an air mass relative to the amount of water in a saturated air mass of the same temperature.

ridge: a northward crest in the wavelike flow of upper-air westerlies, within which exists a high pressure area.

roll cloud: a cloud that looks like a giant, elongated cylinder lying on its side, that is rolling forward. It follows in the wake of a gust front.

saturated: air that contains all of the water vapor it can hold at a given temperature; 100 percent relative humidity.

severe thunderstorm: a thunderstorm with wind gusts of at least 58 mph (93 kph); hailstones at least 3/4 inch (2 centimeters) in diameter; or tornadoes or funnel clouds.

shelf cloud: a fan-shaped cloud with a flat base that forms along the edge of a gust front.

squall line: a moving band of strong thunderstorms.

stable air layer: an atmospheric layer through which an air parcel cannot rise or descend.

Lightning is most often produced by cumulonimbus clouds during the mature stage of a thunderstorm. However, it can also arise from other clouds, including: cumulus clouds; stratus clouds; clouds produced by volcanic eruptions; or even billowing clouds of sand produced during sandstorms.

Lightning, for all of its harmful effects, is generally beneficial to life on Earth. First, it makes possible the conversion of normal oxygen to ozone. Ozone in the upper atmosphere protects plants and animals from harmful ultraviolet radiation. Second, lightning breaks down oxygen and nitrogen in the air, producing ammonia and nitrogen oxides. These chemicals react with rainwater to form nitrogen compounds, which are

WORDS TO KNOW

stepped leader: an invisible stream of electrons that initiates a lightning stroke. A stepped leader surges from the negatively charged region of a cloud, down through the base of the cloud, and travels in a stepwise fashion toward the ground.

stratosphere: the second-lowest layer of Earth's atmosphere, from about 9 to 40 miles (15 to 65 kilometers) above ground.

supercell storm: the most destructive and long-lasting form of a severe thunderstorm, arising from a single, powerful convective cell. It is characterized by strong tornadoes, heavy rain, and hail the size of golf balls or larger.

thermal: a pocket of rising, warm air that is produced by uneven heating of the ground.

thunderstorm: a storm resulting from strong rising air currents; characterized by heavy rain or hail along with thunder and lightning.

tornado: a violently rotating column of air that reaches the ground and is attached to a cumulonimbus cloud; it is nearly always observable as a funnel cloud.

tropopause: the boundary between the troposphere and the stratosphere, between 30,000 and 40,000 feet (9,000 and 12,000 meters) above ground.

troposphere: the lowest atmospheric layer, where clouds exist and virtually all weather occurs.

trough: a southward dip in the wavelike flow of upper-air westerlies, within which exists a low-pressure area.

unsaturated: air that has less than 100 percent relative humidity.

updraft: a column of air blowing upward, inside a vertical cloud.

virga: rain that falls from clouds but evaporates in midair under conditions of very low humidity.

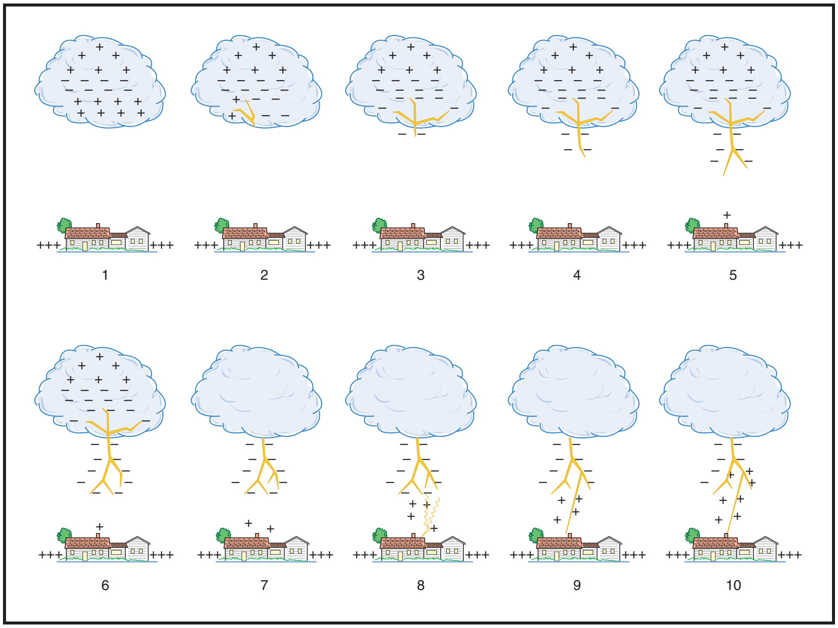
warm front: the leading edge of a moving warm air mass.

wind shear: a condition in which a layer of air is sandwiched between two other layers, each of which is traveling at a different speed and/or direction, causing the sandwiched air layer to roll.

natural fertilizers. Over 100 million tons (90 million metric tons) of nitrogen compounds fall to the ground each year.

If it were not for lightning, however, life might not exist on Earth. Many scientists hypothesize that lightning initiated the series of chemical reactions in the oceans that led to the formation of life.

How lightning is produced In order for lightning to occur, there must be two objects, or regions, carrying different electrical charges. If an object gains electrons, it is said to be negatively charged. If an object loses electrons it is said to be positively charged.



Charge distribution leading up to a lightning strike.

Lightning is a surge of electrons and ions (electrically charged atoms) between regions with opposite electrical charges. The majority of lightning occurs within a single cloud. Most of the rest occurs between a cloud and the ground. Cloud-to-cloud and cloud-to-air lightning occurs less frequently.

Under normal conditions, such as on a clear day, the ground is negatively charged while the upper air is positively charged. When a cumulonimbus cloud forms, the charge distribution changes. The ground beneath the developing cloud becomes positively charged by induction, the process by which excess electrical charges in one object causes the accumulation of opposite electrical charges in another nearby object. A narrow region at the base of the cloud, as well as the upper portion of the cloud, also become positively charged. However, in the lower portion of the cloud, just above the base, there exists a negatively charged, saucer-shaped region. This region may be about 1,000 feet (300 meters) thick and several miles (several kilometers) in diameter.

Under most conditions, air acts as an insulator, meaning electricity does not readily flow through it. During the mature stage of a thunderstorm, however, the electrical charge differential between the cloud and the ground becomes so great that the resistance of air breaks down. Specifically, air loses its insulating properties when the electric field grows stronger than 915,000 volts per foot (about 3 million volts per meter). Then, electricity, which appears as lightning, surges between differently charged regions in order to neutralize the opposing charges.

Meteorologists are still not sure how the distribution of charges in cumulonimbus clouds happens. However, it is clear that the separation of charges requires strong updrafts which carry water droplets upward. As they rise into colder air, the droplets of water become supercooled droplets, that is liquid water that is below freezing (14°F to –4°F or –10 to –20°C). These supercooled droplets collide with ice crystals to form a soft ice-water mixture called graupel.

According to the electrostatic induction theory, opposite charges are driven to different parts of the cloud by strong updrafts and the formation of graupel. The collisions between the supercooled water droplets and the ice crystals results in a slight positive charge being transferred to the ice crystals, and a slight negative charge to the graupel. Updrafts drive the lighter ice crystals upwards, causing the cloud top to accumulate increasing positive charge. The heavier negatively charged graupel falls towards the middle and lower portions of the cloud, building up an increasing negative charge. Charge separation and accumulation continue until the electrical potential becomes sufficient to initiate lightning discharges.

Weather report: The color of lightning

Lightning takes on a range of colors, depending on atmospheric conditions.

- Blue lightning within a cloud indicates the presence of hail.
- Red lightning within a cloud indicates the presence of rain.
- Yellow or orange lightning indicates a large concentration of dust in the air.
- White lightning is a sign of low humidity in the air. Since forest fires break out when the air is relatively dry, white lightning is the most likely type to ignite forest fires.

Cloud-to-ground lightning Lightning that travels between a cloud and the ground accounts for only 20 percent of all lightning, yet this type of lightning has been studied more extensively than any other. Cloud-to-ground lightning is considered the most important by researchers since it is the only type that endangers people and objects on the ground.

Although lightning lasts only for two-tenths of a second and appears as a mere flash of light, it is quite a complex process. It begins when an invisible stream of electrons, called a stepped leader, surges from the negatively charged region of the cloud, down through the base. This is called the stepped leader because it travels in a stepwise fashion down toward the ground. Each portion of the stepped leader covers about 60 to

The most dangerous type of lightning is cloud-to-ground lightning. FMA, INC.

300 feet (20 to 100 meters) in less than a millionth of a second. Then it stops for about 50 millionths of a second before starting off in a new direction. The stepped leader creates a branching pattern, ionizing a path through the air as it goes.

When the stepped leader reaches a point about 300 feet (100 meters) above the ground, a "positive streamer" (a flow of positive ions upward) forms leading upward toward the stepped leader. If the electric field is sufficiently strong, the positive streamer will quickly evolve into a hotter "current leader." The current leader moves upward from the ground and connects with the stepped leader coming down from the cloud, completing a conductive path between the cloud and the ground.

When the two leaders connect, a powerful stroke of electrical current surges up from the ground toward the cloud. This surge of current is called a return stroke. It typically comes from a tall, pointed object, such as an antenna or flagpole, since the induced positive charges on the ground accumulate on tall, pointed objects.

A large concentration of electrons are discharged to the ground through this completed electrical circuit. Then positive ions from the ground shoot back up to the cloud. The upsurge of positive ions generates the bright flash commonly considered "lightning."

The return stroke is 2 to 7 inches (5 to 8 centimeters) in diameter. It travels at nearly one-third the speed of light and takes a mere ten-thousandth of a second to reach the cloud. This flow of positive ions partially neutralizes the charge difference between the cloud and the ground.

In the approximately one-tenth of second that follows, several (usually two to four, but sometimes as many as twenty) more lightning strokes may occur along the ionized channel. These strokes, which serve to discharge the remaining buildup of electrons near the base of the cloud, are initiated by surges from the base of the cloud called dart leaders.

Dart leaders, like stepped leaders, are intercepted by return strokes when they get closer than 300 feet (100 meters) to the ground. These return strokes occur about fifty-thousandths of a second apart. They are individually indistinguishable and appear as a flickering light in the wake of the initial return stroke. The dart leaders cease when the charge differential between the cloud and the ground has been neutralized.

In less than 10 percent of all cases of cloud-to-ground lightning, a positively charged stepped leader surges from the upper portion of the cloud. It travels downward to a negatively charged area on the ground. These powerful discharges occur most commonly during winter storms and produce a flash of light similar to a return stroke.

Ground-to-cloud lightning occurs less frequently than cloud-to-ground lightning. This form of lightning begins with the ascent of a stepped leader, usually positively charged, from the ground. As the stepped leader approaches the cloud above, it triggers the release of a return stroke from the cloud. Ground-to-cloud lightning is most often initiated from very tall points on the surface, such as mountaintops or the tops of towers or antennae.

How close is a thunderstorm?

While we see a lightning flash at almost the exact instant it occurs, we don't hear the thunder until a short time later. The reason for this delay is that lightning travels at the speed of light (186,282 miles per second or 299,914 kilometers per second), which is about one million times faster than the speed of sound (1100 feet per second or 330 meters per second).

One way to tell how close you are to a thunderstorm is to determine the time lapse between the lightning and the thunder. The rule to remember is that it takes thunder about five seconds to cover one mile (three seconds for one kilometer). Therefore, if you hear thunder seven seconds after you see the flash of lightning, the thunderstorm is 1.4 miles (2.3 kilometers) away (7 divided by 5 equals 1.4).

You can tell, in general terms, whether a thunderstorm is near or far, by the quality of the thunder. If it sounds like a sharp crack or clap, the storm is close. If that sound is immediately followed by a loud bang, the storm is *very* near—closer than 330 feet (100 meters).

The thunder from distant storms produces a rumbling sound. One reason for this effect is that the sound waves are bouncing off hills or buildings before reaching you. Another reason is that you first hear the sound from the part of the lightning near the ground, which is closer to you, after which you hear the sound from the upper part of the lightning, which is farther away.

Other kinds of lightning Cloud-to-cloud lightning is the most common form of lightning. It occurs either within a single cloud or between two clouds. In the former case, the lightning runs between the negatively charged lower portion of the cloud and the positively charged upper portion of the cloud. This type of lightning illuminates and provides a brilliant view of a cumulonimbus cloud. The whole cloud lights up spectacularly.

Lightning that runs between two clouds occurs less frequently than it does within a single cloud. Intercloud lightning represents a discharge of electrons from the lower portion of one cloud to the upper portion of an adjacent cloud.

Cloud-to-air lightning is the flow of electricity between areas of a cloud and the surrounding air which have opposite charges. This form of lightning is relatively weak and often occurs at the same time as a cloud-to-ground stroke. Usually, this lightning travels a path between an area of negative charge in the surrounding air and the positively charged top of the cloud. Because cloud-to-air lightning occurs at great heights, it is almost always too distant to have an audible thunder component.

Both cloud-to-cloud lightning and cloud-to-air lightning are often referred to as sheet lightning. Sheet lightning illuminates a cloud or a portion of a cloud. The cloud blocks the distinct pattern of the lightning from view, so the lightning appears as a bright sheet.

Ball lightning is the rarest and most mysterious form of lightning. It has never been photographed but has been witnessed by numerous individuals throughout history. It is reported to look like a dimly-to-brightly lit sphere, ranging from 0.4 to 40 inches (1 to 100 centimeters) in diameter. It lasts between one and five seconds and either hangs in the air or floats horizontally at a rate of about 10 feet (3 meters) per second. It either dissipates silently or with a bang.

The cause of ball lightning is unknown, but many theories have been proposed. One recent theory suggests that it is an "electromagnetic knot" created by linked lines of magnetic force that form in the wake of an ordinary cloud-to-ground lightning strike. Some scientists suggest that ball lightning does not exist, but is merely an optical illusion experienced by an individual who has just witnessed a stroke of lightning.

Forked lightning is much more common. It occurs when a return stroke originates from two different places on the ground at once. This creates two separate ionized channels and the appearance of being "forked."

Lightning that appears to sway from a cloud is called ribbon lightning. It is produced when the wind blows the ionized channel so that its position shifts between return strokes.

Weather report: Lightning rods

Lightning rods are metal poles used to protect buildings from lightning strikes. A lightning rod is attached to the tallest point of a structure and connected, by an insulated conducting cable, to a metal rod buried in the ground. As a cloud with a large accumulation of negative charge passes over head, a positive charge is induced under the cloud on the building or tower, and on the ground. The principle behind lightning rods is that the induced charge collects at the sharp tip of the rod. The electrical field around the sharp tip of the rod becomes so intense that the air nearby begins to ionize. The ionized air harmlessly dissipates the accumulated induced positive charge before lightning can strike. In the event lightning does strike, it may be attracted to the rod and conducted safely into the ground.

A lightning rod. COURTESY WALTER A. LYONS.

A lightning rod provides protection to a cone-shaped area around and beneath it. The tip of the cone is located at the top of the rod. The radius of the base of the cone is equal to the height of the rod. Thus, the taller the lightning rod, the greater the area it protects.

A flash of lightning that resembles a string of beads is called bead lightning. This type of lightning may be the result of a fragmenting ionized channel. An alternative explanation is that part of the lightning stroke is obscured by clouds or falling rain.

Silent lightning from a distant storm, generally more than about 10 miles (16 kilometers) away is called heat lightning or summer lightning. This lightning is not accompanied by thunder since it is too far away for the sound to reach the observer. It often occurs on hot summer nights when the sky above is clear. Heat lightning sometimes appears orange, due to the scattering of light by dust particles in the air.

Downbursts A downburst is an extremely strong, localized downdraft beneath a thunderstorm. It blasts down from a thunderstorm cloud like

Red sprites, blue jets, and elves

Sprites, jets, and elves are three different and poorly understood phenomena that are associated with lightning in clouds. They were first observed by military and airline pilots, shuttle astronauts, and others flying at high altitudes. At first, they were all dismissed by meteorologists as some sort of optical illusion, but have since been photographed by specially equipped television cameras.

Red sprites are extensive but weak luminous red flashes that appear directly above an active thunderstorm system and occur at the same time as cloud-to-ground or cloud-to-cloud lightning strokes. While dim, they are just barely visible by the unaided eye under proper conditions. Sprites appear to be only associated with the rarer positive cloud-to-ground lightning strokes which typically are significantly displaced from the electrically active cores of thunderstorms. Sprites have not been observed to be associated with negative cloud-to-ground strikes (the usual polarity). They are likely due to some sort of electrical discharge or electromagnetic pulse into the upper atmosphere.

Elves also appear to be associated with energetic cloud-to-ground strikes of either polarity. They appear as wide areas of luminosity that occur high above the cloud tops. They may be caused by strong electromagnetic pulses shot up into Earth's ionosphere (a region within Earth's stratosphere where many atoms have lost one or more electrons).

Blue jets are a different high altitude phenomenon, distinct from sprites, but also observed above active thunderstorms. They are also dim, but are visible with the unaided eye and by using low light television systems. Blue jets originate from the tops of the clouds directly above electrically active core regions of thunderstorms. Following emergence, they propagate upward in a narrow cones with vertical speeds of roughly 60 miles per second (100 kilometers per second).

Red sprites, blue jets, and elves have not been observed until recently because they are dim, and rare. They are only associated with around 1 percent of lightning strokes. However, sprites and jets are barely visible to the unaided eye under proper conditions.

The best way to attempt to view these phenomena would be by observing a thunderstorm at a distance of 100–200 miles (200–300 km) from a relatively high vantage point, such as the top of a hill or side of a mountain. The sky would have to be completely dark and clear (well after twilight and without moonlight). There must be no intervening clouds. Your eyes would need to be completely dark-adapted. If you can clearly see the Milky Way, then your eyes are sufficiently dark-adapted and other conditions are optimal.

Now use a piece of dark paper to block the light from the thunderstorm (so that your eyes are not distracted by lightning or lose their dark-adaptation) and carefully gaze at a space above the storm about as wide as your fist held at arm's length. Remember, the sprite or jet will be a very brief flash just on the edge of perceptibility. But with luck and patience, you may be rewarded by a sight that very few people have seen.

water pouring out of fully opened tap. When this vertical wind hits the ground it spreads horizontally. It then travels along the ground, destroying objects in its path.

This red sprite was photographed over a thunderstorm in the Texas panhandle. AP IMAGES.

Downbursts may or may not be accompanied by rain. Dry downbursts generally occur beneath virga, streamers of rain that evaporate in midair. Downbursts are capable of knocking down trees, damaging buildings, and leveling crops, as well as kicking up dust and debris into a "cloud" that tumbles along the ground. In many cases, damage caused by downbursts has been mistakenly attributed to tornadoes.

Downbursts are divided into two categories, macrobursts and microbursts, depending on their size. Downbursts may result in tornado-force, straight-line winds with long lives. These winds are called derechos. For a discussion of derechos, turn to the chapter entitled "Local Winds."

Macrobursts A macroburst is a downburst that creates a path of destruction on the surface greater than 2 miles (4 kilometers) wide. The winds of a macroburst travel at around 130 mph (210 kph) and last for

Who's who: Tetsuya Theodore Fujita

Although Tetsuya Theodore Fujita is most famous for developing the scale of tornado intensity which bears his name, his primary area of research has been downbursts. Fujita was the first to identify these destructive downdrafts of wind. His research on downbursts has been particularly relevant to aviation safety, since microbursts, the smallest and most intense form of downbursts, pose an extreme hazard to aircraft.

Fujita was born in 1920 in Kitakyushu City, Japan. He graduated from Meiji College of Technology with the equivalent of a bachelor's degree in mechanical engineering in 1943. Soon thereafter, Fujita was hired on at the college as an assistant professor of physics.

In 1945, the Japanese cities of Hiroshima and Nagasaki were devastated by atom bombs dropped by U.S. airplanes. Three weeks later, Fujita was part of a research team sent to those cities to survey the damage. Fujita noticed that the destruction was in the shape of a starburst. The hub was located directly beneath the bomb and spokes radiated outward. Fujita also calculated the height from which the bombs must have been dropped to create such a pattern. These findings became relevant in Fujita's later work on downbursts.

In 1949, Fujita moved to Tokyo to pursue his doctorate in atmospheric science at Tokyo University. In 1953, at the invitation of professor and thunderstorm specialist Horace R. Byers, Fujita moved to the United States to join the faculty of the University of Chicago.

Fujita's main topic of research soon became the destructive potential of storm-related winds, particularly tornadoes. Based on his surveys of tornado damage, Fujita created the Fujita Intensity Scale for tornadoes in the late 1960s. Fujita's scale consists six categories of tornado intensity, based on the ground damage created

up to thirty minutes. A macroburst (as well as a microburst) may either follow in the wake of, or its leading edge can develop into, a gust front.

Microbursts A microburst is a smaller downburst that a macroburst, yet it is potentially more dangerous. The path of destruction created by a microburst is between several hundred yards and 2 miles (4 kilometers) wide. Its winds, which only last about ten minutes, may exceed 170 mph (270 kph). Like macrobursts, microbursts may evolve into gust fronts.

Microbursts receive more attention than macrobursts because of the hazard they pose to airplanes during takeoff or landing. Microbursts are accompanied by abrupt changes in the speed or direction of wind at various heights, known as wind shear. Wind shear is something that every pilot seeks to avoid, since it can spell disaster for aircraft. Due to their by the tornado. His scale provided the first objective, uniform way of assessing tornado strength.

In April 1974, Fujita took a plane ride to survey the damage caused by a massive outbreak of tornadoes. Flying over West Virginia, he noticed the same starburst pattern of destruction he had seen in Japan. Fujita proposed that in that area, the damage had been created not by a tornado, but by powerful downdrafts produced by thunderstorms. He then coined the term "downbursts."

At first, Fujita's findings were met with skepticism by his fellow meteorologists. It was commonly accepted at the time that thunderstorms produce downdrafts of air, but it was believed that downdrafts weaken significantly before reaching the ground. Fujita conducted a research project to put his hypothesis to the test. Over a forty-two–day period in the spring and summer of 1978, Fujita and his team of researchers detected fifty microbursts in Chicago's western suburbs.

Dr. Tetsuya Fujita. AP IMAGES.

Fujita retired from teaching in 1991. He passed away quietly in his sleep on November 19, 1998.

small size, microbursts elude detection by airport radar, an instrument which operates by bouncing microwaves off of weather phenomena.

As a plane enters a microburst, it first experiences a strong headwind that sends it upward. Soon thereafter, the plane experiences a strong tailwind which forces it downward. In the thirty-year period from 1964 to 1994, about thirty planes have crashed as a result of microbursts. Microbursts are the second-leading cause of airplane crashes, only exceeded by pilot error.

Microbursts occur with an alarming frequency. In a 1978 study, conducted by Tetsuya Theodore Fujita, fifty microbursts were detected over forty-two days in Chicago's western suburbs. Another study was conducted near Denver's Stapleton International Airport over an eighty-six-day period in the summer of 1982. A total of 186 microbursts were detected.

Flash floods A flash flood is a sudden, intense, localized flood caused by persistent torrential rainfall. In the 1970s, flash floods replaced lightning as the number-one weather-related killer in the United States. Each year throughout the 1980s, flash floods killed an average of 110 people and were responsible for an average of $3 billion in property damage. In the first half of the 1990s the number of deaths due to flash floods rose to an annual average of 140.

Flash floods can be caused by warm-weather thunderstorms that are either slow-moving or stationary. The reason for their lack of movement is that the winds aloft are nearly calm. These storms unleash huge quantities of rain over one location. In contrast, thunderstorms which move more quickly spread their rain across larger areas and don't produce flash floods.

[*See Also* **Climate; Clouds; Flood; Human Influences on Weather and Climate; Local Winds; Precipitation; Tornado; Weather: An Introduction**]

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Tornado

A tornado is a rapidly spinning column of air that extends from a thunderstorm cloud to the ground. The tornado rotates around a vertical axis of extremely low pressure called a vortex. Tornadoes are sometimes called “twisters” or “cyclones,” although the term cyclone is also used to described hurricanes in the Indian Ocean.

A tornado destroys nearly everything in its path. A tornado’s high winds (and to a lesser extent its low pressure), cause walls to buckle and roofs to be lifted off and carried away. The winds can uproot trees and pick up entire buildings, only to deposit them hundreds of yards away. People, animals, cars, and all types of household items have been tossed about by tornadoes.

In the early part of the twentieth century, tornadoes killed an average of two hundred people each year in the United States. Due to improvements in forecasting and emergency preparedness in recent years, this number has been reduced to a yearly average of fewer than fifty people killed. More people die each year in flash floods and from lightning than are killed by tornadoes. In terms of the total population, the death rate has plunged dramatically from 1.8 deaths per million people in the 1920s to fewer than 0.1 deaths per million people in the first decade of the twenty-first century.

While the United States has the greatest number of tornadoes per year, over one thousand, other parts of the world also experience tornadoes. Especially in poorer nations, tornadoes still take many lives each year. In north-central Bangladesh on May 13, 1996, more than seven hundred fatalities were caused by a tornado outbreak, the emergence of a group (also called a family) of tornadoes from a single thunderstorm. In August of 2006, at least seven tornadoes swept through mainland Europe causing thirty-eight injuries but no reported deaths.

Oldest know photograph of a tornado, South Dakota, 1884.

Tri-state tornado delivers death and destruction

The deadliest tornado ever experienced in the United States swept through Missouri, Illinois, and Indiana on March 18, 1925. Known as the Tri-State Tornado, the monster had winds of more than 300 miles (483 kilometers) per hour, took 695 lives, and caused more than 2,000 injuries in 23 cities and towns. The tornado also set records for path length, at 219 miles (352 kilometers); and speed, at an average of 62 miles (100 kilometers) per hour. Its path width varied from 0.5 to 1 mile (0.8 to 1.6 kilometer). Over a three-and-a-half-hour period, it caused more than $16 million in damages—a huge sum by 1925 standards. Because of the massive amount of damage, it was classed as an F5 on the Fujita scale. The Fujita scale measures tornado intensity: F5 is used for the most violent storms.

The greatest number of fatalities in a single town occurred in Murphysboro, Illinois, where 234 people died. The towns of Gorham, Illinois, and Griffin, Indiana, were completely destroyed. Not a single building or home in any of those communities remained after the tornado went through.

The tornado killed farmers, schoolchildren, and factory workers. Miners, working far below ground while the tornado roared above, returned to the surface to find their families dead and their homes gone. Most people did not see the approaching funnel, the cone-shaped

A large tornado on the ground near Union City, Oklahoma. FMA, INC.

spinning column of air that hangs under the thunderstorm cloud, since it was obscured by blowing debris. The tornado came upon them so fast that they had little chance to find adequate shelter.

At least six other tornadoes from the same storm system also resulted in extensive damage and caused fifty-two deaths.

The tornado's beginnings The day of the tornado was a relatively warm and humid one for the Midwest in March, at about 65°F (18°C). At the same time, a cold air mass was moving in from the north. Today's meteorologists would recognize the pattern as being ripe for tornado formation. The United States Weather Bureau (the precursor to the National Weather Service) had called for "rains and strong shifting winds" on that day, but not tornadoes.

The tornado touched ground briefly in Arkansas, but did no damage. It then rose back into the clouds and traveled to the northeast. At 1:00 PM, the funnel returned to Earth, just southwest of the small town of Annapolis (northwest of Ellington), in southeastern Missouri. There it killed its first victim: a farmer. The enormous twister turned from white to black as it sucked up everything it touched, including dirt, fences, trees, and barns. As the twister traveled, it ejected the items with deadly force. The tornado headed right for Annapolis's one-block-long business district and leveled every structure.

WORDS TO KNOW

conventional radar: instrument that detects the location, movement, and intensity of precipitation, and gives indications about the type of precipitation. It operates by emitting microwaves, which are reflected by precipitation. Also called radar.

Doppler radar: a sophisticated type of radar that relies on the Doppler effect (the change in frequency of waves emitted from a moving source) to determine wind speed and direction, as well as the direction in which precipitation is moving.

fair-weather waterspout: relatively harmless waterspout that forms over water and arises either in conjunction with, or independently of, a severe thunderstorm. Also called nontornadic waterspout.

Fujita Intensity scale: scale that measures tornado intensity, based on wind speed and the damage created.

funnel cloud: cone-shaped spinning column of air that hangs well below the base of a thunderstorm cloud.

mesocyclone: region of rotating updrafts created by wind shear within a supercell storm; it may be the beginnings of a tornado.

multi-vortex tornado: tornado in which the vortex divides into several smaller vortices called suction vortices.

NEXRAD: acronym for Next Generation Weather Radar, the network of 156 high-powered Doppler radar units that cover the continental United States, Alaska, Hawaii, Guam, and Korea.

suction vortices: small vortices within a single tornado that continually form and dissipate as the tornado moves along, creating the tornado's strongest surface winds.

supercell storm: the most destructive and long-lasting form of a severe thunderstorm, arising from a single, powerful convective cell. It is characterized by strong tornadoes, heavy rain, and hail the size of golf balls or larger.

tornadic waterspout: tornado that forms over land and travels over water. Tornadic waterspouts are relatively rare and are the most intense form of waterspouts.

tornado: rapidly spinning column of air that extends from a thunderstorm cloud to the ground. Also called a twister.

tornado cyclone: spinning column of air that protrudes through the base of a thunderstorm cloud.

tornado family: a group of tornadoes that develop from a single thunderstorm.

tornado outbreak: emergence of a tornado family. Tornado outbreaks are responsible for the greatest amount of tornado-related damage.

vortex: (plural: vortices) vertical axis of extremely low pressure around which winds rotate.

wall cloud: a roughly circular, rotating cloud that protrudes from the base of a thunderstorm cloud; it is often the beginning of a tornado.

waterspout: rapidly rotating column of air that forms over a large body of water, extending from the base of a cloud to the surface of the water.

A destroyed schoolroom in Murphysboro, Illinois, 1925. ©BETTMANN/CORBIS.

The tornado's next target was another small town, Cape Girardeau. It reduced to ruins a school from which students had been dismissed just minutes earlier. Leaving a total of thirteen dead in Missouri, the tornado cut a path across the plains and into southwestern Illinois.

Mayhem in Murphysboro The tornado next demolished 152 blocks of Murphysboro, Illinois. Murphysboro, population twelve thousand, was a former mining and agricultural community that had become a center for manufacturing and railroad transport. The townspeople were taken by surprise by the swirling black wall of winds that descended upon them. The winds sucked up houses and cars, snapped trees off at their bases and tossed them around as if they were matchsticks, and ripped water pipes right from the ground. Twelve hundred buildings were destroyed; even freight trains were carried away. Three brick school buildings collapsed on the children inside them, killing at least twenty-five students.

Many people were still trapped in piles of wreckage when fire erupted. Firefighting operations throughout the town were greatly hampered due to broken water mains. Even where water was available, the piles of collapsed houses, trees, and vehicles made it nearly impossible to get to the fires. Many

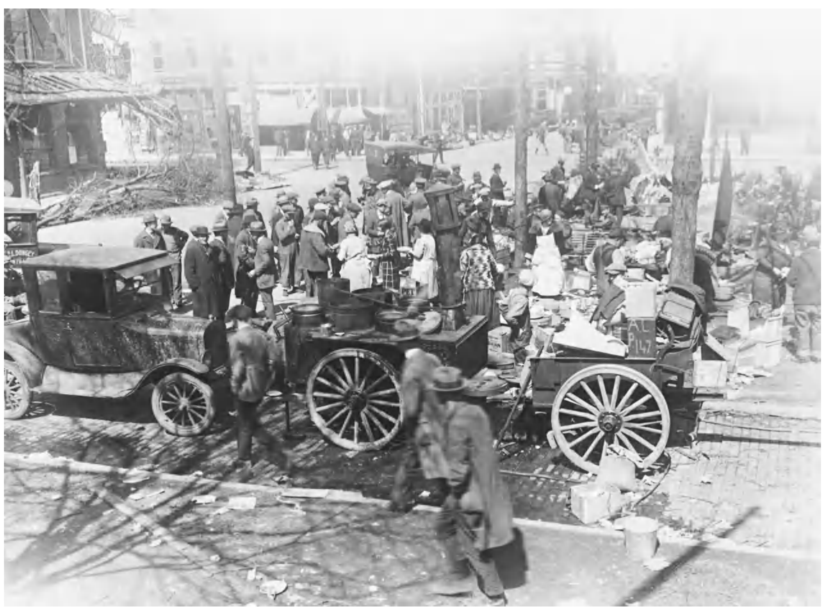
Eyewitness account of destruction in Murphysboro

May Williams, a religious lay worker from St. Louis, was in Murphysboro on March 18, 1925, to attend a revival held by the Reverend and Mrs. Parrott. This eye-witness account was first published in the *St. Louis Post-Dispatch* on March 22, 1925, and was reprinted in the May/June 2000 edition of *American Heritage.*

"Mrs. Parrott . . . had sung the first verse and chorus which we were repeating when it suddenly grew dark and there fell upon us what we thought was hail. Rocks began to break through. We were being showered with glass, stones, trash, bricks, and anything. I saw the concrete wall at the back of the hall collapse and come crumbling in. Then the roof started to give way. From outside as well as from within, we could hear terrible cries, yells, screams, and there was a great popping noise. The wind roared—I cannot describe it and it tore great handfuls of the roof above us. . . .

"Then the storm passed. We went out into the street. We walked the city for an hour or more, terror-struck by what we saw. People went about almost without clothes, with no shoes on, wrapped in rugs or blankets. It was indescribable, the confusion. We picked our way among tangles of wires, trees, poles, brick and lumber to our rooms. . . .

"[After dark] everything was on fire, it seemed. There was no light except the flare of flames. There was no water. We were black from head to foot. . . . Every place that stood was turned into a hospital. We visited the high school where the doctors were sewing up wounds, giving emergency treatment, and where other helpers were hauling out the dead. We saw numberless torn and bleeding bodies. . . . They were dynamiting the city now in their effort to stop the flames, and the roar of the explosions added to the horror of the fires' glare. Everything was ghastly."



An Open Air Emergency Food Station set up in Murphysboro, Illinois, to aid the homeless. ©BETTMANN/CORBIS.

Men survey damage done by a tornado that moved through Griffin, Indiana, in 1925. ©BETTMANN/CORBIS.

trapped people were burned alive. There were 234 deaths and 623 injuries in Murphysboro that day. Damages amounted to $10 million.

Devastation in De Soto The tornado's next target was De Soto, Illinois, population six hundred. People who witnessed the tornado described a boiling black mass of clouds, continually flashing lightning, with a huge funnel swinging like a pendulum. As the tornado blew through De Soto's residential area, it lifted houses, and the people inside them, straight up into the air. Every building in De Soto more than 10 feet (3 meters) tall was demolished. Roof beams were later found 15 miles (24 kilometers) from where they began. The tornado struck a school, ripping off the roof and causing the walls to collapse. One-hundred-and-twenty-five students and teachers were buried in the rubble. Thirty-three of them died, and the rest sustained serious injuries. Sixty-nine people in De Soto and the surrounding area were killed.

Path of destruction continues In the town of West Frankfort (the largest on the twister's path, with a population of 18,500), 127 people were killed

The Oklahoma City twister of 1999

On May 3, 1999, more than seventy tornadoes, spawned by a dozen supercell thunderstorms, blew through central Oklahoma and southern Kansas. The twisters killed forty-three people in all: thirty-eight in Oklahoma and five in Kansas. Nearly 750 people in Oklahoma and 150 in Kansas were injured during the outbreak. The number of deaths and injuries likely would have been much greater if not for the lengthy advance warning given by weather agencies and the up-to-the-minute reporting by local television stations.

The tornado outbreak was the costliest in the nation's history. More than 10,500 homes and 47 businesses in Oklahoma, and some 1,500 buildings in Kansas, were destroyed. Property damages totaled nearly $1.5 billion. Eleven counties in Oklahoma were declared disaster areas.

Throughout the evening of May 3, the National Weather Service placed forty-four of Oklahoma's seventy-seven counties under tornado watch and issued almost two hundred separate tornado warnings. When meteorologists determined that an F5 tornado was headed straight for metropolitan Oklahoma City, police drove through neighborhoods warning residents to take cover.

The tornado had maximum winds of 318 miles (512 kilometers) per hour, the highest wind speed ever recorded. The measurement was taken by a truck-mounted Doppler radar placed in the tornado's path. The tornado was at the upper end of the F5 tornado category. If its wind speed had been just 1 mile per hour greater, it would have been classified as F6, a classification no tornado has ever attained. The tornado was powerful enough to rip pavement from roads and grass from the ground, and hurl freight trains from their tracks. In some places the tornado was accompanied by softball-sized hail.

The monstrous tornado remained on the ground for several hours, twisting out a path about

and 410 were seriously injured. Within a span of a few minutes the tornado cut a swath through one-third of Frankfort's residential district, leveling 250 buildings. Property damage was an estimated $2 million.

Before leaving Illinois, the tornado tore through Akin, Gorham, McLeansboro, Logan, Benton, Enfield, Bush, Thomsonville, Carmi, Crossville, and Parrish. In each town there were fatalities and significant property damage. The destruction of factories and businesses left many of the survivors jobless. Parrish was 90 percent destroyed; there were twenty-two deaths and sixty injuries in the town of 270. Gorham was entirely destroyed and saw thirty-four deaths (more than half the town's residents were injured or killed). In all, the tornado took about 610 lives in Illinois.

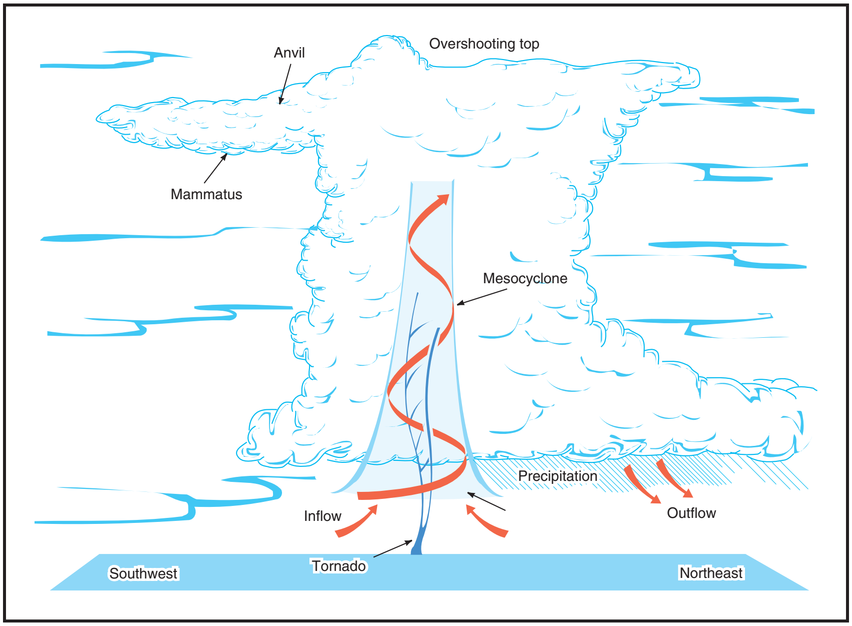
At around 4:00 PM, the tornado entered southwestern Indiana. Traveling at a speed of 73 miles (117 kilometers) per hour, it pounded

90 miles (145 kilometers) long. It struck densely populated areas of Oklahoma City, killing thirty-six people in the city and surrounding suburbs and demolishing entire neighborhoods. The Oklahoma City area alone suffered more than $1 billion in damage.

The aftermath of an F5 tornado that swept through Oklahoma in 1999. ©CORBIS SYGMA.

the towns of Griffin, Poseyville, Elizabeth, Owensville, and Princeton, killing at least 71 people in the state. Griffin, population 400, was wiped off the map; every one of its 200 buildings succumbed to the storm. Any wall left standing after the tornado was reduced to ashes in the fire that consumed the wreckage. In Princeton, with 9,850 residents, the tornado killed 45 people. The Tri-State Tornado finally dissipated at 4:30 PM, 10 miles (16 kilometers) northeast of Princeton.

Relief efforts Word of the disaster was carried to nearby cities by train. The response was rapid and extensive. Doctors and nurses came to tend the wounded, and entire fire departments arrived to battle the blazes. Medical supplies were brought in on trains, and outbound trains carried the wounded to hospitals. Coffins and flowers were sent from St. Louis and Chicago to ease the pain of burying the dead.



Tornado position within a thunderstorm.

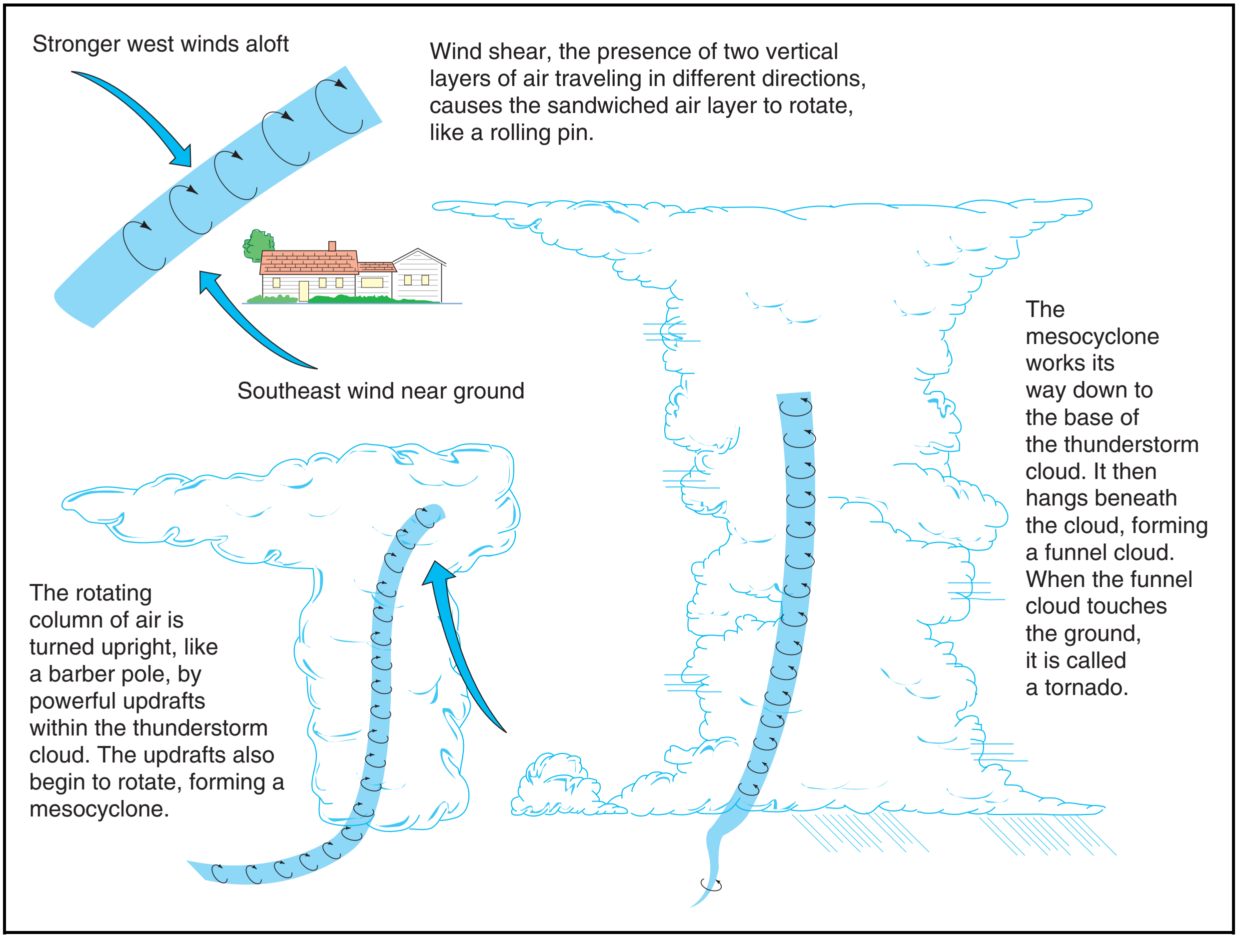
Dangerous science: How tornadoes form

The process of tornado formation remains somewhat mysterious to meteorologists (scientists who study weather and climate). Tornadoes are tricky research subjects because the time and place of their emergence and the paths they travel are nearly impossible to predict. Adding to the difficulty, tornadoes are usually short-lived. In recent years, with the advent of Doppler radar (a sophisticated instrument that determines wind speed and direction, as well as the direction in which precipitation is moving) and computer modeling systems, researchers have developed a likely explanation for how tornadoes develop.

Tornadoes originate within severe thunderstorms—usually in the most destructive and long-lasting breed of severe thunderstorms, called supercell thunderstorms. The first stage of a developing tornado is a mesocyclone, a region of rotating, upward-blowing columns of wind within a mature thunderstorm. The mesocyclone starts in the center region of the thunderstorm cloud and grows downward. Air from below is sucked upward into the low-pressure center (or vortex) of the mesocyclone, making it longer and skinnier. At the same time, the spinning of the mesocyclone becomes more rapid.

When the mesocyclone protrudes below the base of the cloud, it is considered a tornado cyclone. The tornado cyclone grows as updrafts of air rush into the zone of extremely low pressure in its vortex. When the tornado cyclone hangs well below the base of the thunderstorm cloud and has a pronounced cone shape, it is considered a funnel cloud.

The funnel cloud continues to grow downward by attracting air from below. When the incoming air rises, it cools. If the air is moist enough, the water within it condenses and forms a cloud, making the funnel cloud visible. When the funnel cloud reaches the ground, it is classified as a tornado.



Formation of a tornado.

The Fujita scale of tornado intensity

The Fujita scale, created by the late tornado expert T. Theodore Fujita (1920–1998), places tornadoes into six categories. The categories, F0 through F5, are defined by the damage created by the tornado. F0 and F1 tornadoes are "weak"; F2 and F3 tornadoes are "strong"; and F4 and F5 tornadoes are "violent." A Fujita label can only be applied to a tornado once it has passed through an area and the damage has been assessed. Based on the extent of the damage, one can estimate the tornado's wind speeds. (It is very difficult to measure tornado wind speeds directly because regular wind instruments cannot withstand a tornado's strong winds. Recently, however, truck-mounted Doppler instruments, correctly placed in the path of a tornado, have made direct measurements in a handful of tornadoes.)

It is important to remember that the Fujita scale rates tornadoes according to intensity, not size. It is a common misconception that the largest tornadoes are the strongest and that the smallest tornadoes are the weakest. This, however, is not always the case.

F0: Light damage; broken branches, signs and billboards damaged. Winds less than 72 mph (116 kph).

F1: Moderate damage; mobile homes pushed from foundations/overturned, surfaces peeled off roofs. Winds 73 to 112 mph (117 to 180 kph).

F2: Considerable damage; mobile homes demolished, large trees snapped/uprooted, light-object missiles generated. Winds 113 to 157 mph (181 to 251 kph).

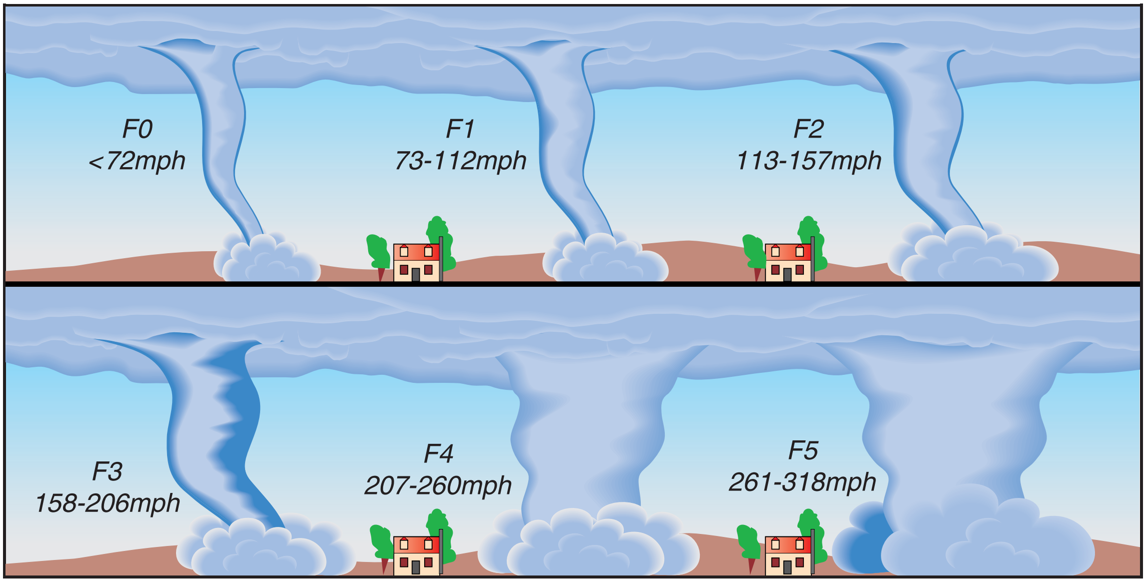
F3: Severe damage; roofs and some walls torn from well-constructed houses, heavy cars lifted off the ground and thrown. Winds 158 to 206 mph (252 to 330 kph).

F4: Devastating damage; well-constructed houses leveled, cars thrown and large missiles generated. Winds 207 to 260 mph (331 to 417 kph).

F5: Incredible damage; houses lifted from foundations or disintegrated; automobile-sized missiles carried through the air. Winds 261 to 318 mph (418 to 512 kph).

Tornadoes travel at a range of speeds, averaging 34 miles (55 kilometers) per hour. While some tornadoes barely inch along, others sprint at 150 miles (241 kilometers) per hour.

Appearance of tornadoes Tornadoes come in a variety of shapes, sizes, and colors. Tornadoes may look like funnels, upside-down bells, elephants' trunks, or long ropelike pendants. Some tornadoes are white, while others appear gray, brown, or black. If the air sucked into the vortex cools to the temperature at which the water vapor within it condenses, then a cloud forms within the tornado. The cloud gives the tornado a white or gray appearance. A tornado will be dark brown or black if debris and dust gets picked up from the ground and spun



The Fujita Intensity scale.

up into the vortex. Occasionally a tornado picks up red dirt or clay, giving it a reddish color.

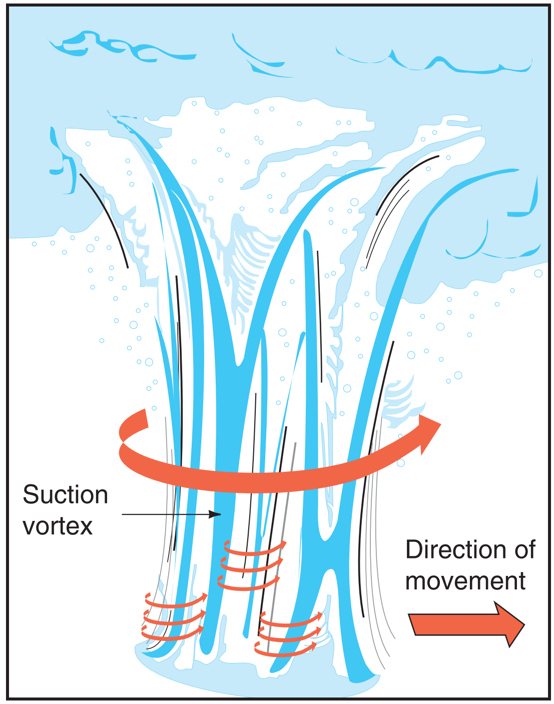
"Weak" and "strong" tornadoes Just less than 70 percent of all tornadoes are classified as "weak tornadoes," with spinning winds of 75 to 110 miles (118 to 177 kilometers) per hour. The damage path created by those tornadoes is, on average, 30 to 190 feet (10 to 60 meters) wide by 5 miles (8 kilometers) long. Contact with the ground lasts less than ten minutes. Weak tornadoes are responsible for less than 5 percent of all tornado deaths.

"Strong tornadoes," with spinning winds of 110 to 200 miles (180 to 320 kilometers) per hour, account for about 29 percent of all tornadoes. Strong tornadoes create a path of destruction that is up to 1 mile (1.6 kilometers) wide and several miles (kilometers) long. They stay on the ground for about twenty minutes and account for almost 30 percent of tornado deaths.

Only 2 percent of all tornadoes are considered "violent tornadoes." The spinning winds of those tornadoes surpass 250 miles (400 kilometers) per hour, gusting to 320 mph (500 kph). A violent tornado

A ghostly white tornado in Kansas, 2004. ©ERIC NGUYEN/JIM REED PHOTOGRAPHY/CORBIS.

creates a path of destruction more than 1 mile (1.6 kilometer) wide and some 100 miles (160 kilometers) long. A tornado of this intensity can remain on the ground more than two hours. Violent tornadoes, despite their relatively small numbers, account for nearly 70 percent of all tornado deaths.



The suction vortex of a multi-vortex tornado.

Life cycles of tornadoes

Similar to the process by which thunderstorms form, tornadoes evolve through a number of stages. The first stage is called the dust-whirl stage. This stage is marked by the formation of a short funnel cloud protruding downward from the base of the thunderstorm cloud. The funnel cloud causes the swirling around of debris on the ground beneath it. Surface winds in this stage are rarely strong enough to cause any damage.

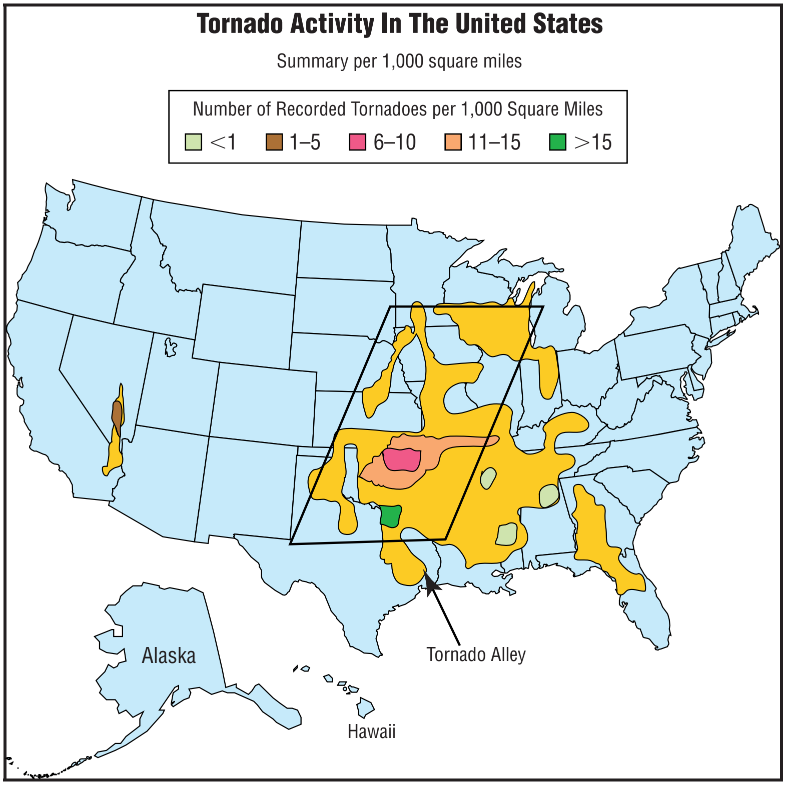
The second stage is called the organizing stage. During this stage, the funnel cloud extends further downward and increases in strength.

A tornado is at its most destructive in the mature stage. The funnel reaches all the way to the ground in this stage and remains in contact with the ground until it dissipates. During this stage, the tornado attains its greatest width and is nearly vertical. This stage lasts only fifteen minutes, on average.

During the mature stage, some tornadoes become multi-vortex tornadoes. In these tornadoes, the vortex divides into several smaller vortices called suction vortices. Suction vortices are responsible for the strongest surface winds. They continually form and dissipate as the powerful tornado moves along.

As a tornado enters the shrinking stage, its funnel narrows. Friction with the ground causes the funnel to tilt. In this stage, which lasts an average of seven to ten minutes, the tornado creates a narrower path of destruction than it did during the mature stage.

The last stage is called the decay stage. In this stage, the funnel narrows further until it is shaped like a rope. It usually twists and turns several times before fragmenting and dissipating.



Not all tornadoes proceed through these five stages. Minor tornadoes may dissipate after the organizing stage, or proceed directly from the organizing stage to the decay stage.

Where tornadoes occur Tornadoes occur wherever severe thunderstorms occur, mainly in the temperate middle latitudes (the regions of the world that lie between of 30° and 60°, north and south). About 75 percent of the world's tornadoes occur in the continental United States. Tornadoes in the United States are, on average, the most severe in the world.

Tornadoes are also common in Australia, New Zealand, South Africa, Argentina, Bangladesh, and much of central Europe as far south as Italy and as far north as Great Britain. Occasional tornadoes have occurred as far north as Stockholm, Sweden, and Saint Petersburg, Russia. Tornadoes sporadically occur in Japan, eastern China, northern India, and Pakistan. Very weak tornadoes sometimes form in tropical regions.

An eyewitness account of a tornado

In the following paragraphs, Roy S. Hall of Texas recounts his experience inside a tornado on May 3, 1948. This story was published in full in *Weatherwise,* January–February 1998.

"Since noon, thunderstorms had been developing to the west and the southwest, muttering and grumbling, miles away. . . . The squall, now about two miles away, was coming directly at us. . . . Lightning was striking all around the house now, adding its horror to the fast-rising din. . . . The deafening noise outside was growing in intensity by the second, and I realized a tornado was right on us.

"And then very suddenly, when I was in the middle of the room, there was no noise of any kind. . . . But I could still feel the house tremble and shake under the impact of the wind. . . . I saw it was growing lighter in the room.

"The light, though, was so unnatural I held the thought for a moment that the house was on fire. The illumination had a peculiar bluish tinge. . . .

"There was a tremendous jar, the floor slid viciously under my feet. . . . All around objects flashed upward. I sensed the roof of the house was gone.

"I know the house had been lifted from its foundation, and feared it was being carried through the air. . . . I sensed a vast relief when I saw that we were still on the ground. The house had been jammed against trees on the east and south and had stopped, partly off its foundation.

"The relief I experienced, however, was very brief. Sixty feet south of our house something had billowed down from above and stood fairly motionless, save for a slow up-and-down pulsation. . . . For a second I was too dumbfounded even to try to fathom its nature, then it burst on my befuddled brain with a paralyzing shock: I was looking at the inside wall of the lower end of the tornado funnel; we were within the tornado itself!

"The bottom of the rim was about twenty feet off the ground, and its leading edge had doubtless destroyed our house as it passed over. The interior of the funnel was hollow . . . and, owing possibly to the light within the funnel, appeared perfectly opaque. Its inside was so slick and even that it resembled the interior of a glazed sandpipe.

"The bottom of the funnel was about 150 yards across. Higher up it was larger, and seemed to be partly filled with a bright cloud, which shimmered like a fluorescent light.

"Where I could observe both the front and back of the funnel's insides, the terrific whirling could be plainly seen. . . . It looked as if the whole column were composed of rings or layers, and when a higher ring moved on toward the southeast, the ring immediately below slipped over to get back under it. This rippling motion continued on down toward the lower tip.

"The peculiar bluish light was now fading, and abruptly was gone. Instantly it was again dark as night. With the darkness, my hearing began to come back. . . . The tornado had passed."

Who's who: Howard Bluestein and the Storm Chasers

The 1995 film *Twister* featured fictional "storm chasers." These adventurers sped along prairie roads in an instrument-loaded vehicle in the hopes of sighting an elusive tornado or violent storm.

University of Oklahoma meteorology professor Howard Bluestein is also the star of a movie, albeit a movie made for public television, but he is a real storm chaser. He knows that things are quite different from what was portrayed in the movie. The most important difference between the real world and the movie is that storm chasers are very careful to not place themselves in the path of the oncoming storm. They are there to gather information, not to risk their lives.

When he is out in the field, Bluestein plays it safe. "I think that we pretty much know where a tornado might form, and we're very careful not to get in its path," said Bluestein in an interview published in the April/May 1996 issue of *Weatherwise* magazine. "The greatest dangers that we have are dangers of driving under bad conditions. Roads that are wet. Narrow country roads. . . . Lightning is also a big scare. We try to stay inside the van if we see a lot of lightning."

Bluestein attended the Massachusetts Institute of Technology, where he majored in electrical engineering until his senior year. Then he switched to meteorology. He went on to complete a Ph.D. in tropical meteorology. Bluestein joined the faculty of the University of Oklahoma in 1976, where he has been ever since.

Since 1977, Bluestein has been leading teams of storm chasers, armed with cameras and portable Doppler radars, all over the Oklahoma countryside. They are seeking answers to questions such as: Why do some thunderstorms spawn tornadoes while others do not, and, how exactly do tornadoes form?

"You need a source of rotation and an updraft to spin it up. Everyone knows that," explained Bluestein in an interview published in the July 12, 1996, *Chronicle of Higher Education*, when asked about tornado formation. "What people don't agree on are the sources of rotation and the sequence of events that leads to the rotation, which produces the

Tornadoes in the United States Tornadoes in the United States are formed by the interaction of cold, dry air migrating south from Canada and the warm, moist air traveling north from the Gulf of Mexico. An average of eight hundred to nine hundred tornadoes occur yearly in the United States, accompanying about 1 percent of all thunderstorms. Most of the tornadoes are short-lived and strike sparsely populated areas. The state that experiences the greatest number of tornadoes is Texas.

"Tornado Alley" is the part of the United States that has the highest per-area concentration of tornadoes. This region encompasses north-seeds of the tornado. We need to understand where the original vortex comes from."

Bluestein and his tornado-chasing colleagues have greatly advanced our understanding of tornadoes. Before tornado chasers began their quest two decades ago, all that was known about tornado formation was that tornadoes originated within supercell thunderstorms. The data collected by storm chasers has enabled forecasters to develop the computer models that more accurately, and farther in advance, predict when and where tornadoes will strike.

Howard Bluestein and his crew track a tornado. COURTESY HERBERT STEIN.

central Texas, Oklahoma, Kansas, Nebraska, and South Dakota. Central Oklahoma has the greatest number of tornadoes per acre. Tornadoes also occur frequently throughout the Mississippi Valley, and in the Midwest, and all the way east to Massachusetts. Tornadoes occur very rarely west of the Rocky Mountains.

Tornadoes occur year-round in the United States, but with the greatest frequency in the spring and early summer (April through June). Their lowest rate of occurrence is in December and January. Tornadoes may develop at all times of day and night, with the peak time between

Waterspouts

Waterspouts are tornado-like phenomena that occur over large bodies of water. They are rapidly rotating columns of air that extend from the base of a cloud to the surface of the water. Where the waterspout makes contact with the surface, water sprays upward. Contrary to what many people believe about waterspouts, water is not drawn upward through the funnel, into the cloud. Rather, the moisture in a waterspout comes from water vapor that has condensed within rising air and formed a cloud.

There are two types of waterspouts: tornadic waterspouts and fair-weather (or nontornadic) waterspouts. A tornadic waterspout is a tornado that has formed over land and traveled over the water; it is the strongest type of waterspout and relatively rare. Fair-weather waterspouts constitute the vast majority of waterspouts. Unlike the tornadic variety, fair-weather waterspouts form over the water and can arise independently of severe thunderstorms.

Fair-weather waterspouts are formed when winds converge (travel toward a common point) and cause the surface air to rise. As the air rises, it cools, and the moisture within it condenses into cloud droplets. The condensation releases latent heat (energy released or absorbed by a substance as it undergoes a phase change), which fuels the continued upward motion of moist air from the surface.

Fair-weather waterspouts are arc-shaped and may appear alone or in clusters. They are relatively small, ranging in diameter from

2:00 PM and 6:00 PM Forty percent of all tornadoes occur during that period. The least likely time for tornado formation is just before sunrise.

Consequences of tornadoes

A tornado leaves a path of near-total destruction in its wake. It picks up and carries away cars, trees, and roofs and walls of buildings. Objects the size of washers and dryers have been picked up by a tornado and transported several miles. They can carry entire buildings for hundreds of yards (meters).

There are reports of tornadoes sucking up the contents of a pond, including frogs and toads, and raining them down further along the storm's path. A violent tornado in 1931 picked up a train car weighing 83 tons (75 metric tons), with 117 passengers on board, and dumped it in a ditch 82 feet (25 meters) away. One tornado snatched a motel sign from Broken Bow, Oklahoma, and dropped it 30 miles (48 km) away in Arkansas. In another tornado a canceled check was blown 305 miles

10 to 325 feet (3 to 100 meters). The speed of their rotating winds only approaches 50 miles (80 kilometers) per hour, and they move along the water at a slow pace. Fair-weather waterspouts usually last ten to fifteen minutes, dissipating when cool air gets drawn into the funnel. They are rarely strong enough to cause damage, except to small boats directly in their path.

Fair-weather waterspouts are common in coastal areas of all tropical oceans. They occur with the greatest frequency near the Florida Keys. The Keys get nearly one hundred fair-weather waterspouts per month during the summer, for a total of four hundred to five hundred water-spouts annually. Waterspouts are also a common sight over the Mediterranean Sea. They occur occasionally over large inland bodies of water, such as the Great Lakes and Utah's Great Salt Lake.

A waterspout off the coast of Cyprus, 2003. ©REUTERS/CORBIS.

(491 kilometers), from Great Bend, Kansas, to just outside of Palmyra, Nebraska.

The human factor

Tornadoes occur throughout such a large geographic area that, especially in the United States, they are virtually impossible to avoid. At present, there is an average of fewer than fifty deaths per year in the United States because of tornadoes. Most of those fatalities occur when people are crushed in collapsing buildings. The best way to reduce the number of deaths caused by tornadoes is for people to have to access to sturdy, tornado-proof structures.

The danger of manufactured housing

Manufactured and mobile homes are particularly vulnerable to tornadoes: not only do they lack basements (the safest place during a tornado), but they are relatively flimsy and lightweight. Even those mobile homes tethered to the ground can usually be picked up and tossed by a tornado's extreme winds. Paul Hebert, director of Miami's National Weather Service forecast office, described mobile homes in a news report as "very vulnerable to any tornado." The National Oceanic and Atmospheric Administration (NOAA) stated that it is safer to be in a ditch with one's hands over one's head than it is to be in a mobile home, if in the path of a tornado.

Ideally, people living in mobile home parks would have access to a concrete structure in which they could take shelter. Unfortunately, only a handful of states require that mobile home park operators provide tornado shelters for their residents.

Weather report: Exploding chicken feathers

A tornado-related oddity is the de-feathering of chickens. Reports of naked chickens abound after tornadoes strike rural areas. Professional and amateur meteorologists alike have been perplexed by this phenomenon for years. The popular theory that the low pressure of the tornado causes the feathers to "explode" off a chicken has been shown to be false. The fact is that a pressure drop great enough to cause feathers to explode off a chicken would also cause the whole chicken to explode.

A more likely explanation for de-feathering is that the frightened chicken induces what is called the "flight molt" response. This self-protective response, evoked by a chicken that is being threatened by a predator, causes the chicken's feathers to loosen. That way, when the predator chomps, it gets a mouthful of feathers instead of a mouthful of chicken. During a tornado, the feathers loosened by the terrified chicken's flight molt response are merely blown away.

Homeowners urged to build "safe rooms" In 1999 the Federal Emergency Management Agency (FEMA) began a push to get owners of homes in tornado-prone areas to construct their own storm shelters or "safe rooms." FEMA provided designs for shelters, which were made of metal-reinforced panels, in basements, crawl spaces, closets, bathrooms, storage areas, and other interior parts of the house. One requirement of a "safe room" is that it have its own walls, separate from the rest of the house, so that it could remain standing even if other parts of the house were knocked down.

"When constructed according to the plans," stated James Lee Witt, director of FEMA, "the safe room can provide protection against winds of up to 250 miles per hour and projectiles [flying objects] traveling at 100 miles per hour."

Technology connection

Forecasters presently have the capability to issue tornado warnings, which are severe weather advisories that mean a tornado has been sighted and may strike a specific area, fifteen to thirty minutes ahead of time (eighteen minutes on average). Tornado watches, which are severe weather advisories

Tornado destroys Jarrell, Texas

Violent thunderstorms developed across central Texas in the afternoon of May 27, 1997, spawning three tornadoes. The first of those tornadoes brought death and destruction to the town of Jarrell, Texas. Jarrell, with a population of fourteen hundred people, experienced twenty-seven deaths and $40 million in property damage.

The tornado that struck Jarrell was rated as F5 on the Fujita scale, meaning it created "incredible" damage. The Austin/San Antonio National Weather Service Office called the twister "a tragic tornado of unimaginable proportions." When the tornado first touched down northwest of Jarrell, it was a thin, rope-shaped funnel. It quickly grew until its base was 0.5 miles (0.8 kilometers) wide and its winds surpassed 261 miles (420 kilometers) per hour. As the tornado headed toward homes in the Double Creek subdivision, just west of downtown Jarrell, it ripped asphalt off the road and demolished one business.

Residents of the Double Creek subdivision, given just twelve minutes warning about the approaching tornado, had few places to seek shelter. Their houses were built on cement slabs and had no basements. Some people jumped in cars and attempted to escape the tornado, while others huddled inside their homes. When the tornado blasted through the area it destroyed fifty homes, making them look as if they had been bulldozed from their foundations. Twenty-seven people inside those homes, including some whole families, were killed.

Debris from the destroyed homes was later found 2 miles (3.2 kilometers) away. The tornado also carried away dozens of cars, ripped bark from trees, pulled grass from the ground, and killed three hundred head of livestock.

A tornado rips through Jarrell, Texas, in 1997. AP IMAGES.

Lax mobile home regulations in Florida

The deadliest tornado outbreak in Florida's history occurred in the late evening of February 22 and early morning of February 23, 1998. The tornadoes, produced by three supercell thunderstorms, took 42 lives and caused 260 injuries. More than 800 residences were destroyed and 3,500 others were damaged. Most of the people killed during the tornadoes were in mobile homes or trailers. (There are 800,000 mobile homes or trailers in Florida, accounting for 16 percent of the state's residences.)

Following Hurricane Andrew in 1992, Florida's most costly natural disaster in recent history, the Florida legislature enacted new building standards for mobile homes. The new standards required that mobile homes be constructed with 2-inch by 6-inch (5-centimeter by 15-centimeter) lumber and be anchored to the ground by cables. Mobile homes constructed in this way would be able to withstand winds of 100 to 110 miles (161 to 177 kilometers) per hour. However, safety advocates argued that this standard was insufficient to protect occupants from all hurricanes, not to mention tornadoes. While hurricane winds range in strength from 74 to 180 miles (119 to 290 kilometers) per hour, tornado winds can reach 318 miles (512 kilometers) per hour.

Moreover, 90 percent of Florida's mobile homes are exempt from the 1992 law's requirements, since they were built prior to that time. Homes constructed between 1976 and 1992 had to be able to withstand winds of 90 miles (145 kilometers) per hour; before 1976 there were no construction requirements at all. To make matters worse, Florida law does not require mobile home parks to provide tornado-proof shelters for their residents.

Florida mobile home park destroyed by Hurricane Andrew. A tornado could cause the same results.

stating that conditions are ripe for tornadoes to develop, may be issued as far as three hours in advance. The advance warning given for tornadoes is far shorter than the twelve to twenty-four hours given for hurricanes, however. The reason for this difference is that tornadoes are much smaller, develop more rapidly, and are far more difficult to detect than hurricanes. Nonetheless, great strides have been made in recent years in tornado detection. The present warning time is a tremendous improvement over the two-minute notice given in the mid-1970s.

Experiment: Tornado in a bottle

You can't make a real tornado in a bottle, but you can simulate its movement with water. Here is what you need:

- two 2-liter clear, clean, empty plastic bottles
- water
- 1-inch metal washer
- duct tape

First, fill one of the bottles two-thirds full of water and put the washer over the opening. Then, turn the second bottle upside down and place it on the washer. Use the duct tape to fasten the two containers and the metal washer together very securely.

Turn the tornado maker, so that the bottle with the water is on top, then swirl the bottle in a circular motion. Watch as a "tornado" forms in the top bottle and rushes into the bottom bottle.

Today's tornado forecasting arsenal includes surface weather stations, satellite images, radar images, and computer models. The cornerstone of the forecasting effort is NEXRAD (Next Generation Weather Radar), a network of 156 high-powered Doppler radars that were installed across the United States in 1996. Doppler radar is a sophisticated type of radar that relies on the Doppler effect, the change in frequency of waves emitted from a moving source, to determine wind speed and direction, as well as the direction in which precipitation is moving. (Radar, which is an acronym for "radio detection and ranging," works by emitting short radio waves called microwaves that can reflect off of precipitation.)

Doppler radar can look within a storm system and map out patterns of air circulation, including wind rotation. This information allows forecasters to identify thunderstorms or tornadoes in their earliest stages. Data from NEXRAD is sent, via high-speed computers, to National Weather Service (NWS) centers and field offices around the country.

At the NWS's Storm Prediction Center in Norman, Oklahoma, meteorologists analyze weather data from NEXRAD and other systems twenty-four hours a day. When they detect conditions that could give rise to tornadoes, they notify the weather center in that area. The local weather center may then issue a tornado watch or warning. Weather forecasters also rely on information delivered by SKYWARN, a network of trained weather spotters who watch for tornadoes and report their findings.

Killer tornadoes in Bangladesh

Some of the world's deadliest tornadoes have occurred in Bangladesh, a small country on India's eastern border. Tornadoes there cause more deaths than in more developed countries, such as the United States, in part because Bangladesh does not have a sophisticated tornado prediction and advance warning system. The relatively high frequency of tornadoes, the lack of sturdy shelters, and the high population density all contribute to tornadoes' high death toll in Bangladesh.

On April 1–2, 1977, a tornado outbreak struck the Madaripur district, 80 miles (128 kilometers) outside of Bangladesh's capital city, Dhaka, killing 505 people. The twisters also left more than six thousand people injured and hundreds of thousands homeless. "The tornado . . . lasted two to three minutes and left behind a trail of devastation," read a report about the most destructive twister in the April 3 *Bangladesh Observer.* "Hundreds of houses were razed to the ground and a large number of cattle head killed and injured. Trees were uprooted and the damage to standing crop is colossal." In the next day's paper, a reporter noted: "Not a single dwelling nor a tree I found standing erect and there was hardly any family which did not suffer losses."

On April 26, 1989, Dhaka, Bangladesh, was hit with another violent twister, the deadliest ever recorded. The tornado killed at least 1,109 people and injured about fifteen thousand. Some forty-eight thousand huts were demolished, leaving one hundred thousand people homeless. The twister also destroyed much of the rice crop (the primary food in the region) and many fruit trees. The tornado came on the heels of a massive flood, which just six months earlier had already damaged the rice crop.

Another massive tornado struck central Bangladesh on May 12, 1996. The tornado killed an estimated 760 people and caused 34,000 injuries in a cluster of villages 95 miles (152 kilometers)

Extending the warning time One of the greatest challenges before meteorologists today is learning more about how tornadoes are formed. This task involves determining why some thunderstorms create tornadoes, while others do not. When tornadoes are better understood, forecasters will be able to lengthen the advance warning time they give; with longer warning times, people have a greater opportunity to get out of harm's way.

In the late 1990s, the National Weather Service sponsored a tornado research program called VORTEX, the Verification of the Origins of Rotation in Tornadoes Experiment. VORTEX staffers placed very high frequency, truck-mounted Doppler radar units in the paths of oncoming severe thunderstorms (storms that were likely to produce tornadoes). When a tornado formed along the path, the equipment took readings north of Dhaka. Many of the casualties were believed to have been caused by corrugated tin roofs that flew through the air like missiles. The winds were so strong that they ripped clothes right off of people, leaving some survivors reluctant to emerge from their hiding places until clothing was distributed by relief agencies.

Residents walk amidst the rubble of their village of Rampur, Bangladesh, after a tornado tore through the area in 1996. AP IMAGES.

of wind gusts, rainfall, and hail, producing a three-dimensional view of the tornado throughout its life cycle.

A more recent tornado project, called STEPS (the Severe Thunderstorm Electrification and Precipitation Study), took place from May 22 through July 16, 2000. The purpose of STEPS, which was coordinated by the National Center for Atmospheric Research, was to identify the processes within towering thunderstorm clouds that give rise to tornadoes and lightning. STEPS researchers, stationed across the plains of Kansas and Colorado, used Doppler radars and a lightning mapping system to produce three-dimensional pictures of storms. They also launched weather balloons directly into thunderheads (towering cumulonimbus clouds likely to produce thunderstorms) to take readings of atmospheric conditions.

NOAA Weather Radio

NOAA Weather Radio, also called the "Voice of the National Weather Service," presents continuous, extensive, local weather information all across the United States. The service is operated by the National Oceanic and Atmospheric Administration, and reports are prepared by local offices of the National Weather Service. Weather reports are usually four to six minutes long and are updated every one to three hours (more frequently during rapidly changing or severe weather). Weather Radio also broadcasts special reports relevant to specific regions. For instance, one region may present marine reports, while another presents agriculture reports and climatological forecasts.

Weather radio broadcasts are transmitted on seven different high-band FM frequencies, ranging from 162.400 to 162.550 megahertz. Picking up the broadcasts requires a special receiver called a "weather radio." In some locations weather radio is carried on certain radio bands like the weather band; citizens band; and some automobile, aircraft, and marine bands. In a few places it can be picked up on standard AM/FM radios.

When severe weather is forecast, NOAA Weather Radio sounds an alarm. That signal alerts the listener to turn up the radio and stay tuned. Some receivers can be programmed to automatically switch on whenever a hazardous-weather alarm is activated.

NOAA Weather Radio broadcasts are sent out from four hundred transmitters throughout the United States, Puerto Rico, Guam, and Saipan (a tiny island north of Guam in the North Pacific Ocean). Each transmitter sends information to receivers within a 40-mile (64-kilometer) radius—the area for which the report is relevant. Presently weather radio broadcasts have the potential to reach about 90 percent of the American population, provided they have the appropriate receivers.

A weather radar truck, also called Doppler on Wheels (DOW), scanning a thunderstorm in Oklahoma.
©JIM REED/CORBIS.

University of Oklahoma storm chasers observing an F5 tornado in 1999. AP IMAGES.

A matter of survival

Tornado watches and warnings are issued in advance of tornadoes and are intended to alert people in a given area that dangerous weather is brewing. During a tornado watch, stay tuned to your radio or television for updates. Prepare to move quickly to a safe place in the event that a tornado warning is issued. Watch the sky, as well. You may spot the warning signs of a tornado before forecasters announce a tornado warning.

In the event of a tornado warning, television and radio programs are interrupted and, in many communities, sirens blare. Immediately move to a safe place when a tornado warning is issued. You may have very little time before a tornado strikes.

If you live in a tornado-prone region, it is wise to have areas designated as "tornado shelters" in your home, at school, and at work. The best place for a tornado shelter is in a basement. If there is no basement, select an interior room (bathrooms and closets are best) or hallway on the first floor, away from windows. Keep a first aid kit and a flashlight with extra batteries in your tornado shelter.

How to tell when a tornado is coming

One warning sign of a tornado is a wall cloud, a roughly circular cloud that is 1 to 4 miles (1.5 to 6.5 kilometers) in diameter and that hangs beneath the thunderstorm cloud. A wall cloud may appear up to one hour before a tornado strikes. Another warning sign is a funnel cloud. This looks like a dimple bulging from the underside of the cloud, which quickly lengthens. A funnel cloud will only be visible if the air rising within it condenses, creating a gray or white funnel. Another indication that a funnel cloud is present is the swirling of debris on the surface. Sometimes, however, falling rain or darkness obscures a funnel cloud.

Two other warning signs of a tornado are the sky turning dark green or hail falling from a large thunderstorm. Some tornadoes make a roaring sound, like several freight trains, loud enough to be heard miles away. Other tornadoes, however, travel quietly.

When a tornado warning is issued

- Go to your designated tornado shelter; or crouch beneath the stairs, a heavy workbench, a mattress, or a sturdy piece of furniture.
- Do not open windows! It was once believed that opening windows would keep buildings from "blowing up" by allowing the indoor and outdoor pressure to equalize. It is now known that opening windows only increases pressure on the opposite wall, making it more likely that the building will collapse.
- If you're outside, seek shelter in a strong building. Stay away from windows and doors. Flying glass and other debris are major tornado hazards.
- If you're in a car, leave it and go into a nearby building. If that's not possible, leave your car and crouch in a ditch or depression or next to a strong building. Do not stay in the car. Tornadoes can pick up cars and hurl them through the air. When the car is dropped to the ground, it may crash with the force of a 100-mile-per-hour (161-kilometer-per-hour) head-on collision.
- If you're in a mobile home, leave. Even properly secured mobile homes can be lifted up by a tornado. Go to a designated tornado shelter or crouch in a ditch.
- Lend assistance to very young children, elderly people, those who are mentally or physically disabled, and people who don't understand the tornado warning due to a language barrier.
- Protect yourself by lying face down with your knees drawn up under you. Put your head down by your knees and cover the back of your head with your hands.

[*See Also* **Climate; Hurricane; Thunderstorm; Weather: An Introduction**]

For More Information

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Tsunami

One early morning over one hundred years ago, a group of fishermen from a small Japanese village sailed out to set their nets. After fishing all day long, they returned late in the evening to find their village and the whole harbor devastated by what appeared to be a huge wave. Since they had felt nothing while out at sea, they concluded it was some sort of freak wave that only happened in harbors. So they called it a *tsu* (harbor) *nami* (wave).

A tsunami (pronounced tsoo-NAH-mee) is not a "harbor wave." It is a long-wavelength, low-amplitude wave or series of waves caused by a large displacement of water. Tsunamis usually move very rapidly across the ocean. In deep water, they are almost undetectable. Only when they move into shallow water do they reach terrifying heights and cause massive destruction. These sea waves have killed more people in Japan than in any other place else in the world. While tsunamis are sometimes called "tidal waves," they have nothing to do with the tides (the rise and fall of water caused by the gravitational attraction of the Sun and Moon).

Tsunamis are triggered by sudden disturbances, most often earthquakes (sudden movements of Earth's outermost layer, or crust) that occur on the ocean bottom or along the coasts. Tsunamis are also set in motion when large amounts of material are cast onto the ocean floor by landslides, volcanic eruptions, or meteorites. The energy released by that activity ripples outward from the point of origin in a series of ring-shaped waves.

Tsunamis are nearly undetectable in deep ocean water, where they are typically around 16 inches (41 centimeters) or less in height. Their wavelengths, the distance between wave peaks (called crests), may be hundreds of miles (hundreds of kilometers). The Japanese fishermen who originally invented the term had returned to port to find the area surrounding their harbor devastated, although they had not been aware of any wave in the open water; tsunamis do not reach their towering heights until they approach land. As the depth of water decreases, the energy of the wave forces water upward into swells that are shorter in length but

Tourists watch a tsunami approaching the beach in Malaysia in 2004. AP IMAGES.

greater in height. It is typical for a tsunami to be 60 to 100 feet (18 to 30 meters) tall by the time it reaches land. The highest tsunami on record, that devastated the Ryukyu Islands south of Japan in 1771 and caused 13,486 deaths, was 280 feet (85 meters) tall.

Large tsunamis are incredibly forceful. When they crash onto land they cause tremendous property damage and loss of life. Tsunamis occur most often in the Pacific Ocean, since the ocean floor in that area is prone to earthquakes and volcanoes. The locations most vulnerable to tsunamis include Japan, Hawaii, Alaska, Russia, the Philippines, Indonesia, Peru, and Ecuador.

Tsunami devastates Papua New Guinea

On July 17, 1998 the most lethal tsunami of the twentieth century struck Papua New Guinea, a poor Pacific Island nation of 4.3 million people

WORDS TO KNOW

crest: the highest point of a wave.

crust: the outermost layer of Earth, varying in thickness from 3.5 miles (5 kilometers) to 50 miles (80 kilometers).

epicenter: the point on Earth's surface directly above the focus of an earthquake, where seismic waves first appear.

focus: the underground starting place of an earthquake (also called the hypocenter).

magnitude: the power of an earthquake.

oceanography: the study and exploration of the ocean.

period: the time between two successive waves.

plate: a large section of Earth's crust.

Richter scale: the scale developed by American seismologist Charles Richter that describes the amount of energy released by an earthquake on a scale from 1 to 10. Each whole number increase in value on the scale indicates a tenfold increase in the energy released. Earthquakes measuring 7 to 7.9 are major and those measuring 8 or above cause widespread destruction.

seismic waves: vibrations that move outward from the focus of an earthquake, causing the ground to shake.

seismograph: an instrument used to detect and measure seismic waves.

tidal station: a floating instrument center in the ocean that records water levels.

trough: the lowest point of a wave.

tsunami: a series of giant ocean wave waves caused by a large displacement of water.

tsunami warning: an alert stating that a tsunami has been detected and is approaching the designated area. People are instructed to move to higher ground immediately.

tsunami watch: an alert stating that an earthquake has occurred with sufficient magnitude to trigger a tsunami. People are instructed to listen for further news.

about 90 miles (145 kilometers) north of Australia. Papua New Guinea occupies the eastern half of the island of New Guinea; the western half is part of Indonesia. The death toll from the disaster was estimated at over two thousand people. Many of those who perished died instantly from the impact of the wave or from drowning. Others were swept into the jungle and died of their injuries before medical help could reach them. At least six hundred people were critically injured and more than six thousand, most of them small farmers and fishermen, were left homeless. The 1998 tsunami was one of the worst natural disasters in Papua New Guinea's history.

Earthquake and landslide cause wave The tsunami was originally believed to have been set in motion by an earthquake of 7.0 magnitude (power) on the Richter scale, the scale that describes the amount of energy released by an earthquake from 1 to 10. The earthquake was located 12 to 30 miles (19 to 48 kilometers) out to sea. This originally puzzled researchers, because earthquakes that size rarely trigger tsunamis, and especially not large tsunamis. Later studies revealed that the earthquake had caused a landslide on the ocean floor. An investigation of the seafloor about 15 miles (24 kilometers) off the coast found that a huge area of soft earth and rock had collapsed and slid into a trench 2.5 miles (4 kilometers) deep. Scientists determined that it was this huge landslide that had generated the tsunami.

Just minutes after the landslide, a series of three giant waves swept onto shore in the rugged and remote northwestern part of the country. The smallest of the waves was estimated at 10 feet (3 meters) tall, and the largest was 32 to 46 feet (9.8 to 13.7 meters). One measurement, based on the height of a fishing net found in a tree, put the height of the largest wave at 57.5 feet (17.5 meters)—as tall as a seven-story building. The waves crashed onshore at speeds of 22 to 44 miles (35 to 71 kilometers) per hour.

Strip of land hit hard by tsunami The area hardest hit by the tsunami was a 22-mile-long (35-kilometer-long) narrow stretch of land that stands between the Pacific Ocean and the Sissano lagoon. (The lagoon itself had been created by a giant tsunami in 1907.) The surrounding jungles and mangrove swamps formerly had a population of about ten thousand people. The 1998 tsunami, however, reduced the area to a barren wasteland. Villages were swallowed up, and their inhabitants were swept into the lagoon or out to sea. The waves destroyed wood and palm-frond houses and concrete schools and churches alike. The wall of water was so strong that it bent iron and steel beams around coconut trees.

The majority of those killed by the tsunami were children and elderly people—those least able to outrun the rushing water or climb trees fast enough to save themselves. Among the tsunami's first victims were about two hundred schoolchildren, on holiday from school and picnicking on the beach in the village of Arop. Along the coastline, so many children died that locals began calling the tragedy "the loss of a whole generation of children." So few children survived the catastrophe that no plans were made to rebuild the schools.

"First the houses trembled," read an account of the disaster in *Asiaweek*. "Then a sound swelled like an approaching jet engine. Excited children ran out onto the shore, expecting a glimpse of a low-flying aircraft in the darkening sky. Instead they met an impenetrable wall of water. There was simply nowhere to run."

People tried desperately to survive the wave by clinging to boats or climbing to treetops. Many survivors experienced the terrifying ordeal of having their children ripped from their arms by the cascading water. One woman managed to save herself and her one-month-old twins by tying herself to a palm tree.

Dr. James Goff of New Zealand's Institute of Geological and Nuclear Sciences described the wave in the *Evening Post* (of Wellington, New Zealand) as follows: "Imagine a four-story wave traveling at 70 kilometers [43 miles] per hour."

"There was so much devastation it was hard to comprehend what happened," Goff continued. "You couldn't see houses or where they had been, the road and even the graveyard had gone."

Relief efforts get underway Immediately after the tsunami, rescue workers began searching for survivors in the jungles and the swamps. Within the first few days they found more than 2,527 people alive. One notable discovery was that of a young girl who had been injured and lost, wandering alone for four days.

Dr. John Sairere, a relief coordinator from Papua New Guinea who lost seventy-one members of his family to the tsunami, helped survivors recover from the emotional trauma. "The hardest thing for me was the horrifying loss of so many relatives," stated Sairere in the Wellington, New Zealand, paper the *Dominion.* "It came and went so fast—in thirty minutes we lost so many. When I got there, there was nothing left, just stumps of coconut trees."

Emergency personnel from around the world, including doctors, nurses, and engineers, arrived on the scene to help treat the injured. Several countries sent food, drinking water, medicine, tents, beds, clothing, tools, medical supplies, and building materials. The United States donated more than $1 million to the rescue effort. Part of that sum was for an earthquake-detection system that would provide advance warning for future tsunamis. New Zealand also donated $1 million in aid. Australia coordinated the international relief operation.

Twelve days after the disaster, search crews gave up hope of finding survivors. The government ordered remaining coastal residents to evacuate a 45-square-mile (120-square-kilometer) area around the lagoon.

Air workers load supplies for tsunami survivors, 2005. AP IMAGES.

The plight of the survivors In the wake of the tsunami, most of the survivors fled inland. They had lost children, friends, spouses, homes, and livelihoods, and brought with them very few, if any, possessions. They vowed never to return to their former homes, both out of fear that another wave would come and the superstitious belief that the dead would haunt the area.

One of the refugees was Fabian Nakisony, who lost his one-year-old son in the tsunami. “We have nothing,” stated Nakisony in the July 22, 1998, *New York Times.* “We can get timber from the bush, but we have no hammer, no nails, no saw.”

Whereas the villagers’ previous staple food had been fish, caught in the lagoon, after the tsunami they subsisted on donated rice, flour, and water, plus the few wild fruits and vegetables they could forage. Within days of the disaster, small villages began to materialize on hills in the jungle. Makeshift dwellings were constructed from woven palm leaves and sticks.

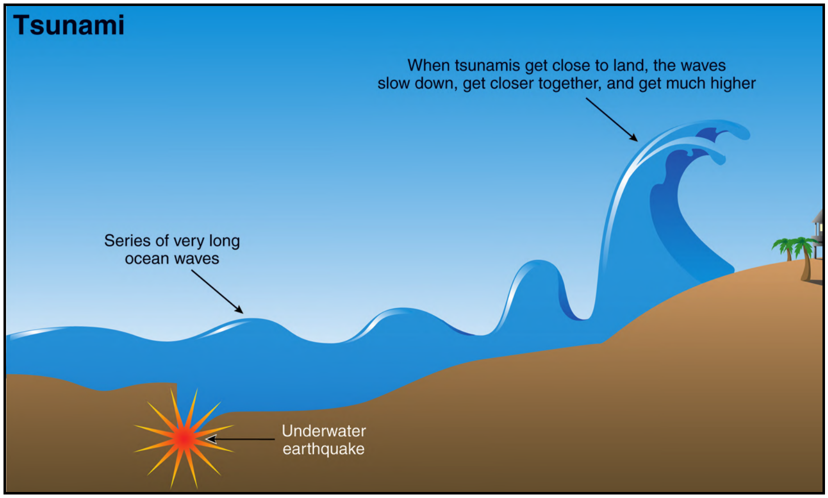
Local hospitals, plus an Australian field hospital, filled up with some seven hundred injured people. As the facilities overflowed, patients had to lie on the floor. Many of those hospitalized had broken bones, cuts, bruises, and internal injuries from being flung against trees or debris by the tsunami. A common problem was the development of gangrene (the death or dying of body tissue) in wounds that had come in contact with bacteria-filled coral sand. Doctors were forced to perform hundreds of

A tsunami hits Phuket Island, December 28, 2004. ©TAIWAN NATIONAL SPACE PROGRAM OFFICE/HANDOUT/REUTERS/CORBIS.

limb amputations to halt the spread of gangrene. Another malady affecting survivors, particularly children, was aspiration pneumonia, which is contracted by inhaling large amounts of seawater into the lungs.

The Indian Ocean tsunami of 2004

The twenty-first century had hardly begun when an even more devastating tsunami struck in the Indian Ocean on December 26, 2004. It was triggered by an earthquake of magnitude 9.3 on the Richter scale. (Magnitude is the power of an earthquake; a magnitude of 7 produces major damage on land and a magnitude of 8 produces widespread destruction.) At 9.3, this may have been the most powerful earthquake ever recorded. It caused a series of lethal tsunamis that killed approximately 230,000 people (including 168,000 in Indonesia alone), making it the deadliest tsunami in recorded history. The tsunami killed people in coastal areas from Indonesia, Thailand, and the northwestern coast of



How a tsunami forms.

Malaysia, to thousands of miles away in Bangladesh, India, Sri Lanka, the Maldives, and even as far as Somalia, Kenya, and Tanzania on the eastern coast of Africa.

Because of the frequent tsunamis in the region, Pacific Ocean countries have an extensive cooperative warning system in place. The tsunami warnings alert people that a tsunami has been detected and is approaching the designated area, and issue instructions to move to higher ground immediately. However, in 2004 there was no similar system in place in the Indian Ocean region. The lack of an organized warning system certainly contributed to the great loss of life. There was no organized alert service covering the Indian Ocean in part because there had been no major tsunami events since the eruption of the island volcano Krakatau in 1883. In response to the devastation resulting from the 2004 Indian Ocean tsunami, UNESCO (United Nations Educational, Scientific and Cultural Organization, established as part of the United Nations in 1945) and other world bodies have called for a worldwide tsunami monitoring system.

Dangerous science: How tsunamis happen

A tsunami is a series of extremely long waves, extending from the ocean floor to the sea surface, that are set in motion when a disturbance—usually an earthquake under the sea or in a coastal region, and sometimes a landslide or volcanic eruption—displaces ocean water. The earthquake or other activity causes the seafloor to suddenly rise or fall. If it rises, it lifts

Waves hit Solimar Beach, California, 1998. ©VICTORIA SAYER/CORBIS SYGMA.

the water above it, all the way to the surface, creating a huge pile of water. If the seafloor falls the water above also falls. At the sea surface, water flows into the low spot (directly above the seafloor depression) from all directions. That action results in the formation of a pile of water. In either case, the piled-up water is then pulled downward by gravity. It travels away from the bulge in rings of waves, similar to the pattern set in motion by tossing a pebble in a pond.

In the deep ocean, tsunamis travel at average speeds of 500 to 600 miles (800 to 965 kilometers) per hour—similar to a jet plane. The deeper the water, the faster the waves travel. Tsunamis in the open sea also have enormous wavelengths, which are measures of length from trough (lowest point) to trough, or crest (highest point) to crest. Far from land they may have wavelengths as great as 600 miles (900 kilometers). The period (time between successive waves) averages about one hour. Out at sea the small height of the waves, an average of 16 inches (41 centimeters), makes them virtually undetectable.

The waves lose very little energy as they travel; they sometimes cross the entire ocean (thousands of miles or kilometers) in less than a day. As a wave enters shallow water near shore, its front end is slowed by friction with the ocean bottom to a speed of about 30 to 200 miles (48 to 322 kilometers) per hour. At the same time, the back of the wave keeps moving at the same speed. As the back catches up to the front, the wavelength shrinks (to less than 10,000 feet [3,050 meters] in most

Tsunami in Hilo, Hawaii

On April 1, 1946, Hawaii experienced its worst natural disaster: a tsunami with 50-foot (15-meter) waves that killed 159 people and injured 163 throughout the island chain. It caused more than $25 million in property damage. The city of Hilo suffered the most from the tsunami; ninety-six of the deaths occurred there, and the waterfront business district was destroyed. The force of the water was so great that it bent parking meters down to the pavement. The tsunami washed away beaches, ripped up railroad tracks, and covered the coastal highways under mountains of sand and debris. Houses could be seen bobbing in the water after the wave washed back to sea.

That tsunami had been set in motion by an earthquake measuring 7.2 on the Richter scale, centered just south of Alaska's Unimak Island, some 2,500 miles (4,000 kilometers) away. The tsunami spurred the creation of the Pacific Tsunami Warning Center (PTWC). Established in 1948, the PTWC monitors ocean conditions and issues tsunami alerts for the Pacific region.

The PTWC's abilities were put to the test in 1960, when Hilo was again targeted by a tsunami. That tsunami was set in motion by an earthquake in the Chilean Andes. Waves measuring 25 feet (7.6 meters) high first damaged the coast of Chile and then moved westward across the Pacific. Besides Hawaii, the tsunami affected New Guinea, New Zealand, Okinawa, the Philippines, and Japan.

When the tsunami hit Hawaii, Hilo experienced three waves between 9:00 PM and 1:00 AM. The first two—just 4 feet (2.3 meters) and 9 feet (2.7 meters) high, respectively—were held back by a seawall in the harbor. The third wave, standing 20 feet (6.1 meters) tall, surged into downtown Hilo. Despite timely tsunami warnings, many people chose not to evacuate and sixty-one of those who stayed behind lost their lives. The

cases) and the period is reduced to 10 to 30 minutes. The energy carried by the waves, which in the open ocean was spread over hundreds of miles, in the shallow water is compressed into a mountain of water that may grow to more than 100 feet (30.5 meters) tall. That water then comes crashing down on the shoreline.

Where tsunamis occur Ninety percent of the world's tsunamis occur in the Pacific Ocean. The Pacific lies above a geologically active section of Earth's crust called the Pacific plate. (Geologically active means that many earthquakes and volcanic eruptions occur along its boundaries.) On the eastern edge of the Pacific plate is the west coast of North America. The plate extends north to Alaska and the Aleutian Islands.

tsunami destroyed some 230 buildings, including the town's power plant, and flooded the streets with tons of sewage, mud, fish, and garbage. The bill for damages totaled more than $20 million. Eight hours later the tsunami hit Japan, where it killed many more people.

Tsunami hitting Hilo, Hawaii, 1946.

On its western edge the plate is bordered by Japan and it extends southward to Indonesia and New Zealand.

At least one tsunami strikes somewhere in the Pacific Ocean each year, and a tsunami with destructive force occurs about once every ten years. Many Pacific nations have long, exposed shorelines, making them especially vulnerable to the effects of tsunamis. The places that are battered by the greatest number of tsunamis include Japan, Hawaii, Alaska, Russia, the Philippines, Indonesia, and western South and Central America. (The west coast of the United States, which experiences tsunamis very rarely, is nonetheless within the zone where tsunamis are likely to occur.) Between the years 1690 and 1990, the three countries with the greatest number of tsunamis were: Japan, with more than 200; Indonesia, with more than 160; and Chile, with more than 150.

Tsunamis occur infrequently in the Atlantic Ocean and the Mediterranean Sea. In 1755, an earthquake centered in Lisbon, Portugal, caused a tsunami that swept onshore and killed thousands in Portugal, Spain, Madeira, France, the British Isles, the Azore Islands, and the West Indies. In 1908 a tsunami struck Sicily, killing some eight thousand people.

Tsunamis in the Atlantic Ocean are caused by undersea landslides more often than earthquakes. A 20-foot-tall (6-meter-tall) tsunami that struck the Virgin Islands and southeastern Puerto Rico in 1867, for instance, was caused by an undersea landslide.

Landslide-induced tsunamis Some of the largest tsunamis are produced by slides of vast quantities of material into bays and lakes. Often, the event that triggers the sudden falling of earth or rock is an earthquake. In Loen Lake, Norway, for example, a 230-foot (70-meter) tsunami swept ashore on September 13, 1936. That wave was generated by the cascading of about 1.25 million cubic yards (950,000 cubic meters) of rock into the water.

Lituya Bay, on the northeast shore of the Alaskan panhandle, experienced four tsunamis caused by landslides between the late-nineteenth and late-twentieth centuries. The deep-water bay, which has just a small opening to the sea, is surrounded by the steep, tree-covered, and rocky Fairweather Range of the Saint Elias Mountains. Three glaciers drape down the slopes and feed into the bay. The largest tsunami ever recorded in Lituya Bay occurred on July 9, 1958, when an earthquake shook a 400,000-square-mile (1 million-square-kilometer) area and caused 90 million tons (82 million metric tons) of rock to fall into the bay from 0.5 mile (0.8 kilometers) overhead. The cascading rocks triggered a 200-foot (60-meter) high tsunami that crashed onto the bay's opposite shore and surged as high as 1,700 feet (520 meters). The wall of water destroyed all vegetation on the mountain's rocky face, even uprooting some enormous trees and snapping others off at the base.

Volcano-induced tsunamis Volcanic eruptions are responsible for triggering a small percentage of tsunamis. When a volcano erupts, it emits ash and magma (molten rock) into the air. Part of the volcano wall, or cone, may break off during an eruption. If the volcano is partially or totally submerged, the material it ejects goes into the ocean and displaces water. When that happens, a tsunami forms.

Aerial photograph of Tamil Nadu, India, showing damage caused by the tsunami that struck the area in 2004. AP IMAGES.

A devastating tsunami was caused by a volcanic explosion on Krakatau, an island in Indonesia's Sunda Strait of the South Java Sea, on August 27, 1883. The volcano spit out 5 cubic miles (20 cubic kilometers) of rock and dirt, after which its peak collapsed, causing two-thirds of the island to sink into the ocean. Millions of gallons of ocean water were displaced and a tsunami was formed. Waves greater than 115 feet (35 meters) high (the height of a twelve-story building) struck the coasts of western Java and southern Sumatra (parts of Indonesia), where they killed more than thirty-six thousand people and destroyed 165 villages. A full-sized ship was carried 2 miles (3.2 kilometers) inland, and the sea was covered for miles with lightweight volcanic pumice stones that floated on the water and built up to a height of 7 feet (2.1 meters) above the surface in some areas. The explosion was heard nearly 3,000 miles (4,800 kilometers) away. The huge amounts of dust and ash emitted by the volcano rose 20 miles (32 kilometers) into the air and drifted four times around the world, causing brilliant red sunsets as far away as London, England, for the next six months or more.

Consequences of tsunamis

The consequences of a tsunami vary widely, depending on the wave's speed and height. The impact of a tsunami is also influenced by the physical characteristics of the ocean floor near the shore and the shore

Sanriku, Japan, socked by tsunamis

Japan has been hit by eight highly destructive tsunamis in the last four hundred years. The worst one occurred on June 14, 1896, when a series of waves, the tallest among them greater than 100 feet (30.5 meters), hit Sanriku on the eastern edge of the main island of Honshu some 300 miles (483 kilometers) north of Tokyo. The tsunami killed between twenty-two thousand and twenty-six thousand people and injured approximately nine thousand others. It destroyed 170 miles (274 kilometers) of coastline, including thirteen thousand homes. Twenty thousand of the dead were of the Shinto faith and had gathered for a festival on the beach at Sanriku. About three-quarters of the population of the neighboring town of Kamaish also lost their lives to the wave.

The tsunami was set in motion by an earthquake beneath the ocean floor, 93 miles (150 kilometers) to the east of Sanriku, at 7:00 PM that evening. Just 20 miles (32 kilometers) out to sea, the wave measured only 15 inches (83 centimeters) and passed undetected beneath the boats of fishermen. The waves reached shore fifty minutes after the earthquake. The fishermen returned to the port the next morning to discover the devastation.

Sanriku was hit again in 1933. The tsunami was caused by an earthquake that measured an incredible 8.9 on the Richter scale. Waves 75 feet (23 meters) tall swept onto shore, sinking eight thousand ships and washing away nine thousand houses. The wall of water killed about three thousand people.

itself, as well as the angle at which the wave strikes the coast. A tsunami's destructive potential is magnified when it squeezes into a funnel-shaped cove. In that case, the vast quantity of water is forced upward into an immense pile of water. Likewise, where the seafloor rises sharply, the tsunami also grows markedly in height. If, on the other hand, a seafloor rises gradually or the coast is protected by barrier islands, some of the tsunami's energy will be absorbed before it strikes the mainland. If a tsunami meets the coast at an angle it will be less forceful than meeting the coast head-on.

Another factor influencing tsunami strength is the tides, since the height of the tsunami wave combines with the tide as it reaches shore. A tsunami at high tide, therefore, will be larger than a tsunami at low tide.

If the coast consists of rocky cliffs, a tsunami will have little effect. If the coastline is relatively flat, in contrast, and contains villages or farms, the tsunami may surge far inland and create incredible damage. Some tsunamis crash down on the shore, shattering any structures they encounter. Other tsunamis force their way ahead like a bulldozer, lifting buildings from their foundations and carrying them inland. When the wave rushes back out to sea, it carries with it virtually everything in its path.

The destructive capabilities of a large, powerful tsunami, in terms of loss of life and property, are almost unimaginable. The wall of water may be as tall as a skyscraper and weigh millions of tons. It comes rushing onward at speeds as great as 150 miles (241 kilometers) per hour, obliterating communities in its path. A 20-foot-high (6.1-meter-high) tsunami traveling at 45 miles (72 kilometers) per hour packs a punch of about 8,000 pounds (3,640 kilograms) on an area the size of an average home's front door.

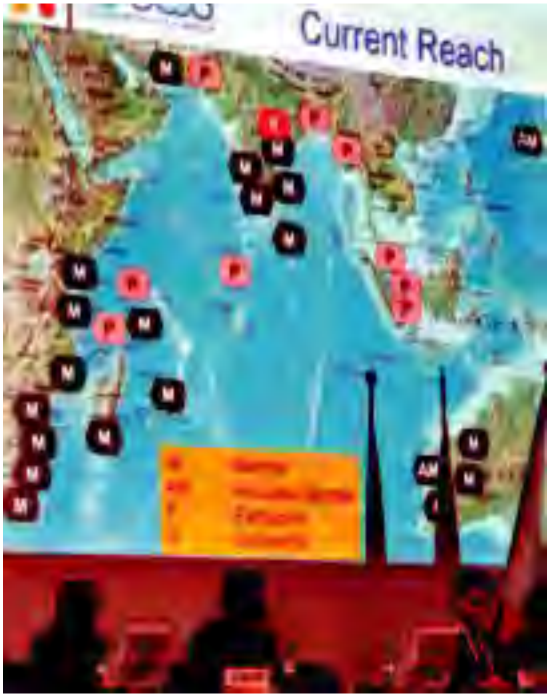
The technology connection

Technology is employed both to lower the death toll and to limit the destruction caused by tsunamis. Tsunami prediction systems, consisting of devices measuring earthquakes and wave patterns, alert coastal-dwellers to potential tsunamis so they can evacuate. Seawalls and tsunami-resistant buildings provide coastal settlements with a measure of protection against tsunamis.

Forecasting tsunamis Tsunami prediction has yet to be perfected. Even when a tsunami is detected at sea, it is difficult to determine how it will behave when it reaches land. As the twentieth century came to a close, oceanographers were pursuing the completion of an accurate tsunami warning system. (Note: The following information pertains to tsunamis that originate at sea and travel great distances before reaching land. When tsunamis are generated by local phenomena, such as offshore earthquakes, the waves reach shore in mere minutes, often before any warning can be sounded.)

Responsibility for monitoring ocean conditions and issuing tsunami alerts for the Pacific region falls to the Pacific Tsunami Warning Center (PTWC), located in Ewa Beach, Hawaii. The PTWC was established in 1948, two years after a tsunami killed 159 people in Hilo, Hawaii. The warning center relies on a network of seismographs (instruments used to detect and measure the vibrations caused by earthquakes) located around the world, as well as tidal stations (floating instrument centers that record water levels) throughout the ocean and near the shore.

The best indication that a tsunami may be brewing is the detection of an earthquake under or near the Pacific Ocean. When an earthquake occurs with a magnitude of 6.75 or greater, strong enough to create a



Plan of tsunami early warning system, Kobe, Japan, 2005. ©ISSEI KATO/REUTERS/CORBIS.

tsunami, a tsunami watch is communicated throughout the area. (Magnitude is the power of an earthquake; a magnitude of 7 produces major damage on land and a magnitude of 8 produces widespread destruction.) The tsunami watch instructs people to listen for further news, and forecasters then give the estimated time of arrival of the potential tsunami. They are able to make that prediction based on water depth at the earthquake's epicenter, the point on Earth's surface directly above the focus, or starting point, of an earthquake. Tsunami speed is directly related to water depth and the distance to shore.

Scientists next check readings from tidal stations near the epicenter of the earthquake. (Tidal stations are strategically located throughout the ocean and along the shores.) If a wave pattern resembling the characteristic up-and-down motion a tsunami is detected, a tsunami warning is posted. Forecasters then follow the progress of the tsunami by checking tidal stations along the waves' routes.

The problem with the current tsunami warning system is that oceanographers (scientists who study the ocean) have no way of determining what size a tsunami will be when it reaches shore. Vibrations caused by earthquakes, called seismic waves, that are detected at sea could be anything from inconsequential to devastating on shore. Complicating matters, the destructive potential of a tsunami depends not only the size of the wave but the physical features of the shoreline and the direction the wave is traveling.

Demonstrating the unreliable nature of tsunami prediction, about 75 percent of tsunami warnings (and subsequent evacuation of coastal-dwellers) in the latter half of the 1900s proved unnecessary. Experts fear that the more times residents are made to evacuate needlessly, the less likely they will be to take future warnings seriously and more likely they may be to choose to stay home when a real tsunami strikes. In addition, false alarms are expensive; an unnecessary evacuation of Honolulu in 1948, for example, cost more than $30 million.

New forecasting tools promise greater accuracy The Pacific Marine Environmental Laboratory (PMEL) of the U.S. National Oceanic and Atmospheric Administration is employing advanced technology to improve the accuracy of tsunami predictions. The Deep-Ocean Assessment and Reporting of Tsunamis (DART) system includes six research stations and sophisticated computer models for forecasting tsunamis. DART has deployed around nineteen buoys in addition to the surface stations and several coastal weather stations operated by the National Weather Service. In 2003, the operation of DART was transferred to the National Data Buoy Center, a part of the U.S. National Tsunami Hazard Mitigation Program (NTHMP). The DART system will enable NTHMP to issue tsunami warnings, with great accuracy, within one hour of an earthquake in the Pacific region.

Okushiri Island, Japan, after an earthquake and a resulting tsunami. AP IMAGES.

The research stations are strategically placed throughout the Pacific Ocean. Each station uses a bottom pressure recorder, which is an instrument on the ocean floor that measures tsunami wave heights with a precision of 0.04 inch (1 millimeter). The recorder transmits the wave-height information to the tsunami forecasting center. Each time an earthquake is detected somewhere in the Pacific, data from the recorder is plugged into the computer model that predicts how the wave will behave across the ocean and on the coasts.

Coastal construction Tsunamis typically wash away buildings they encounter. The damage they inflict is due both to the force of the water and the debris it sweeps along. In some beachfront areas, builders are tackling this problem by creating structures that can withstand the force of a tsunami. They use frames of steel and concrete, with windows and walls that easily give way to the rushing water. With that type of construction, the tsunami crashes through the building yet leaves the frame intact. Occupants of tsunami-resistant high-rise hotels can "evacuate" to

Japanese tale recounts Shimoda tsunami

On December 24, 1854, an earthquake off the shore of Japan caused a tsunami. The 30-foot (9-meter) wave entirely washed away numerous seaside villages along the Pacific coast of the island of Honshu. In the village of Hiro, near the city of Wakayama, the residents' lives were saved by the quick thinking of the town squire (a local dignitary of a rural district or small town), by the name of Gohei. The story of how Gohei saved Hiro is printed in many Japanese primary school texts. The following account was reproduced in the essay "The Role of Public Education and Awareness in Tsunami Hazard Management" by M. I. El-Sabh, included in *Tsunami: Prediction, Disaster Prevention and Warning,* Y. Tsuchiya and N. Shuto, eds., 1995. (Netherlands: Kluwer Academic Publishers. Note: All of this was reprinted in *Tsunami* by Walter C. Dudley and Min Lee, pp. 296–297.)

> "It is not normal," Gohei muttered to himself as he came out of his house. The earthquake was not particularly violent. But the long and slow tremor and the rumbling of the earth were not of the kind old Gohei had ever experienced. It was ominous.
>
> Worriedly he looked down from his garden at the village below. Villagers were so absorbed in the preparation for a harvest festival that they seemed not to notice the earthquake.
>
> Turning his eyes now to the sea, Gohei was transfixed at the sight. Waves were moving back to the sea against the wind. At the next moment the expanse of the sand and black base of rocks came into view.
>
> "My God! It must be a tsunami," Gohei thought. If he didn't do something, the lives of four hundred villagers would be swallowed along with the village. He could not lose even a minute.
>
> "That's it!" he cried and ran into the house. Gohei immediately ran out of the house with a big pine torch. There were piles of rice sheaves lying there ready for collection. "It is a shame I have to burn them, but with this I can save the lives of the villagers." Gohei suddenly lighted one of the rice sheaves. A flame rose instantly fanned by the wind. He ran frantically among the sheaves to light them.
>
> Having lit all the sheaves in his rice field, Gohei threw the torch away. As if dazed

the upper floors if a tsunami hits with little warning. The high cost of this type of construction, however, is too expensive for many developing Pacific nations.

Seawalls made of reinforced concrete also provide protection to communities at risk for tsunamis. These structures block tsunamis, as long as the water remains below the height of the seawall. Some settlements in tsunami-prone areas simply deal with the problem by not allowing construction along the coast where tsunamis are likely to strike.

he stood there and looked at the sea. The sun was already down and it was getting dark. The fire of the rice sheaves rose high in the sky. Someone saw the fire and began to ring the bell of the mountain temple.

"Fire! It is the squire's house!" Young men of the village shouted and ran hurriedly to the hill. Old people, women and children followed the young men. To Gohei, who was looking down the hill, their pace seemed as slow as ants. He felt impatient. Finally about twenty young men ran up to him. They were going to extinguish the fire. "Leave them! There will be a disaster. Have the villagers come here." Gohei shouted in a loud voice. The villagers gathered one by one. He counted the old and young men and women as they came. The people looked at the burning sheaves and Gohei in turn.

At that time he shouted with all his might. "Look over there! It is coming." They looked through the dim light of dusk to where Gohei pointed. At the edge of the sea in the distance they saw a thin dark line. As they watched, it became wider and thicker, rapidly surging forward.

"It is a tsunami!" someone cried. No sooner than they saw the water in front of them as high as a cliff, crashing against the land, they felt the weight as if a mountain was crushing them. They heard a roaring noise as if a hundred thunders roared all at once. The people involuntarily jumped back. They could not see for a while anything but clouds of spray which had advanced to the hill like clouds.

They saw the white fearful sea passing violently over their village. The water moved to and fro over the village two or three times. On the hill there was no voice for a while. The villagers were gazing down in blank dismay at the place where their village had been. It was now gone without a trace, excavated by the waves.

The fire of the rice sheaves began to rise again fanned by the wind. It illuminated the darkened surroundings. The villagers recovered their senses for the first time and realized that they had been saved by this fire. In silence they knelt down before Gohei.

A matter of survival

Imagine yourself enjoying a day at the seashore when the water suddenly recedes, leaving fish flopping and boats stranded, and uncovering rocks you never knew were there. At the same time, the sea makes a great hissing noise. These are sure signals that a tsunami is coming. The rushing away of water merely means that a trough, rather than a peak, of a wave has hit first. You can expect the first wave to wash ashore in as little as five minutes, although it may take as long as two hours. Don't

Notable tsunamis in history

- In 1868, a major earthquake in Chile unleashed a deadly tsunami that struck the northern Chilean city of Arica. Sixty-foot (18-meter) waves inundated the city, sweeping away houses, flooding streets, and destroying ships in the harbor. More than 25,000 people died in the disaster.
- In May 1960, an earthquake off the coast of south-central Chile sent waves across the ocean to Hawaii and Japan. Within minutes of the earthquake, waves killed up to 2,000 people along the coasts of Chile and Peru. The tsunami reached Hilo, Hawaii, fifteen hours later, killing 61 people. Twenty-two to twenty-three hours after that, the tsunami reached Japan, where it drowned 199 people. Total damages due to the tsunami were in excess of $500 million.
- In March 1964, the strongest earthquake ever measured in North America (9.2 on the Richter scale) occurred in Prince William Sound near the Alaskan Kenai Peninsula. The quake set in motion a tsunami that was 30 feet (9.1 meters) tall when it struck the coast at Seward. The rush of water knocked the lids off oil storage tanks, creating a fire that rode and spread on top of the waves. Many coastal settlements were wiped out, and the death toll in Alaska from the tsunami was 106. (The quake itself killed an additional nine people.) The tsunami continued down the coast of the United States. It killed four people on the shore in Oregon, then smashed into the shore at Crescent City, California, in a series of four waves. The last of the four, which at 20 feet (6.1 meters) was the tallest, drowned eleven people. The tsunami traveled so far south that its ripples were detected on the coast of Antarctica.

wait around to see it! Immediately move away from the water to higher ground.

If you live in an area where tsunamis happen, which includes all places with elevations less than 50 feet (15 meters) above sea level along the Pacific coasts, it is important to learn your evacuation route out of town. If a tsunami warning is issued, you may have just minutes, or possibly even seconds, to act. Turn off the water, gas, and electricity in your home and get to higher ground.

Don’t feel that it is safe to return after the first wave has passed. Remember that a tsunami is a series of waves and the first one is often the mildest. The second or third, or even the seventh or eighth wave may be the most powerful. Avoid the danger area until you hear the all-clear signal on radio or television broadcasts.

All buildings in the tsunami warning area should be checked for gas leaks or electrical shorts before being reoccupied. When you return home,

- In August 1976, a major earthquake off the shore of the Philippines triggered a tsunami that left 5,000 (by some estimates as many as 8,000) dead in the Moro Gulf area of Mindanao island.
- The Indonesian island of Flores in December 1992 received a tsunami that left nearly 2,500 people dead and hundreds injured. Thousands of people were left homeless. The tsunami was caused by an earthquake 19 miles (30.6 kilometers) away in the Flores Sea.
- More than 120 (by some estimates as many as 180) people were killed in July 1993 when a 100-foot-tall (30.5-meter-tall) tsunami crashed into the tiny island of Okushiri, in northwestern Japan. The waves were produced by an earthquake that had occurred just five minutes earlier in the Sea of Japan. Damages were estimated at $600 billion.
- On December 26, 2004, the deadliest and most devastating tsunami in recorded history struck the coastline in Indonesia and around the Indian Ocean, eventually reaching as far away as Bangladesh, India, Sri Lanka, the Maldives, and even further in Somalia, Kenya, and Tanzania on the eastern coast of Africa. Approximately 230,000 people were killed.
- A 7.7 magnitude earthquake shocked the Indian Ocean seabed again on July 17, 2006, 125 miles (200 km) south of Pangandaran, a beautiful beach popular with surfers. This earthquake triggered tsunamis whose heights varied from from 6 feet (2 meters) at Cilacap to 18 feet (6 meters) at Cimerak Beach, where it swept away and flattened buildings as far as 1300 feet (400 meters) away from the coastline. More than 600 people were reported killed, and around 150 others were missing.

have your food and water checked for contamination. Toss out contaminated food; if the water source is deemed unsafe, you must boil it before drinking.

[*See Also* **Climate; Earthquake; Volcano; Weather: An Introduction**]

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Volcano

Harry Truman (not the former president of the same name) lived at the Mount St. Helens Lodge on the shore of Spirit Lake at the foot of Mount St. Helens. He had run the Lodge since 1928. Even though he was warned that the mountain could erupt at any time, he refused to leave. Some people consider him a hero and symbol of personal freedom and independence. Others consider him just an ecentric old man who refused to heed appropriate warnings. It no longer matters, because Mount St. Helens erupted with enormous destructive force on May 18, 1980, obliterating both Mount St. Helens Lodge and parts of Spirit Lake. Harry Truman's body was never found.

Mount St. Helens was a dormant volcano that sprang back to life after a long quiet period. A volcano is an opening, or vent, in Earth's surface through which lava, ash (very small pieces of lava or rock), gas, and rock fragments escape. Below the vent is a passageway, called a pipe, that leads down to a reservoir of molten rock, or magma, below the surface. When a volcano erupts, the magma and gases it contains emerge from underground. An eruption may look like curtains of fire, rivers of red-hot lava (magma above ground is called "lava"), or exploding clouds of rock fragments, ash, and dust.

The material ejected by volcanoes forms hills or mountains around the vent. Those landmasses, which are usually cone-shaped and may rise to 19,000 feet (5,800 meters) or higher, are the objects most people think of as volcanoes. Some volcanoes exist singly, looming over a flat landscape, while others exist in groups and form mountain ranges. Volcanic eruptions throughout history have played a major role in shaping Earth's surface. Most volcanoes, however, are not visible because they exist beneath the sea.

Volcanoes may be active, dormant, or extinct. An active volcano is one that has erupted, or shown signs of erupting, in recent times and is likely to erupt in the future. A dormant volcano is one that has not erupted for many years, but may still roar back to life. It is not unusual for

Eruption of Mount St. Helens, Washington, 1980. ©GARY BRAASCH/CORBIS.

volcanoes to go one hundred years between eruptions. An extinct volcano is one that has not erupted since the beginning of recorded history and that scientists are reasonably sure will never erupt again. Extinct-volcano cones are gradually eroded by the action of wind, rain, and ice.

There are about six hundred active volcanoes on Earth today. Some fifty volcanoes worldwide erupt every year; at least one of those eruptions disrupts human lives and settlements. During the decade from 1980 to 1990, about 26,000 people were killed and nearly 450,000 had to flee their homes due to volcanic activity.

The eruption of Mount St. Helens

Mount St. Helens, located in southwestern Washington State in the Cascade mountain range, erupted on May 18, 1980. It was one of the most violent eruptions in modern history, equivalent in its power to the

WORDS TO KNOW

active volcano: a volcano that continues to erupt regularly.

ash: very small, fine fragments of lava or rock that are blasted into the air during volcanic explosions.

basalt: a type of rock that forms from hardened lava.

caldera: a large depression, usually circular or oval shaped, left behind when a volcano's summit collapses.

cinder: a small piece of material thrown from a volcano during an eruption.

cinder cone: a volcanic cone made of lava fragments.

composite volcano: a volcano with steep sides made of layers of lava and ash.

cone: the sloping outer sides of a volcano (not all volcanoes have cones).

conelet: a small cone on the side of a large volcano.

continental drift: the geologic theory that all continents were originally part of a single landmass before they slowly separated and drifted apart.

crater: the bowl-shaped area around the opening at the top of a volcano.

crust: the outermost layer of Earth, varying in thickness from 3.5 miles (5 kilometers) under the ocean to 50 miles (80 kilometers) thick under the continents.

dormant volcano: a volcano that has not erupted for many years.

effusive eruption: the type of eruption in which lava spills over the side of a crater.

eruption: the release of pressure that sends lava, rocks, ash, and gases out of a volcano.

extinct volcano: a volcano that is never expected to erupt again.

fissure: a crack in Earth's surface through which volcanic materials can escape.

flood basalt: high temperature basaltic lava that flows from a fissure in Earth's crust and covers large areas of the landscape. Also known as plateau basalt.

fumarole: a vent in Earth's surface that releases steam and other gases, but generally no lava.

geologist: a scientist who studies the origin, history, and structure of Earth.

geyser: a regular spray of hot water and steam from underground into the air.

hot spot: an area beneath Earth's crust where magma currents rise.

igneous rock: rock made of solidified molten material that made its way from the interior of the planet to the surface.

lahar: a mudflow of volcanic ash and water that sometimes occurs after a volcanic eruption.

lava: molten rock that erupts from a fissure or a vent (see magma).

lava domes: volcanic formations built up from layers of viscous lava, which does not flow far from its source.

lava tube: a tube formed when an outer layer of lava is cooled by the air and hardens and molten lava then flows out of the middle of the tube, leaving it hollow.

largest hydrogen bomb ever exploded. The eruption destroyed 212 square miles (550 square kilometers) of land and claimed sixty-two human lives. Mount St. Helens was the first volcano to erupt in the continental United States (excluding Alaska and Hawaii) since California's Lassen Peak in 1917, and the first eruption in recorded history to claim a life in the continental United States.

Mount St. Helens is classified as a composite volcano (a steep-sided, often symmetrical cone constructed of alternating layers of lava flows, ash, and other volcanic debris). Composite volcanoes, other examples of which include Mount Vesuvius and Krakatau, tend to erupt explosively. Mount St. Helens was no exception.

Prelude to the eruption After being dormant since 1857, Mount St. Helens came alive in March 1980. In the two months before the eruption, Mount St. Helens experienced more than ten thousand small earthquakes and hundreds of small eruptions involving blasts of steam. Also during that time, the north slope of the volcano bulged outward more than 260 feet (80 meters). On March 27 there was an explosion that created a 200-foot (60-meter) hole in the mountainside. The next day a plume of steam, ash, and gas erupted from the volcano and rose 4 miles (6.4 kilometers) into the atmosphere.

Evacuation advised Scientists advised people in the area to evacuate, warning that a larger eruption was likely to occur. Park officials closed Mount St. Helens to campers, hikers, bikers, loggers, fishermen, and others drawn to the popular recreation spot. They established an area called the Red Zone, which they declared was in the greatest danger should the volcano fully erupt, and placed roadblocks around the perimeter. A small number of backpackers and loggers, however, continued to enter the area through old logging roads. One group whose presence at Mount St. Helens *was* sanctioned by authorities was a scientific team of the United States Geological Survey (USGS). More than twenty-four volcano-watchers were assigned to monitor the mountain.

Eruption triggered by earthquake At 8:27 on the morning of May 18 there was a magnitude 5.1 earthquake directly below the north slope. (The Richter scale of earthquake magnitudes is a measure of the damage caused by an earthquake.) This weakened the crater rim (the edge of the bowl-shaped area around the opening), and about ten seconds later the bulging and cracked north face of the volcano collapsed and slid downward at 110 to 155 miles (175 to 250 kilometers) per hour in the largest landslide in recorded history. As the landslide swept across Spirit Lake, it displaced all of the water in the lake and created waves 600 feet (180 meters) high that crashed into a ridge north of the lake. When the water rushed back into the lake basin, it dragged with it thousands of trees that had just been knocked down by the explosion.

As the cone crumbled, gas was released and the magma was exposed. The avalanche of rock that exposed the magma removed the last restraint to eruption, and the magma exploded outward in a lateral blast of hot gas, steam, ash, and rock fragments. The blast was heard all the way in Vancouver, Canada, some 200 miles (300 kilometers) away. Instead of moving straight upward, as material in explosive eruptions usually does, the material in this case traveled sideways to the north and overtook the landslide where the crater rim had been destroyed. The 572°F (300°C) pyroclastic flow (flow of hot ash and gas) raced across the ground at speeds approaching 680 miles (1,100 kilometers) per hour and burned everything it touched. The flying debris, gas, and heat killed millions of animals including deer, elk, birds, and other animals. The windstorm produced by the eruption flattened trees. It was powerful enough to pick up and toss around logging trucks and bulldozers several miles (kilometers) from the vent.

The heat from the eruption melted snow and ice on the volcano. This water combined with ash and chunks of ice to form mudflows called lahars (pronounced LAH-hahrs). The lahars filled riverbeds and lakes, and buried houses, roads, and bridges. Millions of trout

Famous volcano eruptions

Volcano eruptions have had a major impact on world cultures since the beginning of recorded history. Here are a few of the most famous eruptions:

- 79—Vesuvius, Italy. The cities of Pompeii and Herculaneum were destroyed by this eruption.
- 1783—Laki, Iceland. This eruption lasted eight months and killed most of the area livestock. The animals died after eating plants contaminated by gases and rain poisoned by the eruption. A quarter of the residents of the surrounding area died in the famine caused by the eruption.
- 1792—Unzen, Japan. The collapse of a lava dome in this volcano caused a tsunami that killed nearly 15,000 people. This was Japan's worst volcano-related disaster. The volcano was dormant for nearly 200 years after this event, but began showing signs of activity again in the early 1990s.
- 1883—Krakatau, Indonesia. This eruption destroyed the uninhabited volcanic island of Krakatau, triggering massive tsunamis that killed more than 35,000 in coastal communities in the vicinity.
- 1995—Soufrière, Montserrat. The volcano on this Caribbean island had not erupted in all of recorded history, but began showing signs of activity in the 1960s. In 1995, it began producing destructive pyroclastic flows, and continued to do so for two years. About 7,000 of the island's 10,000 residents were forced to evacuate.

and salmon died in the mud-choked rivers. The flow of the Columbia River, a main thoroughfare to the Pacific Ocean, was blocked by mud. Thirty ocean-bound vessels were trapped behind the mud dam.

Ash travels far and wide/ The eruption, which lasted nine hours, sent a cloud containing millions of tons of dust and ash 15 miles (24 kilometers) into the air. The cloud spread across 22,000 square miles (57,000 square kilometers) of western U.S. skies, blocking out the Sun. Residents of Yakima, Washington, 85 miles (137 kilometers) from Mount St. Helens, experienced complete darkness throughout the day of the eruption and had to wear face masks when venturing outside. Ash fell to the ground over the next few days, blanketing crops in parts of Washington, Oregon, and Idaho.

Fifty-seven lives lost In all, fifty-seven lives were lost in the Mount St. Helens eruption. Most of the victims choked to death on volcanic ash. People as far as 18 miles (29 kilometers) to the north of the volcano were killed by heat, ash, showering rocks, and lethal gases in the eruption. It had been determined that 16 miles (26 kilometers) from the volcano was a safe distance, yet experts never predicted the volcano would spew its stream sideways. One of those who lost their lives was David A. Johnston, a thirty-year-old member of the USGS volcano-monitoring team. Johnston had been stationed 6 miles (9.7 kilometers) north of the volcano. His final words by radio to the local USGS office in Vancouver, Washington, were, "Vancouver! Vancouver! This is it!" Johnston's body was never found.

One person who narrowly made it out alive, after stumbling through the dark landscape for nine hours, was a television cameraman, David Crockett. He captured the fear of the moment on audio tape. "I can hear the mountain rumbling behind me," Crockett said in the recording. "I feel the ash in my eyes. Oh dear God, this is hell . . . it's a black hell, totally pitch black. . . . Dear God, help me breathe. I can't see a thing. . . . I honest to God believe I'm dead."

Changes to the mountain Before the eruption, Mount St. Helens had stood at 9,420 feet (2,870 meters) and was the fifth-tallest mountain in Washington. The mountain lost its uppermost 1,300 feet (400 meters) in the eruption, dropping it to the fifteenth-tallest peak in the state. The pre-eruption Mount St. Helens had been a nearly perfect cone shape, picturesque with its cap of snow and ice. During the eruption, however, the

WORDS TO KNOW

magma: molten rock containing dissolved gas and crystals that originates deep within Earth. When it reaches the surface it is called lava.

magma chamber: a reservoir of magma beneath Earth's surface.

mantle: the thick, dense layer of rock that lies beneath Earth's crust. The mantle is about 1,800 miles (2,900 kilometers) thick and accounts for about 84 percent of Earth's volume.

pipe: a narrow passageway that leads from a magma reservoir to a vent.

plate: a large intact section of Earth's crust.

plate tectonics: the geologic theory that Earth's crust is composed of rigid plates that are in constant motion with respect to each other, creating the major geologic features on the planet's surface.

Plinian eruption: a volcanic eruption that releases a deadly cloud of gas, dust, and ash.

pumice: volcanic rock formed during the explosive eruption of magma; it has numerous gas bubbles and may float on water.

pyroclastic flow: a rapid flow of hot material consisting of ash, pumice, other rock fragments, and gas ejected by an explosive eruption.

Ring of Fire: the name given to the geologically active belt that surrounds the Pacific Ocean and is home to more than 75 percent of the world's volcanoes.

shield volcano: a volcano with long, gentle slopes, built primarily by lava flows.

steam eruption: a violent eruption that occurs when water comes in contact with magma, rapidly turns to steam, and causes the mixture to explode.

subduction zone: a region where two plates come together and the edge of one plate slides beneath the other.

vent: an opening in the surface of Earth through which molten rock, lava, ash, and gases escape.

volcano: an opening in the surface of Earth (vent) through which molten rock, lava, ashes, and gases escape; it is also the name for the mountain or hill that is formed by the lava and other erupted material.

crater and north side of the mountain, including the crater rim, were destroyed, leaving the crater clearly visible. After the eruption, the forests that formerly adorned the mountainside lay in ruins, wildlife was nowhere to be seen, lakes had become pools of mud, and a grayish layer of muck covered everything.

Just a few months after the eruption plants and animals began to reappear on Mount St. Helens. First, thistles that had survived the eruption emerged through the layer of ash. The rains washed away the ash and exposed the soil. Seeds blew in from surrounding areas or were dropped by birds. Four months after the eruption, fireweed began

Mount Vesuvius: Destruction preserved

In 79 CE, Mount Vesuvius shook the Roman Empire with a mighty eruption—perhaps the most famous eruption in history. The volcano, near Naples, Italy, had been quiet for hundreds of years. In the years 63 CE through 79 CE Vesuvius awoke with a series of earthquakes. On August 24, 79 CE, an enormous blast jolted the ground. Ash and lava blew out of the top of the volcano and rained down on the mountainside for hours, setting fire to vineyards and fig orchards. Ash clouds also rose and blocked out the sun.

Some people in the prosperous town of Pompeii (population twenty thousand) just south of the mountain, fled at the first signs of eruption and escaped with their lives. Others were trapped in the city and suffocated in the ash cloud. Before long, pyroclastic flows descended on all sides of the mountain, engulfing the smaller towns of Herculaneum and Stabiae, as well as Pompeii. In all, more than two thousand people (possibly many more) were killed by flows of hot gas, ash, and mud.

A detailed written record of the event was made by an eighteen-year-old scholar named Pliny the Younger. Pliny and his mother watched the eruption from 20 miles (32 kilometers) away, in the town of Misenum across the Bay of Naples. Pliny's uncle, Pliny the Elder, a celebrated natural historian, was at the foot of Vesuvius during the eruption and suffocated from the poisonous gases.

Pompeii lay buried under 23 feet (7 meters) of rock, ash, and dust, undisturbed for more than fifteen centuries. Then, in 1595, workers digging a tunnel in the area encountered the ruins of Pompeii. They found buildings, vases, statues, and other artifacts. A systematic excavation of Pompeii did not begin until 1860. The Italian government in that year began overseeing an effort to unearth the entire city—an effort that continues today.

What was uncovered was an archaeologist's treasure trove. Pompeii's streets, houses, stores, theaters, and sports stadium stood as they were when buried. Paintings were still on walls. Intact loaves of bread and bowls of figs and walnuts were recovered; all had had been carbonized (turned to charcoal).

Most remarkable were the remains of people trying to flee when overtaken by poisonous gas or hot ash. While the body tissues had disintegrated, the ash covering the bodies had formed cement-like molds around the spaces where their bodies had been. Hollow areas with only skeletons inside were excavated. These casts represented people in

blooming on the edges of the eruption area. Other plants began to reappear and, slowly but surely, wildlife returned to the region.

Continuing volcanic activity After the May 18 blast, a new vent opened in Mount St. Helens. Volcanic activity, in the form of puffs of steam and ash, continued for months. Thick, pasty lava emerged from the vent and formed a new cone in the crater. By 1986 the cone had grown to a height of 850 feet (260 meters) and had a diameter of about 3,600 feet (1,100 meters). Mount St. Helens is expected to erupt again sometime in the future, but no one can say when.

the positions they had assumed at the moment of death. Many were covering their faces, protecting their children, or clutching their chests as if trying to breathe. The historians and scientists directing the excavation had the molds turned into statues by pouring plaster into the hollow areas. The ruins of Pompeii remain a popular tourist attraction.

There was a repeat of the Mount Vesuvius tragedy in 1631, when an eruption took the lives of some three thousand people. Since that time, Vesuvius has not erupted explosively. While the region continues to be heavily populated, residents are now evacuated when signs of volcanic activity appear.

Aerial view of the ancient Roman town of Pompeii, 2005. Mount Vesuvius is in the background. AP IMAGES.

Mount St. Helens remains active and has experienced several eruptive events since 1980. On October 1, 2004, the mountain ejected a plume of steam and ash to about 9,700 feet (2,950 meters). There were several more steam and ash eruptions over the next few days, along with low-frequency seismic tremors that may indicate movement of magma. One of the most significant recent eruptive events occurred on March 8, 2005, when a 36,000-foot (11-kilometer) plume of steam and ash was witnessed emerging from the volcano, accompanied by a tremor that measured about 2.5 on the Richter scale. If expansion continues at its present rate, the lava dome that has been growing inside the crater will replace all of the material lost in the 1980 eruption within another forty to fifty years.

Despite the continued activity, most trails in Mount St. Helen's National Monument are now open to visitors. It is even possible to climb a summit trail and look down into the crater and view the growing lava dome.

The legend of Atlantis

Most people are familiar with the legend of Atlantis from books and movies. This "lost continent" was mentioned in the writing of the ancient Greek philosopher Plato. Plato recounted the story that Solon, a Greek statesman of the seventh century BCE, supposedly heard from priests at an Egyptian temple. These priests told Solon of a mythic island inhabited by an advanced race about 9,000 years before Plato's time, or nearly 10,000 BCE.

According to legend, the island suffered a cataclysm of some sort and disappeared into the sea. There had been little evidence to support this legend until it was hypothesized that a translation or math error might have caused the date of the disappearance of Atlantis to be placed 9,000 years in the past instead of 900 years in the past. Interestingly enough, 900 years before Plato's time, there was a catastrophic volcanic eruption on the island of Santorini, destroying the island and triggering massive tsunamis. Archaeological evidence now suggests that a highly developed civilization had inhabited Santorini about 3,800 years ago. This has led some historians to speculate that the fate of Santorini might be the foundation for the "Atlantis" legend.

Dangerous science: How volcanoes work

The source of volcanic activity is many miles (kilometers) below ground, in Earth's upper mantle. The interior of Earth is divided into layers, distinguished by their material composition. The core, at the planet's center, which is some 3,975 miles (6,395 kilometers) from the surface, has a solid inner portion and a liquid outer portion. Temperatures in the core are believed to exceed 9,900°F (5,480°C). Surrounding the core is the thick, dense layer of rock called the mantle.

The mantle is divided into two sections: the upper and the lower. It is in the upper mantle, the 40-mile-thick (65-kilometer-thick) section farthest from the core, that magma originates. In the upper mantle, magma exists as a solid mass that is held together by tremendous pressure. The pressure there is about forty thousand times greater than it is on the planet's surface.

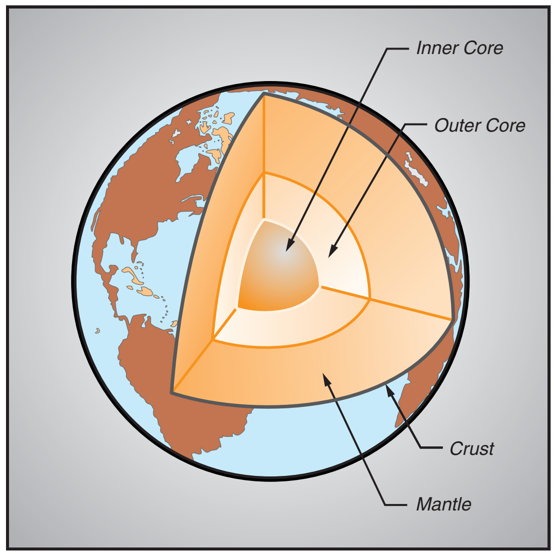
The layer adjacent to the upper mantle is the crust. The crust, which forms Earth's surface, is the thinnest layer. It ranges in thickness from 3 to 35 miles (5 to 50 kilometers) It is thinnest under the ocean basins and thickest under the continents. The crust is divided into several large, interlocking pieces, called tectonic plates (or simply "plates"), which "float" on the mantle. There are seven major and eight minor plates. The plates move very slowly, about 2 to 4 inches (5 to 10 centimeters) per year (about the speed at which fingernails grow), in response to slow-moving convection currents in the mantle beneath them.

The majority of the world's volcanoes are found along the boundaries between plates; specifically, plates that are moving toward each other. When two plates come together, one plate may slide beneath the other, forming a region called a subduction zone. As one plate slowly plunges beneath another, the rock at the leading edge of the buried plate melts. That molten rock, which is less dense than the surrounding crust, then rises toward the surface. Driven by pressure created by trapped gas, the magma forces its way through the weakened layers of rock at the plate boundary and emerges through cracks at the surface. Plates can also pull apart. This is happening along the center ridge of the Atlantic Ocean in a process called seafloor spreading. This process can allow molten magma to burst through the ocean floor creating volcanoes. Iceland is part of this ridge and is also the location of several volcanoes.

When magma reaches a crack or hole in the surface, tremendous pressure is released. The magma, which is about 3,270°F (1,810°C), becomes fluid and runs over the ground. At this point it is called lava. Lava may glow brightly, the color of fire, or may be coated with a layer of blackened rock. The lava cools as it travels along the surface and, in time, hardens.

On the shelves: *Fire in the Sea*

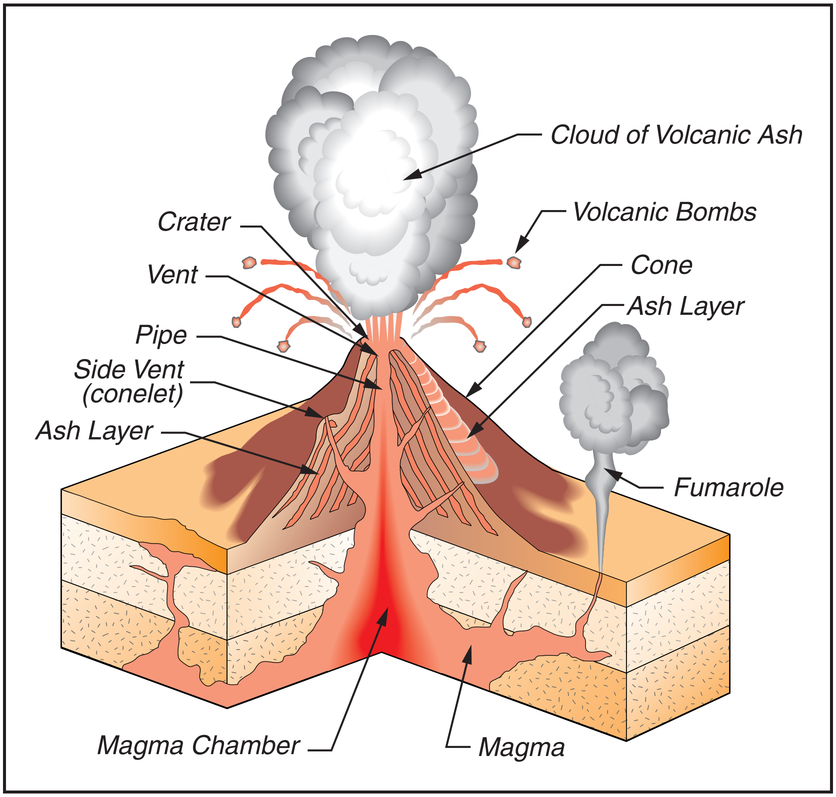
Published in 2000, this examination of the effects of the eruption of Santorini in about 1650 BCE offers possible links between Santorini and the legend of the "lost continent" of Atlantis. Written by Walter L. Friedrich, the book is a carefully constructed case study of one of the biggest natural disasters of the Bronze Age.



Cross-section of Earth.

Anatomy of a volcano The cone-shaped structure we typically think of as a volcano is actually piled-up material (lava, ash, and rocks) that has been ejected during previous eruptions. This landform is called a cone. Smaller cones, called conelets, often form on the slopes of main cones. One of the world's most active volcanoes, Kilauea in Hawaii, for instance, is a conelet on the larger Mauna Loa volcano.

The volcano itself is the opening in the ground through which material erupts. That opening is called a vent. The vent is typically at the center of a crater (a wide, round opening), which is situated at the top of the cone. When the volcano is inactive, the crater may fill with water,



Cross-section of a volcano.

snow, ice, or rocks. Some craters continuously hold pools of bubbling molten rock.

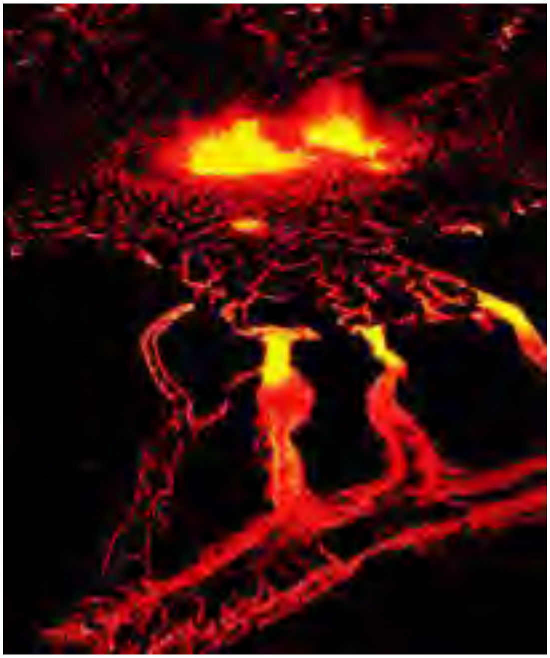
Below the vent is a passageway, called a pipe. The pipe leads down to the magma chamber, a pool of magma in the upper mantle. In some eruptions, magma forces its way through the pipe and out of the vent. In others, magma flows upward and sideways between layers of rock until it finds a weak area at the surface and breaks through. Magma may also reach the surface by melting its way through layers of rock in the crust, near the volcano, or along the sides of the volcano.

Types of eruptions When volcanoes erupt, they spew out gases such as carbon dioxide, nitrogen, and sulfur dioxide. (Poisonous gases cause more deaths than any other substance emitted by volcanoes.) Other materials that may be ejected include lava, steam, and fiery rock fragments (known as pyroclastics) of various sizes. The escaping gases have so much force that they blast hot rock into billions of minuscule pieces, forming a choking cloud of ash and dust. Boulders called volcanic bombs and weighing up to 100 tons, may be thrown out during eruptions. Large rocks usually land near the vent, but are sometimes tossed several miles. Eruptions commonly deposit deep layers of pumice (rock that contains numerous air holes and floats on water) and burned lava pieces.

Volcanic eruptions range in intensity from little puffs of ash and gas to explosions that produce glowing clouds of ash and dust and spew material far across the land. The intensity of the eruption depends upon the density and composition of the magma, the shape and size of the vent, and the presence or absence of water. The most explosive eruptions occur in volcanoes that sit on subduction zones, such as the Cascade Mountains.

Volcanic eruptions in which lava spills from the vent into the crater, sometimes overflowing the rim and running down the sides, are called

Molten lava glows against a night sky in Iceland. NATIONAL AUDOBON SOCIETY COLLECTION/PHOTO RESEARCHERS, INC.



Flowing lava, Kilauea, Hawaii. JLM VISUALS.

effusive eruptions. Effusive eruptions occur when magma is runny, has a high gas content, and has low concentrations of a mineral called silica. (Silica is the mineral that forms quartz, sand, and flint.) The volcanic gas does not explode during eruptions because it can escape from the lava relatively easily. Sometimes escaping gas causes lava to spray high into the air, creating brilliant displays of fire. The volcanoes of Hawaii, for example, experience effusive eruptions.

The volcanoes of the Cascade Mountain Range in the northwestern United States, in contrast, undergo explosive, violent eruptions. The magma in the Cascade volcanoes is thick and viscous. It tends to trap volcanic gases. As the pressure on the magma is released, the gases expand within the magma. Eventually, the gases burst through the surface of the magma, with a great explosion. The magma is shattered into tiny pieces and thrown high into the atmosphere. The tiniest fragments are volcanic ash. They can remain suspended in the air for days or weeks. The larger fragments rain down on the cone and flow down its sides at tremendous speeds. The river of fragments can mix with heated gas and air to form hot and dangerous pyroclastic flows. If this mixture encounters water, destructive lahars are the result.

A steam eruption can be another violent form of eruption. This outburst occurs when water, either from underground rocks or the sea, comes in contact with magma. The water turns to steam, expands outward rapidly, and the mixture explodes. An example of a steam eruption occurred in 1883 at Indonesia's Krakatau volcano.

A particularly deadly type of eruption is the Plinian eruption. In this kind of eruption the volcano releases a suffocating cloud of gas, dust, and ash that can cover great distances. The eruption of Mount Vesuvius in 79 CE, in which some two thousand people died, is a famous example of a Plinian eruption. The name "Plinian" comes from the Roman writer Pliny the Younger, who provided a written record of the Vesuvius eruption.

Some explosive eruptions are due to the presence of hardened lava or boulders over the vent. Material that blocks the vent is called a cap or a plug. The cap prevents magma from breaking through to the surface for a while. When enough pressure builds up beneath the plug or cap, the magma pushes away the cap and bursts through explosively. Some of the most powerful eruptions in history have occurred on volcanoes that have been blocked.

In some very violent eruptions, large portions of the top or side of the cone are destroyed, and the sides of the crater collapse. This destruction occurs because the reservoir of magma beneath the crater becomes mostly or totally emptied. Where the cone used to stand, a shallow, wide, steep-walled, circular depression called a caldera is all that remains. This phenomenon typically occurs when there is a large pool of magma beneath the crater. The magma erupts forcefully, sending lava outward and emptying the crater. The walls of the crater then collapse.

In Oregon, for example, a volcano called Mount Mazama existed until destroyed by a violent eruption sixty-six hundred years ago. All that remains today is a caldera that has filled with water and is called Crater Lake. A small cone called Wizard Island has formed in the center of the lake, but the volcano is now extinct.

Cones that are destroyed in one eruption may be rebuilt in successive eruptions. For example, Indonesia's Krakatau volcano collapsed during its massive eruption in 1883, and a new volcano, called the Anak Krakatau, has since formed in its place.

Steep-sided volcano with large cinder cone crater, Arizona. STOCK MARKET.

Types of cones There are four categories of cones, based on appearance and composition: cinder cones, composite cones, shield cones, and lava domes. Cinder cones are the steepest cones, with slopes of 30 to 40 degrees, and are seldom taller than 1,640 feet (500 meters). They are created by mildly explosive eruptions that send hot rocks into the air. When the rocks rain back down on Earth, they pile up in a steep cone around the vent. Ash and lava also contribute to the formation of cinder cones. Sunset Crater in Arizona, Stromboli in the Mediterranean Sea, and Paricutín in Mexico are examples of cinder cone volcanoes.

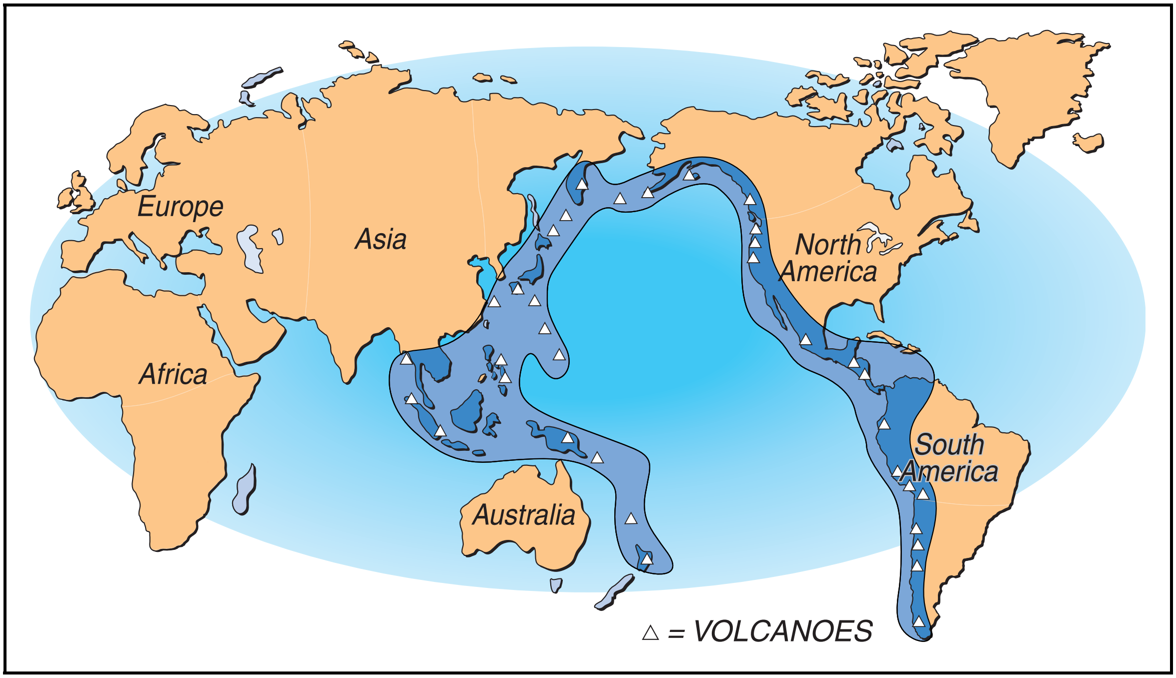
Composite cones are made of intermittent layers of lava and layers of fragmented rock and ash. This physical makeup exists because these volcanoes alternate between nonexplosive, flowing-lava eruptions and violently explosive eruptions. Composites have the most symmetrical cone shapes of any volcanoes. They are not as steep as cinder cones, having slopes less than 30 degrees at the summit and tapering off to 5 degrees at the base. Mount Vesuvius in Italy, Mount Fujiyama (also called Mount Fuji) in Japan, Mount St. Helens in Washington, and Mount Mahon in the Philippines are examples of composite cones.

Shield cones are formed mainly by runny, fast lava flows. They have broad, gentle slopes, seldom more than 10 degrees at the summit and 2 degrees at the base, and resemble warrior shields lying flat with the curved face up. The Hawaiian Islands, including Mauna Loa, the world's largest active volcano, are comprised of shield volcanoes.

The fourth type of volcano landform, the lava dome, is made of hardened, thick, pasty layers of lava that have been squeezed like toothpaste from a tube. Lava domes take on a variety of strange shapes. Examples of lava domes include Lassen Peak and Mono Dome in California.

Where volcanoes occur More than half of the world's active volcanoes above sea level are located in a geographic belt called the "Ring of Fire" or "Circle of Fire." This belt surrounds the Pacific Ocean basin. It marks the boundary between the Pacific plate (the tectonic plate, or large piece of Earth's crust, underlying the Pacific Ocean) and the surrounding plates.

The Ring of Fire follows the west coast of the Americas from Chile to Alaska. It runs through the Andes Mountains, Central America, Mexico, California, the Cascade Mountains, and the Aleutian Islands. It continues



The Ring of Fire.

down the east coast of Asia from Siberia to New Zealand, through Kamchatka, the Kurile Islands, Japan, the Philippines, Celebes, New Guinea, the Solomon Islands, and New Caledonia.

Most of the rest of the world's volcanoes are located in the oceans; some protrude above the water as islands and others lie entirely beneath the surface. Volcanoes are found in the middle of the Pacific Ocean (the Hawaiian Islands, for example), in the northern Atlantic Ocean (Iceland and nearby islands), in the mid-Atlantic between Maine and Spain, in the southern Atlantic between eastern South America and western Africa, and in the southern Pacific east of Australia.

The volcanoes in the Atlantic follow undersea ridges where sections of four different plates come together: the Eurasian plate, the North American plate, the African plate, and the South American plate. The volcanoes east of Australia follow the border between the Pacific plate and the Indo-Australian plate.

The volcanoes in the middle of the Pacific, however, exist on a single plate—in the absence of plate boundaries. Those volcanoes occur above

Volcanoes in the United States

In the United States, the Pacific Northwest, Hawaii, and Alaska are home to several active volcanoes. Historically, the United States trails behind only Indonesia and Japan for having had the greatest number of eruptions in recorded history. About 10 percent of the eruptions that have occurred throughout the world over the last ten thousand years, including some of the largest and most destructive eruptions, have been in the United States.

The largest active volcano—not only in the United States, but in the world—is Hawaii's Mauna Loa. This volcano is 29,500 feet (9,000 meters) tall from its base on the ocean floor to its peak, making it taller than Mount Everest, although the bottom 19,000 feet (5,800 meters) are underwater. The volcano is 62 miles (97 kilometers) wide at its base on the ocean floor. Since 1900, Mauna Loa has erupted fifteen times; eruptions have ranged in duration from one day to one hundred and forty-five days. Mauna Loa's eruptions are nonexplosive. Instead, they cause great quantities of lava to flow over the ground in thin sheets.

Kilauea (pronounced key-lou-AYE-ah) is a volcano that formed on the side of Mauna Loa. Kilauea has been erupting almost continuously since January 1983, making it the longest-erupting volcano in recorded history. Kilauea also erupts nonexplosively, giving scientists an opportunity to make careful studies of its behavior in relative safety. The National Park Service provides a viewing area for tourists to observe Kilauea's activity from a safe distance, earning it the nickname of the "drive-in volcano."

The Cascade Mountain Range, which runs through northern California, Oregon, and Washington, and on into western Canada, is home to several volcanoes that erupt infrequently but explosively. The eruption of Mount St. Helens occurred in a manner typical of Cascade volcanoes. Another volcano in the Cascades of concern to area residents is Washington's Mount Baker. This volcano, which periodically (but not since 1976) expels puffs of smoke and ash, is covered with ice and snow. The fear persists that an eruption by Mount Baker would cause tremendous avalanches and lahars. Similarly, Mount Rainier, a glacier-covered volcano in Washington that has been quiet for five hundred years, is also a source of concern in the region. If the volcano were to become active again, melting ice would trigger massive lahars.

Another region of the United States that is a hotbed of volcanic activity is the Alaskan Panhandle and Aleutian Islands (the land that forms a tail leading into the Bering Sea, in

hot spots, places where magma rises in currents from the upper mantle toward the crust. There is no definitive answer as to why hot spots form where they do, however some geologists (scientists who study the origin, history, and structure of Earth) think hot spots are related to the former positions of plate boundaries. Another theory is that hot spots mark the site where a plate may break apart in the future. At hot spots, the magma melts or otherwise forces its way through the layers of rock leading up to southwestern Alaska). The area is home to about 80 major volcanoes and experiences one or two eruptions per year. One of those eruptions, which occurred in 1912 at Novarupta (in what is now the Katmai National Monument), was the world's largest of the twentieth century. Novarupta ejected some 3.6 cubic miles (15 cubic kilometers) of magma—about 30 times more material than ejected by Mount St. Helens—over a 60-hour period and caused the collapse of Mount Katmai, a volcano 6 miles (10 kilometers) away. A group of scientists who visited the site four years after the eruption discovered that a valley 15 miles (24 kilometers) from Novarupta, covered by ash from the eruption, still emitted jets of steam and was hot enough in places to boil water. They named the area the Valley of Ten Thousand Smokes.

Mauna Loa volcano, Hawaii.

the surface and forms volcanoes. The world's largest volcanoes are located above hot spots.

Consequences of volcanic eruptions

Volcanic eruptions burn and blacken the landscape. They clear an area of plant and animal life and blanket it in a layer of ash. The lethal gases, dust, and ash suffocate people and wildlife. The ash, rocks, and lava that cover

A logging camp on Toutle River in Washington after flooding caused by the eruption of Mount St. Helens in 1980. ©BETTMANN/CORBIS.

the ground, sometimes in deep layers, may smolder for weeks, months, and in some cases for years. Homes, farms, and entire communities may be buried under flows of material ejected from a volcano.

One of the most hazardous elements of a volcanic eruption is a mudflow called a lahar. The lahar is made of volcanic ash and water and may be very hot. Lahars flow for great distances, burying everything they encounter. Another deadly feature of eruptions is a pyroclastic flow, also called pyroclastic surge, a fast-moving mixture of hot gas and ash. Volcanoes near the oceans may trigger tsunamis (pronounced tsoo-NAH-mees), huge ocean waves (also called tidal waves) that result when a large quantity of ocean water is displaced. Tsunamis can destroy coastal towns and cities.

Gradual recovery following an eruption After an eruption, new life emerges from the ashes. This process may take months or generations, depending on the depth of the ash-and-lava layer and the climate type. (Rebound takes longer in harsher climates.) Rain and wind eventually break down the hardened lava into soil in a process called weathering. Other factors that promote weathering are the heat during the day (which makes lava expand) and the cooling at night (which makes lava contract).

Once the soil is reestablished, plant life reappears. Moss and lichens are the first plants to spread across the landscape. Flowering plants, the seeds of which are brought to the area by wind or birds, take hold next. Animals then reestablish their presence on the volcano. It generally takes at least a century before trees attain their pre-eruption size.

After the eruption of Mount St. Helens, Spirit Lake was a poisonous mess still bubbling with volcanic gases seeping from the lake bed. A month after the eruption the lake was completely lacking dissolved oxygen in the water. Scientists predicted that the lake would take many decades to recover. However, they were pleasantly surprised to discover that only three years after the Mount St. Helens eruption Spirit Lake was rich with biological activity. In 1993 scientists were even more surprised to see healthy fish in Spirit Lake. Even though the lake was devastated by Mount St. Helens it has rebounded significantly and is on the way to recovery.

Eruptions produce rich soil For all their hazards, there is at least one positive thing about volcanoes; they create fertile soil. Some of the world's best farmland is located on the slopes and around the base of volcanoes. The soil is formed from broken down volcanic rocks mixed with decaying vegetation. Those rocks, and the layer of soil they form, have large concentrations of minerals that are necessary for plant growth. The fertility of the soil is what draws people to farm the slopes of Mount Vesuvius, Mount Etna, and other famous volcanoes around the world, despite the danger of possible eruptions. In Japan and Indonesia, farmers excavate slopes to create flat areas, or terraces, on which they grow crops. Volcanic ash blown over thousands of square miles has added nutrients to the soil in forests and farmland.

Precious gems and useful rocks Volcanoes are good sources of diamonds; several diamond mines have been established at the sites of ancient volcanoes. Geologists believe that diamonds, which are a form of carbon that has been subjected to high heat and pressure, are created in the pipes leading from magma chambers to volcanic vents. Diamonds have been found in these pipes, as well as in sand and gravel in streams near volcanoes. The diamonds found in streams are thought to have originated in pipes that have eroded over time. While a pipe can be destroyed by wind and water, diamonds, which are among the hardest substances on Earth, survive and erode out of the rock.

Sulfur, marble, tin, and copper are also found in the vicinity of volcanoes. Sulfur is a pale-yellow mineral that is used in making matches,

Lightning strikes over the Pacaya volcano, Amatitlan, Guatemala. ©REUTERS/CORBIS.

gunpowder, and rubber. It is also used in some medicines. Tin and copper are formed by the intense heat and pressure in volcanoes. When in a liquid state, these metals run between layers of rock. When hardened, they can be seen as veins, or lodes, in the rock. Tin is a soft, silvery metal used to coat other metals in order to prevent corrosion. Copper is a flexible, reddish-brown metal that conducts electricity and is used for electrical wiring.

Another useful by-product of volcanoes is a soft white clay called china clay or kaolin. China clay is produced by the action of steam (from underground water) on feldspar, which is a type of crystal in the rock. China clay is used in the production of ceramics, china plates and cups, paper, paint, medicine, and electronic devices.

Effects on weather Volcanic eruptions place large amounts of gases, ash, and dust into the air; those substances may affect the weather in the short term and even influence global climate for long periods of time. While large particles spewed out of volcanoes rain down on the ground, the smallest particles make their way upward, high into the atmosphere. Those particles are carried by upper-air winds for hundreds of miles (kilometers), even circling the globe. They remain suspended in the air, sometimes for months, until they fall to Earth or are washed down with the rain. The presence of volcanic material in the sky is most noticeable at sunset, when the sunlight reflects off the particles and turns the sky red.

The primary effect that airborne volcanic dust has on the weather is increasing the amount of rain. That happens because the specks of dust serve as condensation nuclei—tiny solid particles around which water vapor condenses, or changes to liquid form. The added number of condensation nuclei in the air cause higher-than-normal rates of condensation and, consequently, more rain.

A fascinating side effect of volcanic eruptions is lightning. Lightning flashes occur above an erupting volcano because the particles of dust and ash rub against each other, creating a build-up of static electricity. When the charge builds to a certain point, it is released as lightning.

Effects on climate and the environment Volcanic eruptions have very likely brought about periods of glaciation, extremely cold times when glaciers covered large portions of Earth. In the early stages of Earth's history, thousands of volcanoes dotted the surface. These volcanoes underwent frequent, large eruptions that had a great impact on the climate. In addition to releasing gases that rose up and formed Earth's atmosphere, the eruptions sometimes spewed out ash and dust so thick that they blocked out the sun.

Volcanic eruptions today are far fewer in number and intensity than they once were. A very large volcanic eruption today only affects global climate for a few years. In 1815, for example, the Indonesian volcano Mount Tambora erupted. The Tambora event, together with smaller eruptions of other volcanoes over the preceding four years, led to a short-term decrease in global temperature. There was a severe cold spell in 1816, causing the year to be called "the year without a summer."

Some eruptions discharge large amounts of sulfur gases into the air. Even after the ash and dust clears from the atmosphere, sulfur continues to react with water vapor to produce sulfuric acid particles. These particles collect and form a heavy layer of haze. This layer can remain in the upper atmosphere for years, reflecting away a portion of the incoming sunlight. The result is a decrease in temperature around the world.

Sulfuric acid in the air has another consequence: acid rain. Acid rain, which is rain with an unusually high acidity, is formed when sulfuric acid (or nitric acid, from car exhaust systems or factory smokestacks) mixes with rainwater. Acid rain raises the acidity of lakes and rivers, making them inhospitable to many animal species. It also kills trees and has been recently shown to endanger human health.

Technology connection

Volcanologists (scientists who study volcanoes and volcanic phenomena) use several methods to predict when volcanoes may erupt. The purpose of predicting eruptions is to give people in the vicinity time to evacuate. In most cases, volcanic eruptions can be predicted a few days to a few weeks before they occur. It is difficult to foretell, however, just how a volcano will behave and what it will eject. The United States Geological Survey operates three observatories for the study of active volcanoes, in Hawaii, the Cascade Mountains, and Alaska.

One way that volcanologists and other geologists (scientists who study the origin, history, and structure of Earth) learn about the behavior of volcanoes is by studying past eruptions. They analyze volcanic rock on and around the cone to determine the composition of the materials ejected from the volcano. They also study satellite photographs to create maps of previous lava flows, and read written reports of past eruptions. They put together a timeline that tells when the volcano has erupted in

Scientists atop the Colima volcano, Jalisco, Mexico, 1991. © ROGER RESSMEYER/ CORBIS.

the past and how many years have passed between eruptions. All of this information helps scientists predict when the volcano might erupt next, what materials might be cast out, the probable nature of the eruption, and where the materials will likely travel.

Volcanologists also learn about volcanic behavior by traveling to volcanoes that are showing signs of activity. They use gas detectors to sample and identify the gases being emitted and thermometers to measure the temperature of rocks around the crater. Increased rock temperature is a sign that magma is nearing the surface, because the approaching magma heats the rocks.

Another tool used by volcanologists to predict when a volcano will erupt is a tiltmeter. A tiltmeter measures changes in the shape and angle of a cone's slope. The formation of a bulge on a slope indicates the swelling of the magma chamber beneath the surface and the rising of magma toward the vent. Scientists also use seismographs or seismometers, instruments that detect ground movements. These tools can even pick up movements that are too slight to be felt by humans. The movements may be caused by a swelling of magma or by an earthquake. The swelling of magma is an indicator that a mountain is ready to erupt. Earthquakes, which produce cracks in the ground, often trigger volcanic eruptions.

Controlling volcanic flows While there is no way to stop a volcano from erupting, there are ways to lessen the damage caused by eruptions. People

Mount Etna in Sicily erupts, 2004. ©ANTONIO PARRINELLO/REUTERS/CORBIS.

who live in the vicinity of active volcanoes attempt to control flows of volcanic materials in several ways. Examples include spraying cold water on the lava to cool it and slow it down, constructing dams to prevent the flow from entering certain areas, and digging trenches that direct the flow away from human settlements.

In Iceland, a country situated in an arc of volcanoes, residents had success battling the eruption of the Helgafell volcano in 1973. Aiming to protect the town of Heimaey, people sprayed cold water, pumped from the ocean, on the flowing lava. The method seemed to have achieved some success as the lava slowed down and hardened before it reached the town.

People living near Sicily's Mount Etna are also knowledgeable about volcano damage control. Sicilians have been able to direct lava flows by blasting holes in the sides of hardening lava tubes (hollow tubes formed when the outer layer of lava hardens, while molten lava continues running through the tube). Some of the lava then runs out through the holes and establishes new routes instead of all continuing to flow through the tube.

The Sicilians also bulldoze rocky ground to form walls that keep the lava from flowing into towns. They sometimes fortify those walls with boulders dropped by helicopters. In light of Mount Etna's history of erupting and burying homes and farms, controlling the lava flow is essential to the survival and livelihood of villagers near the volcano.

A matter of survival

For people living in the vicinity of a volcano, even a volcano that has not been active for many years, the best strategy for survival is adequate preparation. (Note that volcanoes that lay dormant for long periods of time generally erupt with greater explosiveness than do volcanoes that have frequent eruptions.) It is imperative to understand what may happen during an eruption and to be familiar with your community's warning systems and emergency plans. Learn your evacuation route and develop an emergency communication plan so that members of your family, if at different places during the day, can find each other during or after an eruption.

A phone booth covered with ash from the Mount St. Helens volcano, 1980. ©BETTMANN/CORBIS.

People living in volcano danger zones should have a pair of goggles and a breathing mask for each member of the family (to be used if ash is falling). Every family should also have a disaster supply kit with the following items: flashlight and extra batteries, first aid kit, bottled water and nonperishable food, manual can opener, and necessary medicines.

American Red Cross guidelines state that if a volcano erupts, people in the danger zone should evacuate when ordered to do so by authorities. People who cannot get away and are caught indoors should close all doors and windows. People trapped outdoors should try to seek shelter indoors. If that is impossible, they should move as far as possible from the volcano and stay upslope from rivers or streams (to avoid mudflows). Do not try to approach the volcano to watch the eruption—such a move can be deadly.

Even people living several miles from a volcano may experience a shower of volcanic ash during an eruption. If you have to go outdoors during an ashfall, wear long pants, a long-sleeved shirt, and goggles. Breathe through a dust mask or a damp cloth. Do not attempt to drive, as the ash may harm your vehicle's engine and the moving vehicle will stir up ash, worsening the situation.

Stay tuned to a battery-powered radio or television for emergency information. After the eruption, try to avoid areas where ash has fallen. People with asthma or other respiratory ailments, in particular, should

Bizarre lava formations

Hardened lava creates some of the world's most unusual land formations. Two of these formations are common in Hawaii and have Hawaiian names: pahoehoe (pronounced pa-HO-eh-HO-eh) and aa (pronounced ah-ah). Pahoehoe, which resembles coiled rope when cooled, is made from fluid lava with high concentrations of gas. A hard skin forms on this lava as its surface cools. Meanwhile, hot lava continues flowing beneath the skin. As the lava moves below, it wrinkles the skin, forming coiled-rope patterns. Lava may continue flowing for miles beneath a hardened pahoehoe skin, which is thick enough to walk on. Hot lava that drips from the roof of pahoehoe skin creates icicle-like rock formations.

Close-up of a pahoehoe formation in Hawaii, 1991. ©GARY BRAASH/CORBIS.

Slow-moving, thicker lava, in contrast, hardens to form blocks called aa. Aa formations have sharp, jagged rocky edges and are difficult to walk on. About 99 percent of the island of Hawaii is composed of aa and pahoehoe.

Another distinctive lava formation is the lava tube. When lava flows as a narrow stream, the outer layer cools and hardens first. Meanwhile, this hardened crust traps the heat inside it and hot lava continues to flow through it. When the lava flow ceases, a hollow tube, called a lava tube, is left.

One of the world's most remarkable lava formations is found in Antrim, in Northern Ireland. The Giant's Causeway, as the formation is called, is comprised of tall, six-sided columns. The columns were formed by flood basalt, which is lava that flowed from cracks in the ground and buried everything in its path. When the lava cooled and hardened, it cracked in patterns similar to parched ground. When the cooling was complete, the basalt (a type of rock formed from lava) had separated into six-sided pillars. Another stunning display of these seemingly unnatural pillars can be seen at Devil's Postpile in California.

avoid breathing ash as much as possible. Offer assistance to those neighbors who are elderly or who have disabilities. If you have been ordered to evacuate, do not return to your home until given the all-clear by authorities.

[*See Also* **Avalanche; Earthquake; Landslide; Tsunami**]

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Wildfire

On August 5, 1949, fifteen young men parachuted into the upper part of Mann Gulch in the wilderness of Montana. Mann Gulch drains westward into the Missouri River about 20 miles (30 kilometers) north of Helena, Montana. The area still remains a rugged, roadless wilderness. The young men were "smokejumpers," firefighters trained to parachute into the area of a wildfire, a large, uncontrolled fire in grass, brush, or trees. At first, this wildfire seemed easy to control and they expected to have it put out by the next day. One of the survivors is quoted in the official report:

> I took a look at the fire and decided it wasn't bad. It was burning on top the ridge and I thought it would continue on up the ridge. I thought it probably wouldn't burn much more that night because it was the end of the burning period (for that day) and it looked like it would have to burn down across a little saddle before it went uphill any more.

The smokejumpers started down the canyon, planning to work the flank of the fire. They were joined by a forest ranger from the nearby Meriwether campground, who had been working alone to try to contain the fire.

As the crew worked their way down the canyon, things went terribly wrong. The fire had burned down the slope in front of them and also jumped to the other side of the gulch. The crew encountered a strong wind blowing up the canyon and bringing the fire in their direction. They turned and tried to run for safety up the ridge to the north of the gulch, dropping their gear as they ran.

Only three of the original crew survived. The crew chief stopped and deliberately started a fire in the dry grass and brush. After this fire had spread over a wider area, he stepped through the flames into the middle of the burned area and lay down. Such a fire is now known as an escape fire, but at the time, none of the other crew members trusted this tactic and continued to run up the slope. Two crew members ran straight up the hill and managed to squeeze through a gap in the rocks on top of the ridge.

An aerial view of the 1949 Mann Gulch fire near Helena, Montana. More than 3,000 acres were burned. AP IMAGES.

WORDS TO KNOW

backfire: a small fire set by firefighters in the path of an oncoming wildfire to burn up the fuel before the main fire arrives, thus blocking it.

crown fire: a fire that spreads through the treetops, or crown, of a forest.

fire line: a strip of ground, cleared of all combustible material, that is dug by firefighters to stop the advance of a wildfire. Also called control line.

fire triangle: the combination of three elements required for any fire: fuel, oxygen, and heat.

firestorm: also called a blowup, it is the most explosive and violent type of wildfire.

ground fire: a fire that burns beneath the layer of dead plant material on the forest floor.

hotshot: a specialized firefighter who ventures into hazardous areas and spends long hours battling blazes.

oxidation: a chemical reaction involving the combination of a material with oxygen.

prescribed burn: a planned, controlled fire that clears flammable debris from the forest floor.

Pulaski: a combination ax and hoe that is used by firefighters to clear brush and create a fire line. It was invented by forest ranger Edward Pulaski in 1903.

regeneration: the process of making or starting anew.

smokejumper: a specialized firefighter who parachutes to strategic locations from airplanes to battle wildfires.

spotting: the starting of new fires, called spot fires, by sparks and embers that drift ahead of an advancing wildfire.

surface fire: a fire with a visible flame that consumes plant material and debris on the forest floor.

troposphere: the lowest atmospheric layer, where clouds exist and virtually all weather occurs.

wildfire: a large, uncontrolled fire in grass, brush, or trees.

They lay down in the middle of a bare rock slope on the other side of the ridge. The other thirteen perished in the fire.

The Mann Gulch disaster remained the worst fire tragedy to strike the United States Forest Service until 1994, when an inferno on Storm King Mountain near Glenwood Springs, Colorado, killed fourteen firefighters, three of them smokejumpers. A small, lightning-caused fire had blown up into an intense firestorm, the most violent type of wildfire. In Mann Gulch and on Storm King Mountain, young men and women lost their lives fighting dangerous, unpredictable wildfires.

A wildfire may begin with just a spark from a campfire or a lightning strike. If it occurs in a forested area, the fire can spread to nearby logs or bark, then climb up the branches of small, dry neighboring trees. From

Notes of a Montana resident during fire season

The following report from wildfire-weary Montana was written by Mary Stange, a professor at Skidmore College and overseer of the Crazy Woman Bison Ranch. The account, titled "Tinder Dry: The Old West," was published in *USA Today* on August 24, 2000.

"We had dry lightning again last night. It's a phenomenon that occurs in various places, but nowhere so dramatically as in Big Sky country during fire season.

"Turgid storm clouds crowd the evening sky. Rumbling ominously, they wait until dark to unleash volleys of blue-white energy. Then the rainless lightning comes, fast and ferocious, in several forms: Some strikes streak across the sky from one cloud to another; some explode within the clouds, suggesting enormous Chinese lanterns; and some, too many, slice jagged paths down from sky to ground. The snapping sound these vertical strikes make has roughly the same effect on the nerves as the buzz of a rattlesnake. These are the strikes that spawn wildfires.

"We ranch in southeastern Montana. It's not the part of the state that the river runs through, or where the nationally reported blazes currently are raging. Those fires, along the Bitterroot Valley and elsewhere in the Rocky Mountain end of this vast state, are hundreds of miles away from here.

there it can jump to taller trees and spread among the treetops. As long as fuel is available, a wildfire will continue to burn.

In the United States, more than three hundred wildfires occur every day. People are responsible for accidentally starting nine out of ten wildfires with campfires, burning leaf piles, cigarettes, or other sources. The most common natural cause of wildfires is lightning.

The regions most affected by wildfires are wilderness areas. As homes, resorts, and suburbs encroach further and further into wildlands, however, the danger to human life and property due to wildfire increases.

Wildfires in the West

A combination of chronic drought, record-breaking high temperatures, strong winds, and the firefighting policies of the U.S. Forest Service are widely considered to be the primary cause of a series of devastating wildfire seasons in the western United States. In addition to a greater number of fires, more people and property have been placed at risk

Nevertheless, we've been smelling their smoke for weeks now, and seeing it in the form of a yellow-brown haze. This haze has an interesting side effect: spectacular sunrises and sunsets. In ranch country, every cloud seems to have an ironic lining.

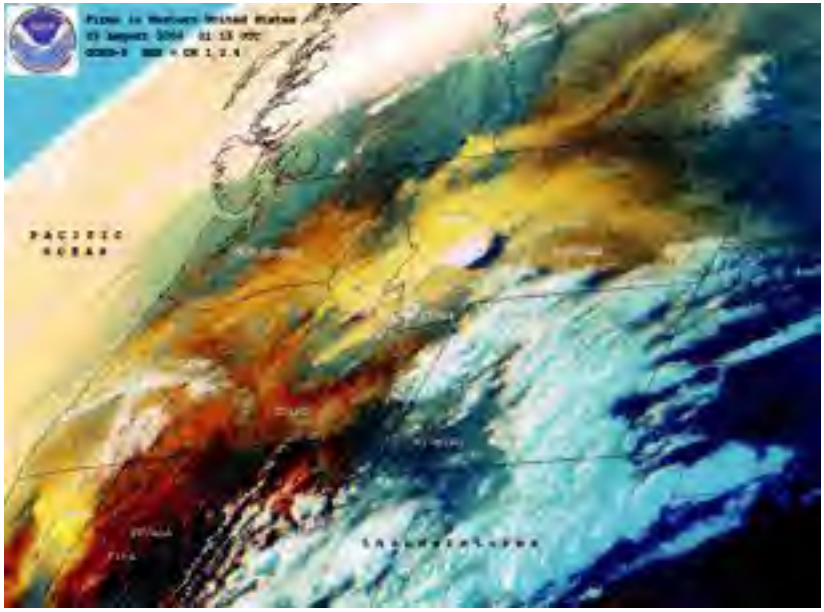
We've had our share of fires in this part of the state, too; we always do this time of year. But this has been an especially rough summer, with unremitting high temperatures and tinder-dry vegetation. Our neighbors had a lightning-caused grass fire this past week; fortunately, they got on it quickly before it could take out more than a piece of one pasture. They were lucky. Thousands of national-forest acres burned earlier this month near Ashland, about 60 miles west of us."

Wildfire on the mountains near Darby, Montana, 2000. ©AFP/CORBIS.

because of the recent increase in construction of homes, resorts, and other buildings in and near wilderness areas.

As the population increases and urban areas in the west expand into canyons and up the slopes of foothills, homes and property are more likely to be endangered by wild land fires. In these circumstances, firefighters are forced to divert their energies from the main task of fighting forest fires in order to protect property. People also make unwise choices in construction techniques, such as building their homes right among the trees. In the humid and well-watered East, this does not pose much risk, but in the relatively arid West, homes should be built well away from forest and brush.

The western United States burns in 2000 In the summer of 2000, the western United States experienced one of its worst fire seasons. Hundreds of fires charred a total of 6.7 million acres (2.7 million hectares) in twelve states throughout the West. Most of the area that burned was federal forestland. At least eight firefighters and two civilians died in the blazes. Hundreds of



A satellite image shows heat signatures (red) and smog (yellow) from many wildfires burning in the western United States in the summer of 2000. ©AFP/CORBIS.

homes were destroyed and thousands of residents had to be evacuated. Nationwide (including Alaska), over 8.4 million acres were burned in 2000.

The major fires of 2000 The 2000 fire season began in May, when a fire swept through the grounds of the federal nuclear laboratory at Los Alamos, New Mexico. The wildfire began as a prescribed burn, deliberately set by Forest Service employees to clear the forest of flammable undergrowth, but was swept out of control by high winds. The fire burned 47,000 acres (18,800 hectares) and two hundred homes before being extinguished.

The worst fires of the summer of 2000 occurred in Montana, where close to 900,000 acres (360,000 hectares) burned, and the blazes were battled by an army of eleven thousand firefighters. Montana's giant fires were concentrated in its southwest portion. The scenic Bitterroot Valley was hardest hit.

In Idaho, more than 200,000 acres (80,000 hectares) burned in the Salmon-Challis National Forest alone. In South Dakota, 64,640 acres (25,860 hectares) burned in the Black Hills National Forest, making it the largest fire in the forest's recorded history. Colorado experienced five major fires. Two of them were in Mesa Verde National Park, forcing the park's closure at times. A third fire took place southwest of Denver, and a fourth burned east of Rocky Mountain National Park. Each charred more than 10,000 acres (4,000 hectares).

One of the last major fires of the season, and the fifth major fire for Colorado that year, consumed 1,087 acres (435 hectares) near Boulder. The fire burned for one week in mid-September. It was believed to have been started by a campfire, despite the fact that any type of open fire was prohibited throughout much of the parched state. A combination of temperatures above 90°F (32°C), low humidity, and shifting winds caused the blaze to spread rapidly through the dry grass and pine needles. The smoke from the fire blanketed Boulder and its surrounding canyons and foothills. Firefighters dug fire lines (areas cleared of combustible material) on the mountainsides and spread fire retardant on the flames to keep the fire out of Boulder. A mountain neighborhood of about two hundred people on the outskirts of town was evacuated as a precaution, but the fire was held in check by firefighters and the evacuees' homes were spared.

Fighting the fires of 2000 Thousands of volunteers, military personnel, and others assisted professional firefighters in battling the blazes during the peak of the summer fire season. Firefighters came from Canada, Mexico, and as far away as New Zealand and Australia. In all, more than twenty-five thousand people were involved in battling the blazes. They used more than 230 helicopters and airplanes to dump hundreds of thousands of gallons of water and fire retardant on the flames. The cost of battling the fires was about $18 million per day; the summer's firefighting expenses were over $1.3 billion.

Military personnel were heavily involved in the firefighting effort throughout the summer. Approximately five hundred soldiers from Fort Hood in Texas were sent to fight a fire in Payette National Forest in Idaho. Another 712 members of the Army National Guard and 213 members of the Air National Guard were spread across ten western states fighting fires. In Southern California, Army National Guardsmen used helicopters to douse flames with suspended buckets that each held as much as 1,300 gallons (5,000 liters) of water. In Montana, more than four hundred National Guard members were called upon to perform mop-up operations after fires had been reduced to embers.

Wildfires continue to wreak havoc Prior to 2006, the worst fire years on record were 1963 (7.1 million acres or 2.9 million hectares), 1988 (7.4 million acres or 3.0 million hectares), 2000 (8.4 million acres or 3.4

million hectare), and 2005 (8.7 million acres or 3.5 million hectares). However, in late 2006, a new record was set. Over 9.8 million acres (4.0 million hectares) were burned by at least 96,000 separate fires.

The unusual fire seasons have been blamed on a combination of extreme drought, record high temperatures, strong winds, and the total fire suppression policy of the U.S. Forest Service. From 1910 through the 1970s, the agency attempted to extinguish every forest fire, regardless of location or cause. This policy helped to create an overabundance of fallen dead timber and other dead and decaying material on the forest floor. According to critics, if forest fires were allowed to occur naturally, this material would be removed by relatively small fires that would not harm the standing timber. Due to total fire suppression, the accumulated material now almost guarantees that every large fire will be a forest disaster.

The summer and fall fires of recent years also endangered more people and property than in previous decades in part because of the recent increase in construction of homes, resorts, and other buildings in and near wilderness areas. Firefighters have been forced to divert their energies from the main task of fighting forest fires in order to protect property.

Major fires since 2000 Wildfires continued to rage across the United States in the years following 2000. Records were set, only to be broken the next or following year. However, 2001 was a relatively quiet year for wildland fires. The number of fires, eighty-four thousand, was relatively high, but the total acreage was relatively low at 3.6 million acres (1.5 million hectares).

Things turned ugly again in 2002, another record-setting year, with over seventy-three thousand fires burning 7.2 million acres (2.9 million hectares). That fire season started with the Rodeo-Chediski fire in Arizona that burned 467,000 acres (189,000 hectares) and four hundred structures. It threatened, but did not burn the town of Show Low, Arizona. That fire was followed by the Hayman fire in Pike National Forest, Colorado, that burned 137,000 acres (56,000 hectares). The Hayman fire caused nine firefighter deaths, and destroyed six hundred structures. Then there was the Florence/Sour Biscuit Complex fire in Oregon that burned 500,000 acres (200,000 hectares). ("Complex fire" is the term used by the forest service to describe a group of separate fires in the same general area that are handled together.) Firefighting in 2002 cost federal agencies a staggering $1.6 billion.

The year 2003 was not as bad in total number of fires or acreage burned. There were sixty-three thousand fires that burned 3.9 million acres, at a total cost to federal agencies of $1.3 billion. The Cramer fire in Idaho burned 13,000 acres (5,000 hectares) and cost the lives of two forest service firefighters.

Despite the relative small number of fires in 2003, disaster struck in California. The Cedar fire, fanned by Santa Ana winds, caused much damage due to its nearness to San Diego. This fire was the second largest wildfire in the history of California and one of 15 fires that started in late October. The Cedar fire burned a total of 721,800 acres (292,100 hectares) and destroyed 3,640 homes. Fifteen lives were lost, including one firefighter and one migrant worker. The fire was intentionally set by a hunter who had become lost. He claimed he was trying to signal rescuers.

The year 2004 was even worse than 2002 in total area burned, with sixty-five thousand fires burning 8.1 million acres (3.3 million hectares). However, the bulk of the area burned was in Alaska, so the total cost to federal agencies of $890 million was relatively low. Many Alaskan wildland fires are in remote, inaccessible areas and are often allowed to burn out naturally unless they threaten homes or other structures. Alaska fires during 2004 burned over 6.4 million acres.

The total number of fires in 2005 was only sixty-seven thousand, but the total acreage was 8.7 million acres (3.5 million hectares). One of the more unusual aspects of the 2005 season was that wildfires broke out across Oklahoma, Texas, and the Southern Plains in late December, well past the usual fire season. Some of these fires continued to burn through January of 2006.

The largest wildland fire in 2005 was the Cave Creek Complex fire, which was started by a lightning strike on June 21. The fire burned more than 248,000 acres (100,000 hectares) and destroyed eleven structures. It involved 580 firefighters in ten crews. They used ten engines, three bulldozers, and eight helicopters to fight the fire. It was the largest fire ever recorded in the Sonoran Desert. The total cost to the federal government for fire suppression in 2005 was $876 million.

All records are broken in 2006 In 2006, there were over ninety-six thousand fires that burned a staggering 9.8 million acres (4.8 million hectares). Unlike 2004, most of the fires in 2006 were in the continental forty-eight states. Alaska fires totaled only about 270,000 acres (110,000 hectares). The fire season was also exceptionally long. The first wildfires of 2006 were fires in Texas and Oklahoma that had started in 2005 and were still burning. Through the spring and into the summer of 2006, severe drought conditions persisted throughout the West. Coupled with record-setting high temperatures, the conditions were right for an extreme fire season.

In June, fire activity started to increase sharply, with fires in Alaska, the Rocky Mountains, and the Southwest. The Brinns fire threatened 621 homes near Sedona, Arizona. Modular Airborne Fire Fighting Systems (large cargo aircraft carrying three-thousand-gallon tanks for water or fire retardant) were ordered to support the Southwest Area. Toward the end of June, Northern California had become the area of national priority reporting thirteen fires greater than five hundred acres.

In July, the Sawtooth Complex in Southern California destroyed 221 structures. The Winters fire in Nevada burned 238,458 acres (96,575 hectares) of grass and sagebrush, but destroyed no homes. The Tripod Complex threatened nine hundred structures, with only two storage sheds actually destroyed.

In early August, firefighting support from the U.S. military and from Canada, Australia, and New Zealand was requested. The Crystal fire burned 223,570 acres with two structures destroyed. The Columbia Complex, at 109,000 acres, destroyed twenty-eight structures. The Devil's Den fire near Oak City, Utah, was a relatively small and easily controlled fire, but it still took the life of one firefighter. Even small fires can be dangerous in rugged terrain.

In September the season continued with several large fires, including the Day fire in Southern California that burned 162,702 acres destroying one home, and the Derby Complex in Montana that burned 223,570 acres and destroyed 26 homes. By the end of October, when the fire season normally wanes, there had been fifteen fires of more than 100,000 acres (40,000 hectares) reported in eight states.

In the late summer and early fall of 2006, an arsonist set a series of fires across Southern California. The last one set, known as the Esperanza fire, was started on October 26, 2006. It cost the lives of five U.S. Forest Service firefighters who were trying to protect a house from the fire. The house was destroyed. The fire burned for six days and consumed 40,200 acres (16,300 hectares), and destroyed thirty-four homes and twenty outbuildings.

In 2006, according to the National Incident Information Center, the highest number of fire starts on a single day occurred July 25 with 548 new fires. During the height of the fire season there were 687 residences, 65 commercial buildings, and 1,436 outbuildings destroyed. There were twenty-five fire-related fatalities. Despite multiple burn bans in effect and widespread publicity about the dangers of burning, 69,515 fires (consuming a total of 3,980,881 acres or 1,612,257 hectares) were human-caused.

The last fire of 2006 was the Curly Horse fire in the Tucson district of Arizona. The fire burned 1,562 acres (637 hectares) before it was contained on December 18, 2006. In all, the fires of 2006 cost the federal government well over $1.5 billion.

Wildfires in the boreal forest in Alaska The boreal forest stretches around the globe from Alaska, across Canada, into Northern Europe and Scandinavia, across Russia, and on into Siberia, where it is called the taiga. Fire is a natural part of the boreal forest ecosystem. Every year, both small- and large-scale wildland fires are ignited by lightning and by humans. The boreal forest and the animals within the forest are well adapted to these fire-caused changes. Without the routine occurrence of fire, organic matter builds up, the permafrost level rises, and ecosystem productivity declines. Fire, as an agent of change, rejuvenates and maintains these systems by removing some or all of the insulating material, thus warming the soil and increasing the availability of nutrients.

Part of the huge increase in wildland fires in recent years in the United States is due to wildland fires in the vast stretches of wildlands and forests in Alaska. Fires in these inaccessible regions are often allowed to burn naturally. The Alaska Division of Forestry has four categories of fire suppression response: critical, full, modified, and limited. Critical protection is provided when human lives are threatened or valuable or historic properties are at risk. Limited protection consists of just watching the fire. This level is provided when the expense of a higher level of protection is not justified or when the fire might benefit wildland ecosystems. During the 2005 Alaska fire season, when 4.7 million acres (1.9 million hectares) burned, 3.6 million acres (1.5 million hectares) or 77 percent were given only limited protection.

The five largest single fires in the U.S. since 1997 were in Alaska, and four of these fires were in 2004. The largest wildland fire ever recorded in Alaska or anywhere in the United States was the Taylor Complex fire on Alaska State Forest lands. It burned 1.3 million acres (530,000 hectares) of primarily boreal forest in 2004.

In an average year in Alaska, around 600,000 acres (200,000 hectares) burn. This is an easily manageable level of wildland fire that is necessary to sustain the health of the boreal forest. However, wildfires have dramatically increased in recent years. In the first years of the twenty-first century, Alaska experienced some of the worst wildfire years on record due to drought and record high temperatures. These conditions may have weakened the trees. Rising temperatures have also caused outbreaks of insect pests such as the spruce bark beetle, which is reproducing at twice its normal rate in the warmer climate. These factors are all likely due to climate change, which seems to have more dramatic effects in the arctic and subarctic regions of the globe than elsewhere. As a result, the boreal forest may be undergoing irreversible changes.

Laying blame for wildfires Western governors, timber company officials, environmentalists, and the federal government have been quick to assign blame for the western fires. The governors of Wyoming, Montana, Utah, South Dakota, Idaho, and Oregon, along with timber company owners, blamed the federal government for its policies strictly limiting logging on federal lands and the ban on building new roads, which may act as fire breaks. They believed that the lack of logging had left too much fuel to burn in the forests. The federal government blamed the past Forest Service policy of putting out every fire, thus allowing brush to accumulate on forest floors and resulting in more crowded, but less healthy, stands of trees. The environmentalists blamed timber companies for harvesting large, fire-resistant trees and replacing them with small fire-prone and disease-prone trees. Everyone blamed developers and wealthy home builders for constructing houses in sensitive wilderness areas.

In 2000, the governors and the federal government came to a compromise: the Forest Service would step up controlled burns and other efforts to clear small, fire-prone trees. (At the time, efforts to thin the forest were being applied on just 6 percent of national forest land.) In addition, the federal government would provide the six states listed above with $700 million each to develop their own fire prevention plans.

Health effects of smoke from wildfires In 2000, smoke from wildfires hung over much of the western United States. The smoke was worst over Montana, eastward through the Dakotas, and into Iowa. In some places, ash fell like snow so that a car parked overnight would be covered with

Fire-induced haze covers the mountains in Redding, California, in 1999.
©ED KASHI/CORBIS.

a layer of ash in the morning. Not only was the smoke and soot bad for people's spirits, it was dangerous for their health.

Many localities set up air-quality hotlines that informed residents of the dangers of going outside. Young children, elderly people, and people with asthma or heart conditions, those most vulnerable to the effects of the smoke, spent many long summer days indoors. In parts of Montana's Bitterroot Valley, all residents were warned not to undertake strenuous activity outdoors. In Missoula, Montana, the air pollution level during the smokiest days measured 500 micrograms per cubic meter of air—more than sixteen times the normal level.

Health professionals treated patients for shortness of breath, headaches, nausea, and dizziness due to the smoke. Throughout the smoky region, pharmacies reported selling more than twice the normal number of inhalers (devices used by people with asthma or other respiratory conditions). Some doctors and nurses expressed concern about the potential, but unknown, long-term health consequences of smoke inhalation.

The air pollution from wildfires can be distributed widely over the globe and the effects of particulate matter in the troposphere are still not well understood. While wildfires contribute a huge amount of carbon dioxide to the atmosphere, thereby increasing the greenhouse effect, the particulate matter may partially shade Earth's surface, which would tend to cool the surface. Atmospheric models suggest that these concentrations

The Peshtigo fire

On October 8, 1871, Peshtigo, Wisconsin, was the location of the deadliest wildfire in the history of the United States. An estimated 1,200 people died as the fire consumed 2,400 square miles (6,140 square kilometers) of forest. By a strange twist of fate, the city of Chicago burned to the ground on that same night. Although the Chicago fire claimed only around three hundred victims, Chicago received almost all of the public's attention. It wasn't until weeks after the Peshtigo fire that the nation learned of the tragedy in the Wisconsin woodlands.

The Peshtigo fire had been preceded by months of drought. The days had been bone dry between a summer rain shower on July 8 and the fire three months later. Throughout September, sporadic fires had begun breaking out in the woods. Residents fought some of the small fires and built fire lines around lumber mills. During the first week of October, the nearby fires in the woods outside of Peshtigo raised temperatures in the town and blanketed it with a layer of haze. The sun appeared as a dull, copper-colored sphere.

On the evening of October 8th, the smoke grew thicker in Peshtigo. Although the town's residents didn't know it, the fires in the nearby woods had merged into a massive inferno that was coming their way. Winds gusted up to 80 miles (130 kilometers) per hour. A deafening roar filled the air. Flaming objects cast ahead of the fire landed in Peshtigo's sawdust streets quickly igniting them.

"In less than five minutes there was fire everywhere," wrote one survivor. "The atmosphere quickly got unbearably warm, and the town was enveloped by a rush of air as hot as though it were issued from a blast furnace. The wind lifted the roofs on houses, toppled chimneys, and showered the town with hot sands and live coals."

Many people were burned alive by the rapidly advancing wall of fire. Others were trampled by stampeding cattle or chose to take their

of sooty particles could increase absorption of incoming solar radiation during winter months by as much as 15 percent.

The ash and carbon dioxide from a fire would normally be deposited in Earth's troposphere. However, a large wildfire can sometimes cause the formation of a pyrocumulonimbus cloud. This is a type of cumulonimbus cloud (a vertical cloud that may produce wind, hail, and heavy rain) whose vertical development is further amplified by the rapidly rising hot air from the fires. These clouds can have all of the severe weather normally expected from a cumulonimbus cloud and, in addition, can inject soot, ash, carbon dioxide, and carbon monoxide directly into the stratosphere. Once in the stratosphere, these combustion byproducts could be carried around the globe.

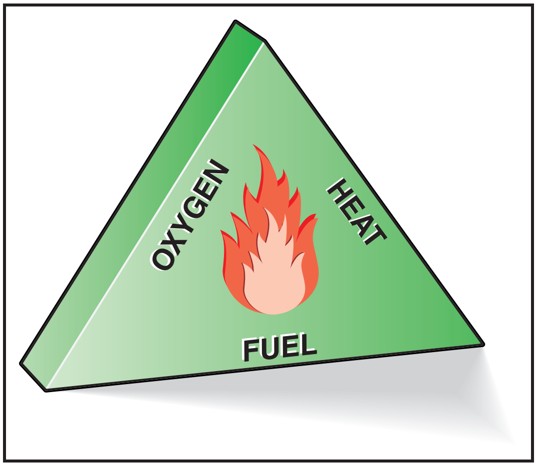
own lives rather than suffer a fiery death. In just one hour the fire leveled the town. One of the few places that residents found refuge from the fire was the Peshtigo River, which ran through the middle of the town. Once the fire had moved on to the northeast, hundreds of people emerged from the river—stunned and singed, but alive.

Drawing depicting the Great Fire of Peshtigo, Wisconsin, 1871. ©BETTMANN/CORBIS.

Dangerous science: How wildfires happen

Fire is a type of chemical reaction called oxidation, which is the combination of oxygen with material such as wood or leaves. Fire, which is a particularly rapid and violent form of oxidation, releases heat, light, carbon dioxide, carbon monoxide, water, and smoke into the air and leaves ashes on the ground. Other forms of oxidation, such as rotting wood and rusting iron, are much slower processes.

Ingredients of a fire Any fire requires the following three ingredients: fuel, oxygen, and heat. These three elements are called the fire triangle. Oxygen, which makes up about 21 percent of the air we breathe, is always readily available for wildfires. Wood and other plant matter contains a



Fire Triangle.

variety of different flammable materials, such as carbohydrates, proteins, and oils. Wood also contains plastic-like resins. The oxygen chemically combines with these materials within the fuel. Heat from the fire also breaks down carbohydrates and other materials to produce carbon and hydrogen, which burn and produce carbon dioxide and water vapor. Other substances such as oils and resins in the fuel are turned into vapor by the heat. This vapor burns, releasing more carbon dioxide and water vapor. Partial oxidation of the carbon produces toxic carbon monoxide.

The fuel for wildfires is usually dry vegetation, such as brush, grass, pine needles, leaves, and moss. The heat source (lightning, for instance) dries out the material and raises the temperature to the point where it ignites, or starts burning. A wildfire will continue burning as long as fuel, oxygen, and heat are available.

Once a fire gets started, it provides its own heat. The leading edge of a fire heats materials it encounters, causing them to ignite. After the leading edge has passed through an area, it leaves behind red-hot embers. The embers may continue to smolder for days or even weeks after flames are no longer visible, sometimes igniting new fires.

Certain conditions encourage the start of wildfires. For instance, wildfires are an especially bad problem during times of drought, when dry vegetation is plentiful, as well as when temperatures are high. Wet material is harder to ignite and burns more slowly than dry material, because the water in the substance must be heated and evaporated before the material can catch fire.

Causes of fire The most common natural cause of wildfires is lightning. Another natural heat source is the burning material spewed out by volcanic eruptions. Throughout the United States, however, about 90 percent of all wildfires are started by human activity, some due to carelessness, some deliberate. Some wildfires are set by the combined actions of nature and humans. Earthquakes or windstorms, for example, can down power lines and start blazes.

Worldwide, lightning is a significant cause of wildfires. Each day the planet is struck by about one hundred thousand strokes hot enough to start a fire. Lightning is responsible for around ten thousand brushfires

Lightning storm over Tucson, Arizona. NATIONAL AUDOBON SOCIETY COLLECTION/PHOTO RESEARCHERS, INC.

and forest fires each year in North America, particularly in the western United States, western Canada, and Alaska. About 80 percent of these fires are small, consuming just 10 acres (4 hectares) or less.

Lightning is a short-lived, bright flash of light produced by a 100-million volt electrical discharge. It heats the air through which it travels to around 50,000°F (28,000°C), a temperature even hotter than the surface of the Sun. At any given moment, there are approximately one hundred lightning flashes occurring worldwide.

Lightning is most likely to start fires in areas that are unusually dry. For example, a jagged bolt of lightning strikes the top of a tall tree. The strike explodes the tree and sends a shower of flaming fragments outward and downward. The embers land on and ignite dry leaves, twigs, and pine needles. The flames grow larger, spread to a small tree, and then upward to a taller tree. The flames touch neighboring trees, setting them afire. A wildfire is born.

The human factor About 90 percent of all wildfires in the United States are started by human activity. People start wildfires with unattended campfires or the burning of leaves, for example. Fireworks are another major starter of wildfires; they spark about fifty thousand fires a year in the United States. Cigarette butts carelessly tossed into the woods can start fires. Downed power lines and chainsaws also give off sparks that ignite fires. A few fires are caused by arson, when a person deliberately starts a fire.

The western United States entered an era of human-induced wildfires in the 1800s, as pioneers pushed westward across the continent. Burning embers from railroad steam engines were cast into the forests and grasslands. Flames from loggers' piles of burning brush spread to trees. Explosives used by miners ignited vegetation. The campfires of hunters and trappers were left to smolder, setting the ground material afire.

Building too close to fire zones In recent decades, people in the United States have made the danger of wildfires worse by moving into rural or wooded areas where flammable vegetation is plentiful. Many houses and resorts in scenic areas have been built with little regard to fire danger. Building in forested areas poses new challenges to firefighters. While firefighters were previously concerned with protecting the forests, they now have the added burden of protecting people and property.

Nowhere is this situation better illustrated than in southern California, where construction of homes in or near forests or scrublands has occurred at a record pace. "Sixty-one percent of California is covered with wildlands," stated Karen Terill, spokesperson for California's Department of Forestry and Fire Prevention, in a published report by Leigh Wood titled *Fires*. "Fire is just part of California's ecological makeup. California was built to burn."

Due to the combination of hot, dry Santa Ana winds, high temperatures, dry vegetation, and scarce rain—especially during the summer months—much of Southern California is very susceptible to fire. Since the start of Southern California's building boom, wildfires have caused billions of dollars in property damage and claimed scores of lives. Following are some examples of wildfire-related calamities in the state:

- In October 1991, following five years of drought (the longest in California's recorded history), wildfire invaded Oakland and Berkeley. The flames were whipped by strong winds into 100-foot

A woman cries as a neighbor's house burns in Altadena, California, 1993; Santa Ana winds fueled fires across the southern part of the state that year. AP IMAGES.

(30-meter) towers. In a ten-hour period, approximately three thousand homes were destroyed and twenty-five people were killed. Estimates of property damage ran as high as $1.5 billion.

- In the hot, dry month of October 1993, twenty-six separate firestorms (several of them ignited by people) raged across California, from Ventura County to the Mexican border. The fires burned more than 140,000 acres (56,000 hectares), destroyed more than one thousand homes, and caused four deaths. Damages totaled more than $1 billion. One month later, fires fanned by winds of 100 miles (160 kilometers) per hour ravaged the outskirts of the exclusive beach community of Malibu.
- In October 1995, a wildfire in Marin County consumed 12,354 acres (4,942 hectares), including forty-five homes.
- In October 1996, fires in Malibu and Harmony Grove destroyed more than 150 homes and burned more than 41,000 acres (16,400 hectares).
- In July 2002, the human-caused McNally fire near Tulare burned 150,696 acres (61,031 hectares) and destroyed seventeen structures.
- In October 2003, the Cedar fire, set by a lost hunter, burned 273,246 acres (110,665 hectares) near San Diego, destroyed 4,847 structures, and took fifteen lives. The Simi fire burned 108,204 acres

(43,823 hectares) and destroyed 300 structures. The arsonist-set Old fire burned 91,281 acres (36,969 hectares), destroyed 1,003 structures, and caused six deaths.

- In September 2006, the Day fire burned 162,702 acres (65,894 hectares) and destroyed eleven structures.

Types of fire There are three types of wildfire: ground fire, surface fire, and crown fire. A ground fire is a fire that burns the organic matter on the forest floor, and burns into the underlying soil, such as a peat fire. It differs from a surface fire by being invulnerable to wind. Since oxygen is in short supply, these fires burn slowly and produce a lot of white smoke, but typically show no visible flame. They may burn for weeks on end, undetected, weaving an unpredictable pattern through the forest floor. In rare instances, a slow-burning ground fire can ignite a subterranean bed of coal. The coal beds beneath the town of Centralia, Illinois, were accidentally ignited when the town burned trash in a pit. The coal beds have been slowly burning for more than forty years. At Burning Mountain Nature Reserve, in northeastern New South Wales, Australia, a coal seam has been burning for an estimated five thousand years.

While ground fires usually burn out on their own, occasionally one ignites dry plant material or debris on the surface. In that case it becomes a surface fire. A surface fire has visible flames, but can smolder for hours before any flames appear. There is a range of risk in surface fires, from slow-moving fires that can be extinguished by hand tools and water to rapidly moving fires that pose great risk. They can travel at speeds up to 30 miles (48 kilometers) per hour, consuming dead wood and other material on the forest floor. When the debris on the forest floor is loosely packed, and therefore full of air that provides oxygen, the surface fire spreads more rapidly and burns hotter than it does when the debris is densely packed. While surface fires are the most common type of wildfires, they generally do not harm trees.

In very dry conditions, a surface fire can climb the branches of a small tree like a ladder. The flame may then spread to the tops of taller, adjacent trees, becoming a crown fire. (The crown, or canopy, of a forest consists of the treetops.)

Crown fires are the most harmful type of wildfires, destroying everything in their path. They present the greatest challenge to firefighters and are sometimes impossible to bring under control. The situation is intensified if high winds are present, providing increased oxygen and drying out wet, unburned materials. High winds push flames from treetop to treetop and can even thrust fire across a road, a small body of water, or cleared land. A small fire in the presence of strong winds rapidly becomes a large fire.

The wind carries flaming branches or embers up to 1 mile (1.6 kilometers) ahead of a crown fire to start new fires. The fires started in this manner, called spot fires, can jump over fire lines to make firefighters retreat and start fighting again in a new location.

Firestorms A firestorm, also called a blowup, is the most explosive and violent type of wildfire. A firestorm develops when a wildfire comes upon large quantities of dry wood or other plant material at the same time that strong, low-level winds are blowing. The fire suddenly explodes into a swirling bundle of flames containing powerful drafts and whirlwinds (caused by the rising of the hot air and the rushing in of cool air to take its place). This creates even stronger winds that make the fire burn hotter. Trees can explode as the moisture within them is turned to steam and rapidly expands.

A firestorm sucks loose objects into itself. As the flames whip ahead, they snap off trees. The whirlwind, which can be as great as 500 feet (150 meters) in diameter, tosses around trees like matchsticks. Firebrands (burning chunks of wood), sometimes thrown for miles, create spot fires where they land. Those spot fires grow and may merge with the advancing firestorm.

Firestorms build upward dramatically, fueling their own growth. Their heat rises into a column up to 5 miles (8 kilometers) tall, and oxygen is sucked into the bottom of the column, fueling the upward growth of the inferno. Gas bubbles rise within the column and explode in a display of fireworks.

The movement of firestorms is unpredictable and erratic, and their heat is extraordinary. Those factors, combined with the shower of embers they eject, make firestorms uncontrollable. All firefighters can do is stay out of their path and wait for them to become tamed naturally—either due to rain, a lack of fuel, or calmed winds. When the firestorm settles down, firefighters can move in to confront the flames. It was a firestorm that took the lives of fourteen firefighters on Storm King Mountain near Glenwood Springs, Colorado, in 1994.

The Shoshone Fire of 1988 in Yellowstone National Park, Wyoming. ©RAYMOND GEHMAN/CORBIS.

Wildfire seasons The times of year in which wildfires are most likely to occur vary from region to region throughout the world. In North America alone there are fifteen different fire seasons. In general, the fire season for a given area is the time of year when temperatures are highest and precipitation is lowest. Thunderstorms (with lightning, which ignites fires) and high winds are most common during warm periods.

In the region of the United States west of the Rocky Mountains, for instance, fire season normally starts in the middle of the summer when rain is scarce, making for dry forests. However, the fire season in the Northern Rockies has been starting earlier in recent years, due to early spring snow melts followed by warm days. In Southern California and in Florida's Everglades, fire season is in the dry months of fall and winter. In the northeastern United States and Canada, fire season comes twice each year: in the spring after the snow melts and in the late fall when rainfall is scarce.

The Santa Ana winds The Santa Ana winds are warm, dry gusting winds from the east or northeast that create a major wildfire hazard in southern California. These winds occur between the months of October and February, peaking in intensity in December, and blow, on average, at a speed of 40 miles (64 kilometers) per hour and gust 57 to 115 miles (92 to 185 kilometers) per hour. According to the National Weather Service, in order to be classified as "Santa Anas" the wind must be at least 29 miles (46 kilometers) per hour.

Santa Ana winds originate over the elevated plateau of the Mojave Desert and wind their way through the San Gabriel and San Bernadino mountains. They gain speed as they travel through the canyons and reach tremendous speeds in the Santa Ana Canyon (for which the winds are named). The winds then blow onto the foothills of the Los Angeles Basin and the San Fernando Valley. This air, which originates over the desert, is dry at the outset and becomes warmer and drier as it descends. Santa Ana winds bring on heat waves throughout southern coastal California, with temperatures of 100°F (38°C) or higher.

As the Santa Ana winds travel across the dry, scrubby Southern California vegetation of manzanita shrubs, tall grass, oak and eucalyptus trees, they further dry these plants and turn them into perfect brush-fire fuel. The Santa Ana winds create conditions such that a single spark can set off a wildfire. Once the fire begins, the winds fan the flames into an inferno. The Santa Anas are also known for changing direction rapidly, thus spreading fire to new areas.

Consequences of wildfires

Wildfires have a devastating effect on the landscape. They blacken and topple trees, clear away all greenery, and cover the ground with a layer of ash. They drive most wildlife out of the region and kill the animals that are unable to escape. They muddy clear rivers and streams with soil, charcoal, and ash, harming the fish and other animals that live in the water or drink from it. Wildfire can create lasting change. In the absence of trees, grasses may take hold and turn the area into a prairie. Erosion commonly occurs as a result of the loss of trees and shrubs that once held the soil in place, and landslides are a frequent menace once the burning has stopped.

Wildfires claim the lives of many people each year—most of them firefighters. Surprisingly, most wildfires do not take a large toll on larger animal populations. Birds fly out of the burning areas and other animals are able to run or walk away from the flames. Some rodents, such as squirrels and mice, dig holes underground and wait out the fire. In general, animals face a bigger threat from the scarcity of food in winter than they do from wildfire.

The positive aspect of wildfires The consequences of wildfires are not entirely negative. Fire is part of a natural cycle of forest regeneration (the process of making or starting anew). Periodic fires clear out diseased, dead, and decaying trees and material on the forest floor, creating a mineral-rich layer of ash. If the dead material is not removed from time to time, however, it can accumulate until it finally succumbs to fire; then it burns out of control and causes a great deal more destruction. In either case, though, the minerals left behind fortify the soil and enhance new plant growth.

Furthermore, when the leaves of the canopy are burned off, more sunlight reaches the forest floor and supports new growth. Fire also returns carbon dioxide to the air, thus aiding photosynthesis (the chemical process by which plants convert carbon dioxide and water into carbohydrates, releasing oxygen as a by-product, in the presence of sunlight).

Shortly after a fire sweeps through an area, a blanket of grasses, wildflowers, shrubs, and other plants appears. Deer, elk, and other wildlife return to the young forest and feed on the nutritious, tender green shoots. Woodpeckers fly to fallen trees and dig for insects beneath the bark. Bluebirds and tree swallows make their nests in dead trees. Owls and hawks return to burned areas and have a clearer view of prey on the forest floor. Studies show that three times as many plants and animals populate a forest after a fire as before one. If you walk through a natural area just a few years after a fire, it may be impossible to tell that the fire ever happened there.

Certain tree species, such as jack pine, ponderosa pine, and lodgepole pine, rely on fire for their reproduction. The cones of these trees contain a resin that is highly flammable and must be melted to open, thus dispersing the seeds. The trees' needles drop to the forest floor and dry out, providing a ready source of fuel for fires. After the Yellowstone fires of 1988 the park saw an explosion of young lodgepole pines. Other evergreens, such as the Douglas fir, only grow well in spaces that have been cleared by fire.

Another example of fire-dependent plants is the chaparral of Southern California, a dense growth of tangled, thorny shrubs and small trees. The seeds of chaparral plants can only be forced open by the heat of a fire. Unfortunately, the chaparral itself is a primary source of fuel for those fires, thus making ideal conditions for another fire in the future.

Only in recent decades have foresters recognized that fire plays a vital role in forest ecology (the science of the relationship between living organisms and their environment). Accordingly, they have changed

Healthy lodgepole pine seedlings that have sprouted seven years after the 1988 fires in Yellowstone National Park. ©RAYMOND GEHMAN/ CORBIS.

their policy from fighting *every* forest fire to allowing some—specifically those that started naturally and do not threaten populated areas—to burn until they put themselves out. Of course, they keep a careful eye on such fires to make sure they do not become dangerous.

A possible connection between wildfires and global warming

Wildfire activity in the forests of the western United States forest has increased dramatically in recent decades. According to an article in the August 18, 2006, issue of *Science*, much of the increase may be due to climate change. Researchers examined records of wildfires in the Northern Rockies since 1970, and concluded that the greatest increase had occurred at mid-elevations, where human land-use patterns would have had little effect on fire risks.

The researchers proposed instead that the sharp increase in wildfire frequency, size, and duration, and the lengthening of the wildfire season since the 1980s, has been due to increased spring and summer temperatures and an earlier spring snowmelt. Both of these regional climate changes may be related to global climate change. The researchers concluded that higher average temperatures played the biggest role in recent wildfire increases. Wildfire frequency was most closely connected to the

The Yellowstone fires

Yellowstone National Park, located in the northwest corner of Wyoming and extending into small portions of Montana and Idaho, was the scene of huge forest fires in the summer of 1988. In all, eight fires devastated 793,000 acres (317,000 hectares) in the park, about one-third of the parkland, and 600,000 acres (240,000 hectares) near the park. Twenty-four buildings inside the park burned, as did another forty outside the park. There were two deaths due to the blaze. The stage for fire had been set by the extreme drought throughout the western United States that summer. All but one of the fires are believed to have been started by lightning; the other was caused by human carelessness.

Some days the fires advanced as far as 14 miles (23 kilometers). The largest burn in a single day occurred on August 20, a day nicknamed Black Saturday. On that day, 165,000 acres (66,000 hectares), an area twice the size of Chicago, was burning. This acreage was greater than the total of all Yellowstone parkland that had burned since the park was first opened in 1872.

At first Yellowstone officials allowed the natural fires to burn, convinced that fire was needed to restore the park's ecological balance. Due to high winds, however, the fires spread rapidly. The flames grew to 200 feet (61 meters) and were hot enough to melt steel. By mid-July, 16,600 acres (6,640 hectares) had burned, new fires had been sparked by lightning, and no rain was in the forecast. As the blaze threatened to travel beyond the bounds of the park, officials decided it was time to step in. By then, however, the fire had become impossible to control.

Approximately twenty-five thousand firefighters and four thousand military personnel from across the nation were enlisted in one of the largest battles against fire in history. The blaze was fought using hand tools, fire trucks, bulldozers, dozens of helicopters, and airplanes. Aircraft dropped some 10 million gallons (45 million liters) of water and more than 1 million gallons (4.5 million liters) of fire retardant on the flames. Around $120 million was spent fighting the Yellowstone fires, making it the highest firefighting bill in the history of the United States to that time. Despite these monumental efforts, it took two months and September rains to stop the burning. Some areas continued to smolder into November.

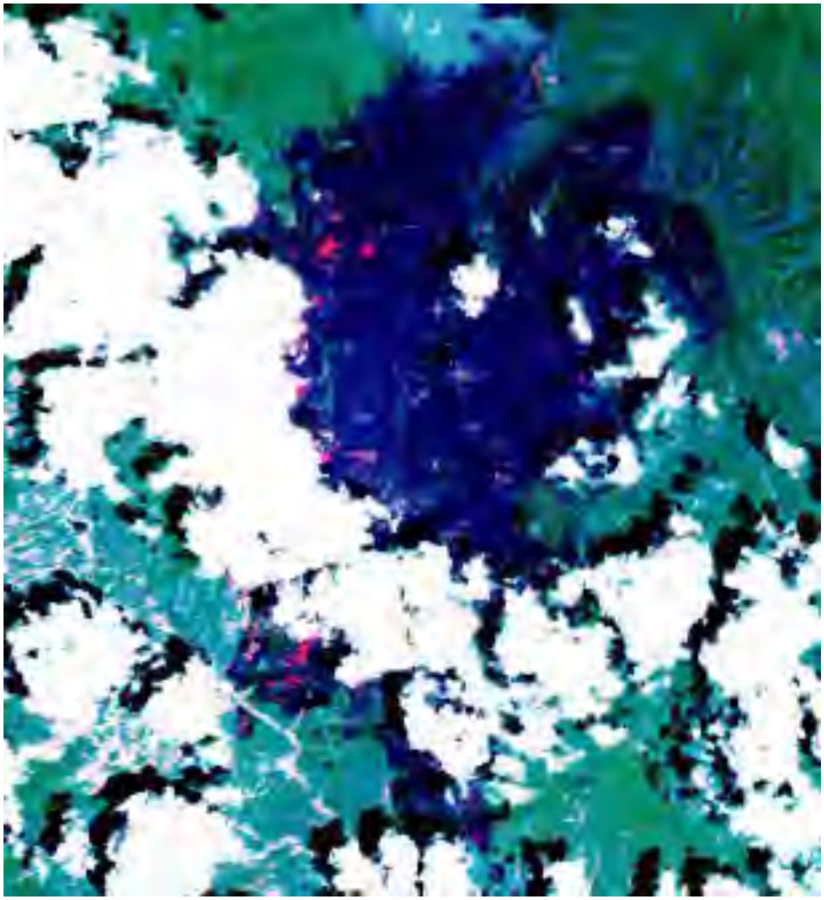
timing of the spring snowmelt. An earlier snowmelt resulted in a drier, longer fire season. The year-round fire season of 2005–2006 could become the norm rather than the exception.

This conclusion is important to forest managers because the currently proposed solutions to the problem of increased fire risk, ecological restoration, and fuels management are based on the assumption that increased risk is primarily due to prior land use. If increased risks are largely due to recent climate change, then ecological restoration and fuels management may be ineffective.

Many people were upset about the extent of the damage caused by the Yellowstone fires and blamed the park management for initially letting the blaze burn. Yellowstone Superintendent Robert Barbee defended the park management's actions. "Yellowstone is still the magnificent place it always has been," stated Barbee in a published report. "Fires are a part of the life processes here, and the park will heal and regenerate its natural scars as it has countless times before. I'm excited about that process."

Fire burns in Yellowstone National Park, 1988. ©JONATHAN BLAIR/CORBIS.

It may also be possible that increased wildfires are contributing to global warming. Forests, such as the boreal forests of Alaska, are in carbon balance. The amount of carbon stored in the vegetation of forestland remains relatively constant over long periods. Trees die and decay or portions of the forest burn, but these dead trees and burned portions are replaced by new growth. However, if a significant portion of the forest burns, or losses due to fire exceeds the forest's ability to regenerate, then there could be an overall increase in greenhouse gases in Earth's atmosphere.



Satellite image of the Hayman fire in Colorado in 2002. The dark blue areas are charred vegetation; red areas are active fires. COURTESY NASA/GSFC/METI/ERSDAC/JAROS, AND U.S. /JAPAN ASTER SCIENCE TEAM.

Fighting fires: The technology connection

Many types of technology are employed in both the detection and the fighting of fires. Today, the forest ranger in a lookout tower plays a minor role in finding wildfires. While the U.S. Forest Service still owns more than five thousand towers, only a few are in use. Helicopters and airplanes are now on the front lines of both finding fires and putting them out.

Lookout aircraft are outfitted with infrared cameras that "see" heat, even at night. Infrared is a type of electromagnetic radiation that has a wavelength longer than visible light. Infrared cameras create color-coded maps of an area, with each color representing a specific temperature range. These maps pinpoint "hot spots," places where fires are beginning. Infrared cameras can identify a hot spot 6 inches (15 centimeters) wide from a height of 8,000 feet (2,400 meters). Some aircraft are also equipped with special cameras that detect water in vegetation. Those cameras identify the driest areas so rangers and pilots can keep a close eye there for fire.

Aircraft also monitor sites reported by weather stations to have been struck by lightning. Lightning strikes are observed by sensors mounted on poles throughout the western United States. The sensors transfer information about strikes to weather stations, and the stations forward this data to fire-detection aircraft.

Once a blaze has been identified, aircraft pilots transmit the fire's location by radio. Firefighters are then notified and transported to the scene quickly.

Methods of fighting fires Firefighters employ numerous methods in the fight against wildfires. Each of those methods is aimed at depriving a fire of one or more of its essential ingredients: fuel, oxygen, and heat.

One method of fighting a fire is creating a fire line, or control line. A fire line is a cleared strip of ground constructed in the path of the approaching fire. Firefighters chop away brush using a tool called a Pulaski, which is a combination of an ax and a hoe. If possible, chainsaws and bulldozers are

Firefighters mop up hot spots from a wildfire in Oregon, 1996. AP IMAGES.

brought in to help do the job. The purpose of the fire line is to keep the fire from spreading by creating an area without any fuel. Firefighters sometimes also use natural fire lines such as bodies of water, rocky cliffs, bare mountaintops, or clearings in the woods.

Another way to stop a wildfire is to set a small fire, called a backfire, in the path of the oncoming blaze. The backfire is a controlled fire that consumes the vegetation in a given area, so that fuel will be unavailable once the main wildfire arrives. To start a backfire, firefighters shoot flares into the desired area or spread flaming gasoline or diesel fuel using a drip torch. Backfires must be treated with extreme caution to make sure they do not get out of control and become wildfires themselves.

Firefighters also try to stop the fire with water sprayed from hoses or dropped from the air by helicopters. When water hits the flames it creates steam. The steam creates an insulating layer around the flames that deprives the flames of oxygen. Water also lowers the temperature of the fuel, thereby reducing the heat. Many fire vehicles, both on the ground and in the air, use a water-foam mixture instead of just water. This foam penetrates and coats fuels more effectively to reduce the heat and extinguish the fire.

Another way to slow the spread of wildfires is to apply fire retardant on the fuel ahead of the flames. The mixture of water, chemicals (which

A firefighter attempts to stop a rapidly spreading wildfire in Varibobi, a village in Greece, in 1998. AP IMAGES.

Fire-fighting planes

Water or fire retardant is often dropped by a C-130 cargo aircraft carrying a specially designed five-tank system called a Modular Airborne FireFighting System (MAFFS). These carry 3,000 gallons (11,370 liters) of fire retardant. The MAFFS is a freestanding unit and can be loaded into any suitable C-130 aircraft. A newer model, the MAFFS II is built of carbon fiber, so it is lighter but can hold more, up to 3600 gallons (14,000 liters), can drop partial loads, and can operate with the cargo bay doors closed.

A fire-fighting plane flies over Yellowstone National Park, 1988. ©JONATHAN BLAIR/CORBIS.

encourage new plant growth), and sticky gum is dropped on fires from aircraft. The retardant works against fires by coating the vegetation and thereby restricting the fire's supply of fuel. Fire retardants, often colored red so aircraft pilots can see which areas they have covered, are dropped on vegetation ahead of a fire to create a zone of nonflammable material.

Classes of firefighters There are several different groups of firefighters, each of which utilizes their particular skills to battle blazes. The largest groups of firefighters, which may consist of hundreds of professionals and volunteers, are called line crews. These firefighters dig fire lines and spray water on the flames. They also conduct the final stage of the operation: a lengthy process called mopping-up, in which they seek out heat sources that may reignite fires, such as smoldering logs, and cover them with water or dirt. Line crews also dig up patches of underground fires, such as smoldering roots, and put them out.

Some firefighters are part of engine crews. For fires accessible by road, engine crews travel to the scene on specially equipped, four-wheel-drive fire engines. The engines have large water tanks and hoses with high-pressure nozzles.

There are two elite groups of firefighters employed to fight large and small wildfires: hotshots and smokejumpers. Hotshots are teams that venture into very dangerous areas and work long shifts to contain fires; they are often the first firefighters on the scene. In 2007, ninety-two crews were available for the fire season, employed by the USDA Forest Service, Bureau of Land Management, National Park Service, various Native American tribes, and the states of Alaska and Utah.

Smokejumpers are firefighters who parachute from airplanes into remote locations to battle newly identified blazes. They wear padded, fire-resistant jumpsuits and helmets with face masks (for protection from the trees they may encounter on their descent). Once they land, they retrieve their heavy backpacks full of equipment, weighing up to 110 pounds (50 kilograms), that are also sent down by parachute. The primary way they fight the fire is by digging fire lines. When smokejumpers have finished fighting a fire, they typically have to walk several miles (kilometers) with the heavy backpacks to get out of the forest.

Smokejumpers must be in top-notch physical condition, and the training to become a smokejumper is very rigorous. Many smokejumpers, when they decide to stop jumping out of airplanes, become hotshots. In recent years the role of smokejumpers has expanded to include assisting in the management of natural resources.

The perils of firefighting Putting out a wildfire is difficult, dangerous, exhausting, and dirty work, and many firefighters die each year while fighting fires. There is no safe haven in the vicinity of a wildfire. When the winds shift, a hill that may have seemed out of the way can abruptly be set aflame. A sudden gust of wind can turn a moderate blaze into a firestorm. Wildfires typically occur in remote areas, far from hospitals and fire stations. If a firefighter is injured, help may be hours away.

Firefighters can inhale as much smoke in one day as one would get from four packs of cigarettes. The smoke sometimes makes it difficult to breathe and is irritating to the eyes. In addition, firefighters face dangers from falling trees or limbs (that are sometimes aflame), rock slides, and wild animals. Firefighters work long shifts around the clock, sometimes thirty-six to forty hours straight. They work in all types of weather and in intense heat, and get little sleep.

An August 1910 wildfire in the Idaho panhandle was one of the deadliest for firefighters in U.S. history. The fire, called the Big Burn, consumed 3 million acres (1.2 million hectares). It took the lives of seventy-eight firefighters as well as seven civilians. One firefighter, a ranger named Edward Pulaski, became a hero by saving the lives of thirty-nine of his crew members. Pulaski guided the men into a cave and instructed them to wet themselves down with spring water. Although the men temporarily lost consciousness due to the smoke and gases in the cave, they emerged alive after the fire had passed.

It was after that fire that the U.S. Forest Service instituted its policy of putting out all blazes, no matter what their cause. Specifically, park officials were charged with extinguishing any blaze before ten o'clock the following day. If they could not meet that order, they would have to fill out lengthy reports explaining why they had failed.

More recently, in the summer of 1994, fourteen firefighters, some of them smokejumpers, were killed battling a fast-moving blaze near Glenwood Springs, Colorado. The fire spread from 50 acres (20 hectares) to 2,000 acres (800 hectares) in just a few hours because of wind gusts. Some of the burned area contained areas of highly flammable Gambel oaks. The flames were as tall as a ten-story building.

Wildland firefighters, like other firefighters, must deal with arsonists (people who deliberately set fires). In the late summer and early fall of 2006, an arsonist set a series of fires across Southern California. The last one set, known as the Esperanza fire, was started on October 26, 2006. The fire burned for six days and consumed 40,200 acres (16,300 hectares), cost the lives of five firefighters and destroyed many homes and outbuildings. A suspect was arrested and charged with five counts of murder, multiple counts of arson, and multiple counts of using an incendiary device. He was linked to a total of twenty-three fires.

Prescribed burns prevent fires One technique used by foresters to prevent wildfires is the prescribed burn, which is a planned, controlled fire that

Shelters save firefighters' lives

One essential item that all wildland firefighters carry with them is a portable shelter, which is a thin, lightweight sheet of aluminum-coated fiberglass cloth (aluminum reflects away heat). Shelters are only used when firefighters become trapped in rapidly expanding fires. If a firefighter lies on the ground inside the shelter, he or she can survive temperatures as high as 1,600°F (871°C) for short periods. The shelter, also called a shell, is the size of a newspaper when folded and unfolds to a small tent in a matter of seconds.

Affectionately referred to as "shake and bakes," shelters have saved many lives. In August 1985, for example, seventy-three firefighters took refuge in their shelters during an explosive wildfire in Idaho's Salmon National Forest and came out alive. Unfortunately, shelters are not effective against extremely hot fires, or ones in which the high temperatures last for more than a few minutes. They also do not provide air for breathing, so firefighters must hold their breath or try to keep enough air trapped inside the shelter.

clears flammable debris from the forest floor. The goal of a prescribed burn is to keep dead vegetation from piling up and becoming fuel for a wildfire. Before a prescribed burn is set, fire lines are carefully constructed. The fire is only set when winds are calm and conditions are relatively wet, to prevent the accidental spread of the fire beyond the prescribed area. In Yosemite National Park, for instance, prescribed burns are conducted on hundreds to thousands of acres each year.

A matter of survival

There are several fire safety rules that, if followed, minimize the risk of starting fires. The first is to never play with matches. Matches and lighters should be kept out of reach of children. Adults, too, should be monitored for their use of matches. Matches, cigarettes, and other items that involve fire should be disposed of properly.

Always build campfires away from nearby trees or shrubs. Keep a bucket of water or a fire extinguisher nearby in case the flames suddenly leap beyond the fire enclosure. Do not leave a fire unattended while it is still burning. When the flames have disappeared, pour water on the coals and stir. Repeat this step and feel for heat. Only leave a campfire when the coals are wet and cold.

Fireworks, many of which are illegal, are one of the biggest causes of wildfire. Only use fireworks that are legal, and with adult supervision. Keep fireworks away from flammable materials. Do not set off fireworks in natural areas or during dry periods.

Finally, if you are a visiting a park or forest, learn the fire danger in that area. In national parks, daily fire-danger ratings are issued that describe the likelihood of fires. When there are high ratings, campfires may not be allowed. If you are in a natural area that is experiencing a wildfire, follow the instructions of park officials. Evacuate the area immediately if told to do so. If you observe someone being careless with fire, report that person's actions to park officials or the nearest fire station.

Smokey Bear

Smokey Bear (which is the official name; not Smokey *the* Bear, as popularly called) is a character that was developed by the U.S. Forest Service in 1945 to help spread the message of fire prevention. The anti-fire campaign, called the Cooperative Forest Fire Prevention (CFFP) program, resulted from a need to protect forests and thereby ensure a supply of lumber for the United States during World War II (1939–45). In the beginning of the campaign, the CFFP used wartime slogans on its posters. In 1944, it made the Disney character, Bambi, its official spokes-animal. The following year Bambi was replaced by Smokey Bear. Smokey was named for ''Smokey'' Joe Martin, Assistant Chief of the New York City Fire Department from 1919 to 1930.

Smokey became famous on posters and radio announcements with the message: ''Only YOU Can Prevent Forest Fires.'' The campaign educated citizens about how people cause forest fires and ways to prevent their occurrence. Since the beginning of this public education program, the damage caused by forest fires started by people in the United States has been reduced by 80 percent.

In 1950, the name Smokey was given to a real bear cub. That cub, which was found badly burned and clinging to a tree after a forest fire in the Lincoln National Forest in New Mexico, was treated for its wounds and then placed in the National Zoo in Washington, D.C. The real-life Smokey Bear became the official, if unknowing, symbol of the anti–forest fire campaign. Smokey was made an honorary member of the Washington, D.C. Fire Department. He remained at the zoo until his death in 1976.

Smokey Bear on a roadside fire danger sign. ©JOSEPH SOHM/VISIONS OF AMERICA/CORBIS.

Rules for residents of fire-prone areas People who live in or near wilderness areas can take several steps to lessen the danger of fire. If constructing a new property, it is best to locate it at the edge of a forest—as close as possible to fire-protection facilities. Use fire-resistant materials when building or renovating and be sure they are in compliance with local building codes. Avoid the use of untreated wood shingles, for instance, since they burn easily. Stone walls are useful for deflecting heat and flames. Smoke detectors should be installed on every floor and near bedrooms, and the home should have several accessible fire exits.

It is also wise to build patios and swimming pools at wildland homes, since those structures provide a safety zone from encroaching fire. Homeowners with swimming pools can purchase pumps to spray water on flames.

The following steps are also recommended to residents who live in or near wildlands:

- Keep the chimney clean and cover it with wire mesh .5 inch (1.3 cm) or smaller to prevent the ejection of fiery debris.
- Regularly clear the roof and rain gutters of dead limbs, leaves, and needles.
- Store firewood piles away from the house and clear the area around the house of dead vegetation.
- Replace native vegetation around the house with fire-resistant plants, such as periwinkle, ice plant, or Texas privet shrub.
- Keep branches near the house pruned to less than 10 feet (3 meters) and remove dead limbs and moss from nearby trees. Trees near the house should not be closer than 10 feet (3 meters) from one another.
- Avoid the open burning of leaves or other materials.

[*See Also* **Climate; Climate Change and Global Warming; Human Influences on Weather and Climate; Landslide; Thunderstorm**]

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Forecasting

Weather forecasts assist people in many ways, such as helping them to decide when to plan a trip or when to plant their gardens. Predicting the weather, defined as the set of conditions of temperature, humidity, cloud cover, and wind speed at a given time, may also be a matter of life and death. Winter storms, hurricanes (the strongest form of tropical cyclones), tornadoes (violently rotating columns of air), and thunderstorms (small but intense storms) are all potential killers. A forecast can serve as a warning to those who are in the path of deadly weather.

Over the last century, meteorology and weather forecasting have made great advances. Meteorology is the scientific study of the atmosphere and atmospheric processes, especially weather and climate. Climate is the weather experienced by a given location, averaged over several decades. Meteorologists now have access to sophisticated technology and advanced methods of information gathering and analysis of atmospheric conditions, all of which make forecasting easier. The ability to make accurate forecasts is a sign that meteorology has entered the modern scientific era, not to mention every meteorologist's professional triumph.

What is a forecast?

A weather forecast is a prediction of what the weather will be like in the future, based on present and past conditions. Methods of forecasting range from very simple techniques based on wind speed and direction, temperature, cloud patterns, and experience, to very complex techniques using sophisticated computer modeling and large databases of historic information. Simple forecasting methods may be based on sayings, such as a "clear moon, frost soon"; or natural signs, such as the opening and closing of pinecones in response to humidity. Some of these sayings and so-called folk wisdom are useful, while others have no basis in fact.

On the other end of the forecasting scale are scientific methods, which involve the continuous measurement and analysis of atmospheric

WORDS TO KNOW

absolute humidity: the amount of water vapor in the air, expressed as a ratio of the amount of water per unit of air.

agricultural report: a specialized weather report tailored to the needs of farmers, which includes current temperature, precipitation, and wind speed and direction, as well as frost warnings and predictions of temperature and precipitation for the days to come.

air mass: a large quantity of air throughout which temperature and moisture content are fairly constant.

air pressure: the pressure exerted by the weight of air over a given area of Earth's surface. Also called atmospheric pressure or barometric pressure.

anemometer: an instrument used to measure wind speed. A common type is the cup anemometer.

aneroid barometer: a type of barometer that consists of a vacuum-sealed metal capsule, within which a spring expands or contracts with changing air pressure.

aviation report: a specialized weather report tailored to the needs of pilots, which provides information on the height of the clouds, visibility, and storm systems.

backing wind: a wind that shifts direction, rotating counterclockwise higher in the atmosphere.

barograph: an aneroid barometer that records changes in air pressure over time on a rotating drum.

barometer: an instrument used to measure air pressure.

blizzard: the most severe type of winter storm, characterized by winds of 35 mph (56 kph) or greater, large quantities of snow, and temperatures of 20°F (–6°C) or lower.

chaos theory: the theory that the weather, by its very nature, is unpredictable. Every time one atmospheric variable (such as heat, air pressure, or water) changes, every other variable also changes—but in ways that are out of proportion with the first variable's change.

climate: the weather experienced by a given location, averaged over several decades.

cold front: the line behind which a cold air mass is advancing, and in front of which a warm air mass is retreating.

dispersion: the selective refraction of light that results in the separation of light into the spectrum of colors.

Doppler radar: a sophisticated type of radar that relies on the Doppler effect, the change in frequency of waves emitted from a moving source, to determine wind speed and direction as well as the direction in which precipitation is moving.

drought: an extended period of abnormal dryness.

El Niño: means "the Christ child" in Spanish. A period of unusual warming of the Pacific Ocean waters off the coast of Peru and Ecuador. It usually starts around Christmas, which is how it got its name.

flash flood: a sudden, intense, localized flooding caused by persistent heavy rainfall or the failure of a levee or dam.

fog: a cloud that forms near or on the ground.

front: the dividing line between two air masses.

Pinecones react to weather changes. JLM VISUALS.

conditions. With basic weather tools, local forecasts can easily be created. With today's high-tech instruments, professional meteorologists can create global forecasts with considerable accuracy.

Skilled versus unskilled forecasts Anyone can guess at what the weather will be like tomorrow and have a fair chance of being correct. Since there is a limited range of possibilities for weather conditions at any season of the year, simple guesses will often match actual conditions. This is an example of an "unskilled" forecast. A "skilled" forecast, on the other hand, is based on observation and analysis of atmospheric conditions.

Skilled forecasting is not limited to professional meteorologists, however. Farmers and ranchers, whose livelihoods depend on the weather, can become quite skilled at predicting the weather over a twenty-four- to forty-eight-hour period, based on simple observations and experience.

When it comes to short-range weather forecasting, there are two principal types of unskilled forecasts. One is based on persistence and the other is based on long-range climatic predictions. The "persistence method" is simply predicting that tomorrow's weather will be the same as today's. If it has been hot and dry for several days, predicting another day of hot, dry weather is probably an accurate forecast. This method also works well in locations where the weather tends to be unchanging for days on end. Two examples are Los Angeles, California, where there tends to

A meteorologist studies weather patterns. ©VISUALS UNLIMITED/CORBIS.

be haze (high humidity and lots of airborne particles) in the morning and sunshine in the afternoon; and Seattle, Washington, where it is often cool and drizzling. Predicting mild and sunny weather for San Diego, California, is also a safe bet, since its weather is moderated by cold ocean currents.

Another type of unskilled forecast is created by studying weather information recorded over several decades to find the average conditions for a given location in a particular time of year. This is the kind of information often included in various almanacs. For example, the state of Michigan historically averages ten days of rain in September. Since there are thirty days in September this means that it rains, on average, on one-third of the days.

A skilled forecast, in contrast, is one that draws on global as well as local atmospheric observations. These observations include information not available to the average person, such as barometric pressure (the pressure exerted by the weight of air), winds at upper altitudes, dew point, and others. The forecasts given on television incorporate observations taken all over the world that have been processed by computers. The end result is a weather map showing temperatures, pressure highs and lows, precipitation (water falling to the ground), fronts (the dividing lines between air masses), and predictions as to how these conditions will change over the coming few days.

A skilled forecast is expected to be more accurate than an unskilled forecast. After all, wild guesses alone could produce forecasts that are accurate about half of the time. Thus the success rate of forecasting is not determined simply by how often the forecasts are correct, but by how far they exceed the success rate of unskilled forecasts.

Forecasting is a global endeavor Modern-day forecasters look at weather as a global process. The reason for this approach is that the atmosphere, where weather occurs, forms a continuous blanket around the entire planet. Therefore, weather conditions in one part of the world may eventually affect conditions in another part of the world. Although it is not necessary to have information from all around the world to produce forecasts for the short term (a few days), such information becomes necessary when making longer-term forecasts.

As a general rule, simple observation of local atmospheric conditions will be useful for predicting the weather for the following few hours. To get a picture of what the weather will be tomorrow or the next day requires regional or statewide weather data. Accurate predictions for three or more days require information from the whole continent. For still longer periods global weather, observations are necessary.

International cooperation in data collection The World Meteorological Organization (WMO) is responsible for organizing international cooperation in weather observations and reporting. This network of more than 180 national weather services, based in Geneva, Switzerland, is an agency of the United Nations. The WMO, through its World Weather Watch (WWW) program, oversees the worldwide collection and standardization of measurements of atmospheric conditions.

The WWW receives information from thousands of weather stations. About twelve thousand of these stations are on land, and another seven thousand are located at sea, on ships and oil rigs. Nearly one thousand more are radiosondes, instrument packages carried on board small weather balloons that take readings in the upper air. In addition, observations are collected from numerous aircraft, radar stations (stations that detect the location, movement and intensity of precipitation) and weather satellites, which are equipped with infrared and visible imaging equipment. Weather observers at land and sea stations are either weather professionals with government organizations or private industry, or trained nonprofessionals.

Who's Who: Hurd Willett

Hurd "Doc" Willett (1903–1992) was one of the most respected and skilled long-range forecasters of all time. Throughout his sixty-two-year career, Willett worked as a forecaster, teacher, and researcher. He authored over one hundred books and articles on meteorology and forecasting.

Willett's primary research topic was one that is still controversial within the meteorological community: the connection between sunspot cycles and long-range weather patterns. Astronomers have determined that the energy output of the sun varies somewhat with sunspot number. Willett theorized that climate change is linked to the sunspot cycles. This connection is known as the solar-climate relationship.

When Willett was nine years old he began recording winter storms and cold temperatures in a diary. Just before turning eleven, Willett knew what his future held: "In 10 years, one week, and three days, I will reach my majority," he wrote. "When I grow up, I want to be a weather man."

Willett began his career in weather science in 1925, when the discipline was still relatively undeveloped. He did much to advance the field. In the late 1920s and 1930s, Willett pushed for the integration of the polar front theory into U.S. meteorology. The polar front theory states that the storms of the middle latitudes are brought about by the mixing of cold, polar air from the north and warmer air from the south. The latitude at which this mixing occurs, approximately 60° north, is known as the polar front. Willett also developed some of the long-range forecasting principles that are now used in computer models.

Willett was made famous by his article, "Cold Weather Ahead," which was published in the *Saturday Evening Post.* In the article, Willett predicted that the series of devastating hurricanes that had pounded the East Coast from 1938 to 1955 would cease by 1965. He also predicted that after 1960, the Northwest, Rocky Mountains, and the Midwest would no longer experience droughts, except for a possible period of drought from about 1975 until 1980. Willett was astonishingly accurate. New England was free of major hurricanes from 1960 until 1985. The only drought to plague the northern United States between 1960 and the early 1980s lasted from 1976 to 1978.

Willett received the first-ever Distinguished Scientific Achievement Award from the American Meteorological Society in 1951 for his contributions to meteorology and to our understanding of the large-scale circulation patterns of the atmosphere.

Processing the information Observers in the WWW network take measurements, at set time intervals, of temperature, humidity, precipitation, wind speed and direction, and air pressure. They also observe the clouds, noting their type, height, movement, and the amount of sky they cover. Observers send this information to local weather centers, where it is encoded, or translated into a type of shorthand using abbreviations and symbols. Those reports are then transferred to the three World Meteorological Centers of the WMO, located outside of Washington, D.C., in Moscow, Russia, and in Melbourne, Australia.

At the World Meteorological Centers, the reports are entered into supercomputers, which produce maps and charts representing a complete picture of the world's weather conditions. General weather forecasts are made from this information and sent out every six hours to national weather agencies. Next, these forecasts are sent to local weather agencies where they are used along with other data to create local forecasts. The local forecasts are then made available to the general public through the news media, such as newspapers, radio, television, and the Internet.

How data collection works in the United States The collection of weather information in the United States is coordinated by the National Weather Service (NWS), an agency of the National Oceanic and Atmospheric Administration (NOAA). The NWS receives information from approximately one thousand land-based weather stations across the United States, most of which are located at airports. While many of these stations are operated by NWS staff, others are run by employees of other government agencies, such as the Federal Aviation Administration, or by private citizens. Weather conditions are also recorded on more than two thousand ships and over one hundred automated stations on oil rigs, lighthouses, or buoys. These stations are located on the Great Lakes and in parts of the oceans that influence weather in the United States. Over 125 radiosondes (electronic instrument packages used in weather balloons) measure temperature, air pressure, and relative humidity as they ascend from ground level to a maximum of about 20 miles (30 kilometers) above ground.

Measurements from land and sea stations are sent to the NWS every hour. Those from radiosondes are sent twice daily. The NWS also receives information from stations around the world every three hours. In addition, about twelve thousand volunteer weather-watchers send monthly logs to the NWS. These volunteers are private citizens who take daily readings of precipitation and maximum/minimum temperatures. Some volunteers work at cooperative weather stations with equipment supplied by the NWS. Information supplied to the NWS by volunteer weather-watchers is included in studies of long-term climatic change.

Short-, medium-, and long-range forecasts A forecast is considered "short-range," "medium-range," or "long-range," depending on how far in the future its predictions extend. Short-range forecasts give detailed information about what to expect over the following twenty-four to forty-eight hours in terms of the temperature, wind speed and direction, cloud cover, and precipitation. Medium-range forecasts cover a period of two to ten days in the future. They predict the day-to-day temperature and precipitation up to five days in advance and describe likely temperature and precipitation averages for six to ten days in advance. Long-range forecasts make general weather predictions as far as three months in advance. These forecasts are limited to predicting whether rainfall and temperatures will be above or below average.

Short- and medium-range forecasts are produced by examining present atmospheric conditions. Long-range forecasts differ in that they are based on records of what the weather has been like, on average, for a particular climate at a particular time of year. Long-range forecasts are not intended to describe what the weather will be like from one day to the next, but are general guides as to what type of weather can be expected to dominate for that period, that is, warmer, colder, wetter, or drier than usual.

How accurate are forecasts? Many people recall times that forecasts have been incorrect more readily than they recall times that forecasts have been correct. This may be the case because the memory of a ruined picnic is more vivid than the memory of outdoor activities undisturbed by the weather.

The reality is that, for most parts of the world, forecasts for twelve to twenty-four hours in advance are accurate about 87 percent of the time; twenty-four hours in advance they are accurate 80 percent of the time; and three to five days in advance they are accurate 65 percent of the time.

There is every reason to believe that forecasting will continue to become more accurate in the future, and yet, the accuracy of forecasting will always have its limits. The basic problem meteorologists have to deal

Chaos theory and butterfly effect

In the early 1960s, Edward Lorenz made a discovery that has had a profound effect on weather forecasting. Lorenz's "chaos theory" explains that weather, by its very nature, is unpredictable. Lorenz used mathematical computer models to show that every time one atmospheric variable (e.g., heat, air pressure, water) changes, every other variable also changes. Furthermore, he found that even a slight change in one variable could produce significant changes in other variables. Thus, when Lorenz programmed two nearly identical sets of initial conditions into his computer model, he came up with two completely different forecasts.

Lorenz concluded that weather forecasting is chaotic because it is impossible to know, with absolute precision, every atmospheric condition at every moment. There will always be tiny discrepancies between the data used to create computerized forecasts and the actual atmospheric conditions. The effect of these discrepancies increases daily throughout a forecast so that by day ten a forecast may bear little resemblance to reality.

In theory, a small disturbance occurring in one part of the world can eventually have major implications in another part of the world. This condition is known as the butterfly effect. It gets its name from the idea that the flapping of a butterfly's wings in China, for instance, may trigger a storm system in New York.

The major conclusion of the chaos theory and the butterfly effect is that it will never be possible to predict, with complete certainty, the day-to-day weather for more than two weeks in advance.

with is the overwhelming complexity of the atmosphere. There are too many rapidly changing and erratic variables that affect weather patterns to get a complete and exact picture of the atmosphere.

Meteorologists first began to suspect that weather prediction would never be an exact science in the early 1950s. Computer modeling of weather patterns had revolutionized weather forecasting, and meteorologists believed that the new technology would rapidly and drastically improve the accuracy of forecasts. However, they were disappointed in

What can be forecast and when?

- Forecasters predict the path of a quick and violent storm, such as a tornado, from a few minutes to an hour before it strikes.
- Forecasters can warn of a large-scale storm system (such as a hurricane or heavy rain storm or snow storm) up to forty-eight hours before it arrives.
- Forecasters can alert people to an approaching cold front three to five days in advance.
- Forecasters can tell the average temperature and precipitation to expect for six to ten days into the future.

the results. While the forecasts were improving, that improvement was painfully slow. It seemed that while the technology grew by leaps and bounds, the increased accuracy of forecasts barely inched along. This led mathematician and meteorologist Edward Lorenz (1917–), a professor at the Massachusetts Institute of Technology, to investigate the slow improvement rate of forecasts.

Making your own forecast

The concepts covered in the chapter, "Weather: An Introduction" together with the information contained in this section are sufficient to allow people to make very basic forecasts. Of course, these forecasts will not be as accurate as the National Weather Service and will not include global or long-range forecasts. But it may still be instructive to create short-range, local forecasts and compare their accuracy with those broadcast on television or printed in the newspaper.

Interpreting natural signs Throughout the ages, people have associated all sorts of natural occurrences with approaching weather. These phenomena have included animal and plant behavior as well as the appearance of the sky and shifting winds. Some of these associations have proven accurate and are scientifically sound. That is not to say that animals and plants have predictive powers. Rather, they behave as they do because they are responding to current atmospheric conditions. These conditions happen to precede certain types of weather. Other aspects of natural forecasting, particularly those based on mythology and folklore, have been shown time and again to be invalid.

While natural signs alone will not provide everything needed to prepare forecasts, they can provide important clues. Animals and plants are generally more sensitive to environmental change than are humans. Clouds and winds are also reliable indicators of certain types of weather.

All other factors being equal, the forecaster with an understanding of natural signs is likely to enjoy a higher rate of success than one without that understanding. What follows are descriptions of some of the most

Cows often lie down before it rains. ©TIM GRAHAM/ CORBIS.

common natural signs of impending weather for the middle latitudes (including the United States and Canada), where weather patterns generally move from west to east.

Animals Many animal species react to decreasing air pressure or increasing humidity, both of which are signs of rain. For instance, cows often lie down or huddle together in the grass before the rain comes. The reason for this behavior is not completely understood. One hypothesis for this behavior is that cows are preserving patches of dry grass, since they do not like to lie on wet grass. An alternate theory is that falling air pressure affects the digestive system of cows, making it more likely that they will choose to lie down rather than roam through the pasture grazing.

It is also common to see birds and bats flying at high altitudes before it rains. One proposed reason for this behavior is that they are chasing insects, which are carried upward by rising currents of warm air. This is a condition that typically precedes a thunderstorm.

A fisherman can sometimes tell that a storm is coming by the number of nibbles at his line. This pattern may be caused by fish trying to catch a meal before it is time to seek deeper, calmer waters. Rabbits, rattlesnakes, and other animal species are also known to intensify their food-gathering efforts before being driven to shelter by rain.

Other signs of rain are bees returning to their hives, gulls staying close to shore, and insects becoming more active. A whole chorus of animals seems to announce the rain: Frogs croak, geese honk, cicadas hum, and bees buzz, all more loudly than usual. Each of these types of behavior are responses to increasing humidity and/or decreasing air pressure.

One way to predict that a thunderstorm is on its way is to observe the behavior of pets. Animals are made uncomfortable by the static electricity in their fur, so a cat grooming itself constantly or a dog acting restless may indicate that a storm is approaching.

Plants Pinecones close in response to rising humidity as do some flowers (tulips, African marigolds, scarlet pimpernels, dandelions, clover, and many others). One theory is that flowers close in response to moisture so the rain will not wash away their pollen. The leaves on trees may curl up in response to high humidity, something a person could notice as a sign of oncoming rain.

The sky Two or three generations ago, people were much better at predicting the weather because they watched the sky much more than is common now. They especially watched cloud formations and learned how they could be used to predict weather. Cloud formations are probably the most reliable signs of an approaching storm or change in the weather. Far in advance of a warm front (the line behind which a warm air mass is moving), for example, the thin, high cirrus clouds known as "mare's tails" often appear in the sky. As the front gets closer, there may be an accumulation of high-level and or middle-level clouds as a possible indicator that a storm is brewing. The formation of low-level clouds after the middle- and high-level clouds have moved in means that rain or snow will soon follow.

An old weather proverb says: "Red sky at night, sailors' delight; red sky in morning, sailors take warning." This simple saying is often correct because weather patterns generally move from west to east. Thus, if skies are red at night, the sunlight, which is coming from the west where skies are clear, is reflecting off clouds to the east. However, if skies are red in the morning it is because the sunlight, in the east, is reflecting off clouds to the west. Clouds in the west may indicate that a storm is approaching.

Rainbows can be similarly interpreted. They are produced by the dispersion (selective bending) of sunlight through the rain. People can observe a rainbow only when the Sun is at their backs. If the rainbow is to the east, the rain has already passed. However, if a rainbow appears to the west of an observer, the rain is probably coming in her direction.

WORDS TO KNOW

frontal system: a weather pattern that accompanies an advancing front.

frostbite: the freezing of the skin.

geostationary satellite: weather satellite that remains above a given point on Earth's equator, traveling at the same speed as Earth's rotation about 22,300 miles (35,900 kilometers) above the surface.

hair hygrometer: an instrument that measures relative humidity. It uses hairs (human or horse), which grow longer and shorter in response to changing humidity.

halo: a thin ring of light that appears around the Sun or the Moon, caused by the refraction of light by ice crystals.

haze: the uniform, milky-white appearance of the sky that results when humidity is high and there are a large number of particles in the air.

heating-degree-days: the number of degrees difference between the day's mean (average) temperature and the temperature at which most people set their thermostats. The total number of heating-degree-days in a season is an indicator of how much heating fuel has been consumed.

humiture index: an index that combines temperature and relative humidity to determine how hot it actually feels and, consequently, how stressful outdoor activity will be. Also called temperature-humidity index or heat index.

hurricane: the most intense form of tropical cyclone. A hurricane is a storm made up of a series of tightly coiled bands of thunderstorm clouds, with a well-defined pattern of rotating winds and maximum sustained winds greater than 74 mph (119 kph).

hygrometer: an instrument used to measure relative humidity. It consists of a dry-bulb thermometer and a wet-bulb thermometer. Also called psychrometer.

isobar: an imaginary line that connects areas of equal air pressure, after the air pressure measurements have been adjusted to sea level.

isotherm: an imaginary line connecting areas of similar temperature.

jet stream: the world's fastest upper-air winds. Jet streams travel in a west-to-east direction, at speeds between 80 to 190 mph (129 to 290 kph) around 30,000 feet (9,100 meters) above the ground. Jet streams occur where largest differences in air temperature and air pressure exist. (In North America, jet streams are typically found over central Canada and over the southern United States.)

latent heat: the energy that is either absorbed by or released by a substance as it undergoes a phase change.

latitude: an imaginary line encircling Earth, parallel to the equator, that tells one's position north or south on the globe.

marine forecast: a specialized weather forecast of interest to coastal residents and mariners, which gives projections of the times of high and low tide, wave height, wind speed and direction, and visibility.

meteorology: the scientific study of the atmosphere and atmospheric processes, namely weather and climate.

NEXRAD: acronym for Next Generation Weather Radar, the network of high-powered Doppler radar units that cover the continental United States, Alaska, Hawaii, Guam, and South Korea.

A third reliable optical sign is a halo. A halo looks like a fuzzy white (or sometimes colored) ring of light around the Sun or Moon. It is produced by the refraction (bending) of sunlight or moonlight by ice crystals that have formed at high altitudes. These ice crystals are contained within thin, upper-level clouds that may mark the beginning of an approaching storm front. In general, the larger the halo, the closer the front, and the sooner it will rain. If the halo is small, the storm is far away. There are limitations to this method of prediction, however. Whether the halo is large or small, there is no telling if it will rain or if the storm will change directions before arriving in an area.

Wind The movement of clouds at different altitudes moving in different directions is a sign that the weather is about to change. For example, when a cold front (the line behind which cold air is moving) reaches an area, winds shift in a counterclockwise direction (as viewed from above) producing a pattern known as a backing wind. A backing wind blows low-level clouds from the north, middle-level clouds from the northwest, and high-level clouds from the west. Since winds travel counterclockwise around a low-pressure system, and low pressure is associated with rainy or stormy weather, a backing wind can often be a sign of an approaching storm.

On the other hand, winds shift clockwise after a warm front has entered a region, producing a veering wind. An example of a veering wind is one that blows low-level clouds from the north, middle-level clouds from the northeast, and high-level clouds from the east. Since winds travel clockwise around a high-pressure system, and high pressure is associated with fair weather, a veering wind may signal the approach of warm, clear skies.

A key reference to: Fahrenheit and Celsius scales

Two main temperature scales are in use throughout the world: Fahrenheit and Celsius. The Fahrenheit scale was developed first, in 1714, by German-Dutch physicist Gabriel Fahrenheit (1686–1736). Fahrenheit also invented the first mercury thermometer. According to the way Fahrenheit arranged the gradations on his scale, fresh water freezes at 32°F and boils at 212°F, while saltwater freezes at approximately 0°F. The Fahrenheit scale is the one commonly used in the United States.

Anders Celsius (1701–1744), a Swedish astronomer, created his scale in 1742. Celsius felt it would be more convenient to use a system in which the freezing point of fresh water was designated as 0° and the boiling point as 100°. There was widespread agreement that these numbers were easier to work with, which prompted most of the world to adopt the Celsius scale.

A Celsius degree (°C)is larger than a Fahrenheit degree (°F). Specifically, one Celsius degree is equal to 1.8 Fahrenheit degrees. To convert from Celsius to Fahrenheit, multiply the degrees Celsius by 1.8, then add 32. To convert from Fahrenheit to Celsius, subtract 32 from the degrees Fahrenheit, then multiply by 0.56.

In other words:

$°F = (1.8 \times °C) + 32$ OR $°F = (9/5 \times °C) + 32$

$°C = 0.56(°F - 32)$ OR $°C = 5/9(°F - 32)$

Instead of clockwise and counterclockwise rules, it may be easier to remember that a veering wind is changing its direction to your right as you face it while a backing wind changes directions to your left as you face it. Remember the old sailor's rule: "A veering wind will clear the sky; a backing wind says storms are nigh."

A systematic approach to data collection To be an amateur weather forecaster requires more than observing the clues in nature about impending weather. It also necessary to measure and record specific atmospheric conditions daily. Using this information, which can be collected in a backyard, it is possible to create short-term, local forecasts, as well as to contribute to information meteorologists rely on in their study of long-term climatic conditions.

Installing your home weather center The first step is to set up a station at home where you can make observations. A home weather station should include a number of basic instruments, such as a thermometer to measure temperature; a psychrometer or hygrometer to measure relative humidity; a barometer to measure air pressure; a wind sock to measure wind direction; an anemometer to measure wind speed; and a rain gauge to measure rainfall. While this equipment is relatively simple compared to the satellites and supercomputers used by forecasters at the National Weather Service, it is adequate for recording local weather conditions.

Choosing the best location In order to make daily observations, you will need to establish a permanent outdoor location for your instruments. Ideally, the site should be at least 32 feet (10 meters) from trees or buildings and large enough to accommodate an instrument shelter plus other instruments. If this arrangement is not possible, choose any outdoor site to which you have access. Just keep in mind that trees and buildings may affect readings of wind and temperature. To test the adequacy of your location, compare your air temperature readings with those announced on your local weather station. The official readings announced at this station are usually taken at the closest airport.

The instrument shelter The instrument shelter is also called a Stevenson screen or a weather shack. It is a place to store and protect instruments outdoors. Its other purpose is to provide standard conditions under which readings are taken. The shelter is essentially a ventilated wooden box on legs, about 4 feet (1.2 meters) above ground. It protects

A weather instrument shelter. FMA, INC.

the instruments from rain, direct sunlight, and wind, yet its slanted slats allow air to pass through the station. The roof of the shelter is double-layered, which helps prevent the sunlight from raising the temperature inside the shelter above that of the outside air. Finally, the whole shelter is painted white to reflect sunlight.

At a minimum, an instrument shelter should contain at least a thermometer, hygrometer, and barometer. It may also contain modified, automatically recording versions of these instruments as well as maximum and minimum thermometers. The other instruments—namely the wind sock, anemometer, and rain/snow gauge—should be placed near the instrument shelter, but far enough apart so that they do not interfere with each other's operation.

Where to get your instruments Some of the instruments for your home weather center can be made, but others are more complex and should be purchased. Fortunately, all of the instruments can be purchased relatively inexpensively. Various models, however, range from the inexpensive to the very expensive. You can buy instruments at hardware stores, hobby shops, electronics stores, or catalogs. The best idea is to look into several catalogs to learn about the range of products and prices.

Measuring atmospheric conditions Once the shelter is set up with the necessary instruments, you are ready to make measurements of weather conditions.

Temperature Temperature is most commonly measured with a thermometer. A thermometer is a sealed narrow glass tube that has no air inside, with a bulb in the bottom containing a liquid. This liquid is usually mercury or red-dyed alcohol. When the surrounding air is warmed, the liquid expands and creeps upward through a tiny opening from the bulb into the tube. When the air is cooled, the liquid contracts and drops to a lower level in the tube. Tiny markings on the outside of the tube indicate the degree to which the liquid has risen or fallen—the temperature.

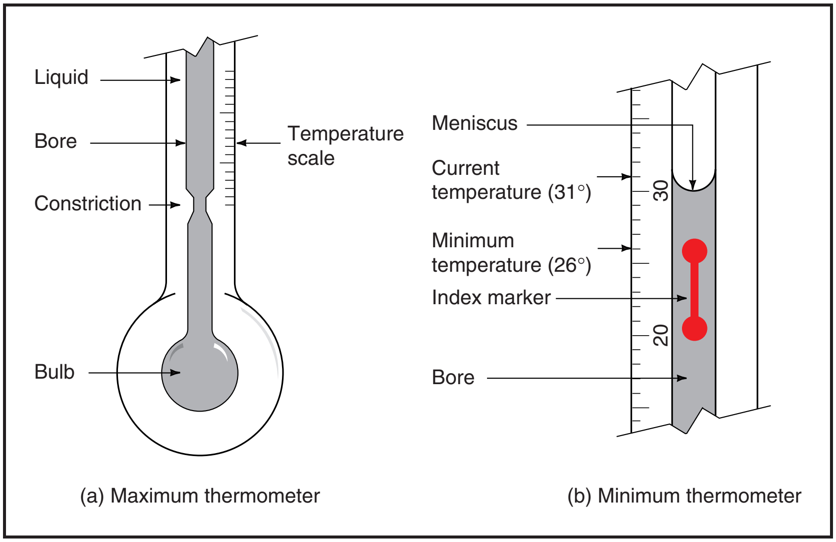
A thermograph. FMA, INC.

A type of thermometer that continually records the temperature is called a thermograph. This instrument has a needle that makes marks on a rotating drum covered with graph paper. A thermograph works by the expansion and contraction of two metal strips (usually iron and brass), welded together. When the temperature increases, each strip expands, but by different amounts. This expansion produces a slight bending of the strips, which causes a series of levers to move. The levers lead to the needle that etches on the drum.

Maximum and minimum thermometers tell the highest and lowest temperatures during an observation period (usually one day). The liquid within the tube rises in the maximum thermometer as long as the air temperature increases. The hole that connects the bulb to the tube, however, is narrower than in a regular thermometer. It is wide enough to allow the liquid to rise through it, however it prevents the liquid from passing back into the bulb. The liquid remains "stuck" at the maximum temperature.

A maximum thermometer can be reset by spinning or shaking it. In this respect, a maximum thermometer is similar to the old-fashioned, non-digital type of thermometer used to take a sick person's temperature.

A minimum thermometer usually contains alcohol, since alcohol has a much lower freezing point than mercury (–91°F [–71°C] for alcohol and –40°F [–40°C] for mercury). It looks like a regular thermometer,



Sections of maximum and minimum thermometers.

except it is mounted horizontally. The minimum temperature is marked in this thermometer by a small dumbbell-shaped glass bar within the bore of the thermometer.

As the air temperature cools and the liquid contracts back into the bulb, surface tension drags the bar with it. However, when the temperature warms and the alcohol expands, it flows past the bar. (Surface tension causes the bar to move only when it is at the surface of the column of liquid.) The bar remains stationary, indicating the minimum temperature. This thermometer can be reset by turning it upside down, so that gravity pulls the bar to the surface of the column of alcohol.

Maximum and minimum thermometers come in other forms as well. One form is a U-shaped maximum-minimum thermometer with two temperature scales, one on each of the vertical branches. In this instrument, columns of liquid move small bars that mark the high and low temperatures. Digital thermometers with built-in memory can also serve as maximum-minimum thermometers.

Minimum temperature is the best standard by which to compare daily temperatures, since the day's low is usually reached after the sun goes down. When sunlight strikes a thermometer, the thermometer not only measures the energy of the surrounding air molecules (the true temperature), but it also measures the radiant energy from the Sun. This effect produces a higher temperature reading than the actual air temperature. Temperature readings during the day are much more

Dew-Point Temperature
Wet-bulb depression

Current Temperature	1.8°F (1.0°C)	3.6°F (2.0°C)	5.4°F (3.0°C)	7.2°F (4.0°C)	9.0°F (5.0°C)
14.0°F (−10.0°C)	5.9°F (−14.5°C)	−6.3°F (−21.3°C)	−33.3°F (−36.3°C)		
18.5°F (−7.5°C)	11.5°F (−11.4°C)	1.9°F (−16.7°C)	−13.9°F (−25.5°C)		
23.0°F (−5.0°C)	16.9°F (−8.4°C)	9.0°F (−12.8°C)	−2−2°F (−19.0°C)	−24.3°F (−31.3°C)	
27.5°F (−2.5°C)	22.1°F (−5.5°C)	15.4°F (−9.2°C)	6.6°F (−14.1°C)	−6.7°F (−21.5°C)	−42.3°F (−41.3°C)
32.0°F (0.0°C)	27.1°F (−2.7°C)	21.4°F (−5.9°C)	14.4°F (−9.8°C)	4.6°F (−15.2°C)	−11.0°F (−23.9°C)
36.5°F (2.5°C)	32.2°F (0.1°C)	27.1°F (−2.7°C)	21.0°F (−6.1°C)	13.5°F (−10.3°C)	3.0°F (3.0°C)
41.0°F (5.0°C)	37.0°F (2.8°C)	32.5°F (0.3°C)	27.3°F (−2.6°C)	21.0°F (−6.1°C)	13.3°F (−10.4°C)
45.5°F (7.5°C)	41.9°F (5.5°C)	37.8°F (3.2°C)	33.3°F (0.7°C)	27.9°F (−2.3°C)	21.6°F (−5.8°C)
50.0°F (10.0°C)	46.6°F (8.1°C)	42.8°F (6.0°C)	38.8°F (3.8°C)	34.2°F (1.2°C)	28.8°F (−1.8°C)
54.5°F (12.5°C)	51.3°F (10.7°C)	47.8°F (8.8°C)	44.1°F (6.7°C)	40.1°F (4.5°C)	35.4°F (1.9°C)
59.0°F (15.0°C)	55.9°F (13.3°C)	52.9°F (11.6°C)	49.2°F (9.6°C)	45.7°F (7.6°C)	41.5°F (5.3°C)
63.5°F (17.5°C)	60.6°F (15.9°C)	57.7°F (14.3°C)	54.5°F (12.5°C)	51.1°F (10.6°C)	47.3°F (8.5°C)
68.0°F (20.0°C)	65.3°F (18.5°C)	62.4°F (16.9°C)	59.5°F (15.3°C)	56.3°F (13.5°C)	52.9°F (11.6°C)
72.5°F (22.5°C)	70.0°F (21.1°C)	67.3°F (19.6°C)	64.4°F (18.0°C)	61.3°F (16.4°C)	58.3°F (14.6°C)
77.0°F (25.0°C)	75.7°F (24.3°C)	72.0°F (22.2°C)	69.3°F (20.7°C)	66.3°F (19.1°C)	63.5°F (17.5°C)
81.5°F (27.5°C)	79.2°F (26.2°C)	76.6°F (24.8°C)	73.9°F (23.3°C)	71.4°F (21.9°C)	68.5°F (20.3°C)
86.0°F (30.0°C)	83.7°F (28.7°C)	81.3°F (27.4°C)	78.8°F (26.0°C)	76.3°F (24.6°C)	73.6°F (23.1°C)
90.5°F (32.5°C)	88.2°F (31.2°C)	85.8°F (29.9°C)	83.5°F (28.6°C)	81.0°F (27.2°C)	78.4°F (25.8°C)
95.0°F (35.0°C)	92.8°F (33.8°C)	90.5°F (32.5°C)	88.2°F (31.2°C)	85.8°F (29.9°C)	83.3°F (28.5°C)
99.5°F (37.5°C)	97.3°F (36.3°C)	95.2°F (35.1°C)	92.8°F (33.8°C)	90.5°F (32.5°C)	88.2°F (31.2°C)
104.0°F (40.0°C)	101.8°F (38.8°C)	99.7°F (37.6°C)	97.5°F (36.4°C)	95.2°F (35.1°C)	93.0°F (33.9°C)

Relative Humidity
Wet-bulb depression

Current Temperature	2.0°F (1°C)	3.6°F (2°C)	5.4°F (3°C)	7.2°F (4°C)	9.0°F (5°C)
14.0°F (−10.0°C)	69%	39%	10%		
18.5°F (−7.5°C)	73%	48%	32%		
23.0°F (−5.0°C)	77%	54%	32%	11%	
27.5°F (−2.5°C)	80%	60%	41%	22%	3%
32.0°F (0.0°C)	82%	65%	47%	31%	15%
36.5°F (2.5°C)	84%	68%	53%	38%	24%
41.0°F (5.0°C)	86%	71%	58%	45%	32%
45.5°F (7.5°C)	87%	74%	62%	50%	38%
50.0°F (10.0°C)	88%	76%	65%	54%	44%
54.5°F (12.5°C)	89%	78%	68%	58%	48%
59.0°F (15.0°C)	90%	80%	70%	61%	52%
63.5°F (17.5°C)	90%	81%	72%	64%	55%
68.0°F (20.0°C)	91%	82%	74%	66%	58%
72.5°F (22.5°C)	92%	83%	76%	68%	61%
77.0°F (25.0°C)	92%	84%	77%	70%	63%
81.5°F (27.5°C)	92%	85%	78%	71%	65%
86.0°F (30.0°C)	93%	86%	79%	73%	67%
90.5°F (32.5°C)	93%	86%	80%	74%	68%
95.0°F (35.0°C)	93%	87%	81%	75%	69%
99.5°F (37.5°C)	94%	87%	82%	76%	70%
104.0°F (40.0°C)	94%	88%	82%	77%	72%

accurate when taken in the shade than in the sun. However, even indirect sunlight alters the actual air temperature somewhat.

Humidity The most useful measure of humidity is the relative humidity. Relative humidity is a measure of the amount of water in air compared to the total amount of water the air can hold at a given temperature. Remember that warm air can hold more water than cold air. Relative humidity is expressed as a percentage and tells how wet the air feels.

The simplest way to find the relative humidity is with a psychrometer, an instrument that consists of a dry-bulb thermometer and a wet-bulb thermometer. The dry-bulb thermometer tells the actual air temperature and the wet-bulb thermometer tells the saturated air temperature. The difference between these two temperatures is called the wet-bulb depression. Once you know the actual air temperature and the wet-bulb depression, you can refer to a standardized chart to find the relative humidity.

A dry-bulb thermometer is a regular thermometer, as described above. A wet-bulb thermometer is a thermometer with wet fabric placed around the bulb. An ideal fabric is a cotton weave called muslin, which retains moisture well. The wet cloth around the bulb provides an environment comparable to that of saturated air.

The wet-bulb thermometer almost always gives a lower temperature reading than the dry-bulb thermometer. The reason is that water from the cloth evaporates and absorbs latent heat from the bulb of the thermometer, thus cooling the thermometer. Latent heat is the heat released during the phase change, as the water turns from liquid to gas. The only exception to this is when wet-bulb and dry-bulb thermometers give equivalent readings, which occurs when water ceases to evaporate from the cloth. At this point the surrounding air is at its saturation point, meaning there is 100 percent relative humidity. The temperature at which both thermometers give the same reading is the dew point, which is the temperature at which any moisture in the air will condense and fall as snow or rain. You can determine the dew point from a standardized chart if you know the actual air temperature and the wet-bulb depression.

The greater the difference between the two temperatures (wet-bulb depression), the more water evaporates into the air, and the lower the relative humidity. A small wet-bulb depression indicates that little water is evaporating into the air, hence the relative humidity is high.

A variation on this instrument is the sling psychrometer. It consists of a dry-bulb thermometer and a wet-bulb thermometer mounted side by side on a metal strip, which rotates on a handle at one end. Operate it by holding the handle and spinning the metal strip in circles. This speeds up evaporation at the wet bulb, resulting in a quicker wet-bulb temperature reading.

Another tool for measuring humidity is the hair hygrometer. This instrument uses hairs (human or horse), which expand and contract in response to changing humidity. When there is more water in the air, the hair absorbs moisture and becomes longer. Conversely, when the air is drier, the hair loses moisture and becomes shorter. In fact, hair length changes by as much as 2.5 percent depending on the humidity. The same principle on which a hair hygrometer works can be observed in people's hair. Straight hair becomes limp in high humidity, and curly hair needs extra moisture to combat frizziness.

The hair hygrometer looks something like a thermograph in that its moving needle etches marks on a paper-covered, clock-driven, rotating drum. It works like this: Several hairs are attached to a system of levers.

Experiment: Make your own paper hygrometer

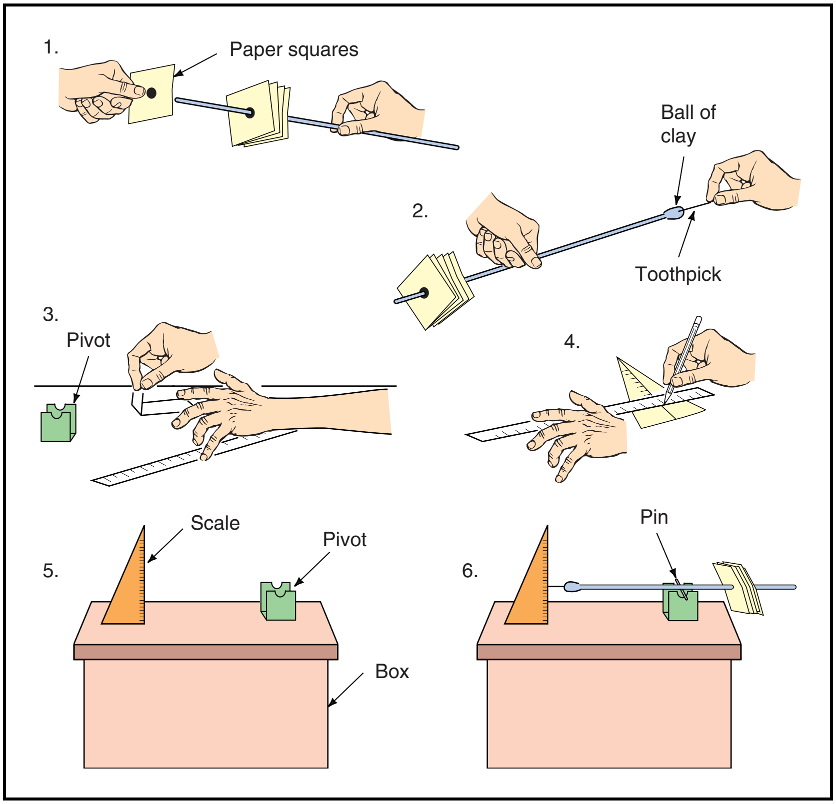
Paper can be used instead of hair to measure relative humidity, since it also absorbs water in the air. Using the following basic materials, you can create your own paper hygrometer: a piece of paper, a drinking straw, a small ball of modeling clay, a cardboard box at least one foot wide, a piece of poster board, and a toothpick.

1. To make the pointer, cut out five paper squares, each about 2 inches (5 centimeters) across. Use a hole-punch to make a hole through the center of each square. Push the straw through the holes so that the paper squares are grouped together on one end of the straw.
2. On the other end of the straw, affix a small ball of clay. Poke a toothpick into the clay, so that it extends in the line of the straw.
3. To make the pivot, cut a strip out of the poster board that is 6 inches (15 centimeters) long by 2 inches (5 centimeters) wide. Fold it twice into three squares. Unfold it to form a three-sided box and place the middle portion flat on the table, with the other two portions sticking straight up. Cut a small notch at the top-center of each of the two vertical sides.
4. To create the scale, cut an isosceles triangle (a triangle with at least two equal sides) out of the poster board that is 4 inches (10 centimeters) at the base and 6 inches (15 centimeters) tall. Fold it in half lengthwise. Draw a series of evenly spaced dashes on one side of the fold that are perpendicular to the fold.
5. Position the triangle scale at one end of the box top, so that the base is on the surface and the fold extends straight upward. The fold should point toward the opposite end of the box top. Position the pivot at the other end, across from the scale. Glue the pivot and scale into place.
6. Stick a pin through the straw, about two-thirds of the way toward the back of the straw (it should be closer to the paper than the toothpick). Balance the pointer by resting the edges of the pin in the notches of the pivot. You may have to adjust the position of the paper squares to get the pointer to balance.

When the relative humidity is high, the paper squares will absorb water and become heavier, making the pointer aim higher on the scale. When the relative humidity is low, the paper squares will be lighter and the pointer will aim lower.

When the hair length changes, it causes the levers to shift. The last lever is attached to the needle, which records the motion. The paper on the moving drum is imprinted with horizontal lines representing percentages of relative humidity. The up-and-down motion of the needle is calibrated with this scale, so the markings tell the relative humidity over time.

Air pressure Air pressure, also called "atmospheric pressure" or "barometric pressure," is measured with a barometer. This tool was invented by Italian mathematician Evangelista Torricelli (1608–1647) in 1643. Torricelli filled a small glass tube with one sealed end with mercury. He then



Make your own paper hygrometer.

turned the tube upside down and placed the open end in a dish of mercury. The level of mercury in the tube began dropping. It stabilized when the weight of the mercury in the tube equaled the weight of the air pushing down on the surface of the mercury in the dish. The stable mercury level in the tube gave a way to describe the air pressure.

Mercury barometers still provide the most accurate method of measuring of air pressure. One drawback to using them, however, is that they must be "reduced" to sea level by calibrating the barometer so that it gives readings as if at sea level, compensating for differences caused by altitude. To calibrate a barometer to your altitude above sea level, call your local weather service office for an official reading. It is also necessary to adjust this type of barometer regularly to account for the expansion and contraction of the mercury in response to temperature change.

While the aneroid barometer is not as accurate as the mercury barometer, it needs no adjustment, making it the most convenient tool

Air pressure can be described in units of length or pressure

Units of length:
inches (in)
millimeters (mm)
(These units refer to the height of the column of mercury in a barometer)

Units of pressure:
pascals (Pa)
millibars (mb)
(These units describe air pressure specifically)

Air pressure at sea level:
between 28.64 and 30.71 in (727.45 and 780.03 mm)
between 970 and 1040 mb

Average air pressure at sea level:
29.92 in (760 mm)
1013.25 mb

for the job. In addition, aneroid barometers are smaller and easier to transport than mercury barometers. It is also possible to use an aneroid barometer in a recording device called a barograph. Aneroid barometers are the more widely used variety today.

The aneroid barometer has a vacuum-sealed capsule made of steel or beryllium alloy. The capsule contains a spring that changes in size with air pressure. When the pressure falls the capsule expands, and when the pressure rises the capsule contracts. This movement triggers a series of levers that are connected to a pointer. This pointer indicates the air pressure on a dial.

The dial of an aneroid barometer, in addition to units of atmospheric pressure, may have zones designated "rain," "change," and "fair." These terms should not be taken literally. Just because the air pressure is low does not necessarily mean it will rain. A much more useful indication of future weather is how air pressure rises or falls over time. Falling air pressure is a sign of rain and rising air pressure is a sign of clearing skies.

Mercury and aneroid barometers can be placed indoors or outdoors, since indoor air pressure adjusts very quickly to outdoor air pressure. The barometer should be mounted vertically and kept out of direct sunlight.

A variation on the aneroid barometer is the barograph. It works the same way as an aneroid barometer except in the barograph (similar to the thermograph or hair hygrometer), the levers are connected to a needle that etches its movements onto a paper-covered, rotating drum. A barograph measures changes in air pressure over time.

Wind direction Wind socks and wind vanes are both simple instruments used to determine the direction of the wind. A wind sock is a cone-shaped cloth bag, open on both ends, mounted on a pole. The wind enters through the wide end and exits through the narrow end. Thus, the wide end points to the direction from which the wind is coming. (Note: the "wind direction" in weather reports is the direction from which the wind comes, as opposed to the direction it is heading. For example, an "east wind" is one that is coming out of the east and moving to the west.)

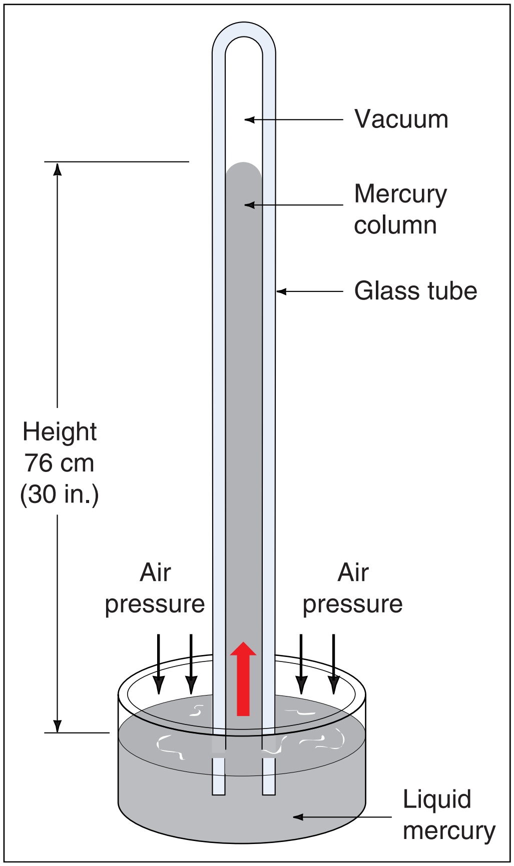
You can buy a wind sock at a hardware store or construct your own. The sock is made by stretching a piece of weatherproof material over a series of increasingly larger metal rings, to form a cone-shape. The metal rings can be made from sturdy metal wire or cable that is cut into progressively longer pieces and twisted or clamped together at the ends. The sock is then attached to a tall, lightweight pole by a freely rotating metal ring.

Choose a place as far as possible from buildings and trees to erect the pole. The sock should be up high enough so that surface features do not interfere with the direction of the wind (10 feet or higher is ideal). Once your wind sock is up and working, you can use a compass to determine the direction the wind is blowing. When the wind is calm, it is recorded as "zero degrees." An east wind is 90 degrees, a south wind is 180 degrees, a west wind is 270 degrees, and a north wind is 360 degrees.

Another tool for measuring wind direction is a wind vane, or "weather vane." A wind vane is a free-swinging horizontal metal bar with a vertically oriented, flat metal sheet (often in the shape of a rooster or other animal) serving as a weight at one end of the bar and an arrow weighing down the other end. The arrow always points *into* the wind, toward the direction the wind is coming from.

Evangelista Torricelli.

On some weather vanes, a stationary, horizontal metal cross is positioned beneath the swinging bar, with the cardinal directions (north, south, east, and west) inscribed on the four ends. You can tell the wind direction with this type of wind vane by comparing the position of the arrow on the swinging bar with the directional cross beneath it. When there is only the swinging bar, you must use a compass to determine the direction in which the arrow is pointing. (Sometimes the wind is blowing too lightly to move a wind vane. If that is the case, use an



A mercury barometer.

alternate method, such as looking at a wind sock or flag, to determine wind direction.)

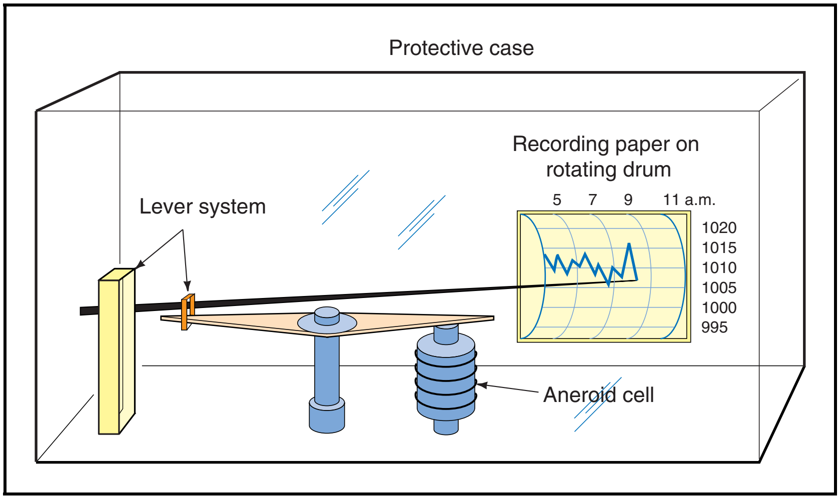
Wind speed Wind speed is measured by a tool called a cup anemometer. This device works like a speedometer. It consists of three or four cups, positioned on their sides, connected to a cap by horizontal spokes. The cap sits on top of a pole. The cap/spokes/cups unit rotates freely on the pole. The faster the wind blows, the faster the cups spin. This motion generates a weak electric current which is measured and displayed on a dial. To obtain an accurate measurement, the observer should check the wind speed several times over one minute and take the average value.

Wind speed is usually measured in units of miles per hour (mph) or kilometers per hour (kph). One kilometer is equal to 0.62 miles. The speed of wind over the water is commonly given in knots. One knot equals 1.15 mph (1.85 kph).

It is best to mount an anemometer away from buildings and trees. Place it as high as possible, but do not put it on a rooftop because winds accelerate over rooftops. If you do not have access to a suitable outdoor location, use a handheld anemometer. This device is a small instrument you can carry into a clearing to check the wind speed.

Precipitation The final condition to monitor in your home weather station is precipitation; that is, rainfall and snowfall. This measurement is relatively easy to make and, best of all, requires no equipment purchase. A rain gauge is simply a container that catches the rain. Any transparent container with a flat bottom and straight sides (like a drinking glass) can be used. Once or twice a day, take a ruler and measure (in inches or millimeters) the height of the water in the container. Then empty the container and set it up again.

This device will give you a rough idea of the amount of rainfall. For a more accurate and precise measure of precipitation, you can invest in the type of rain gauge used by the National Weather Service. This instrument consists of two nested cylinders (a smaller one that fits inside of a larger one), with a funnel that fits over the outer cylinder and directs water into



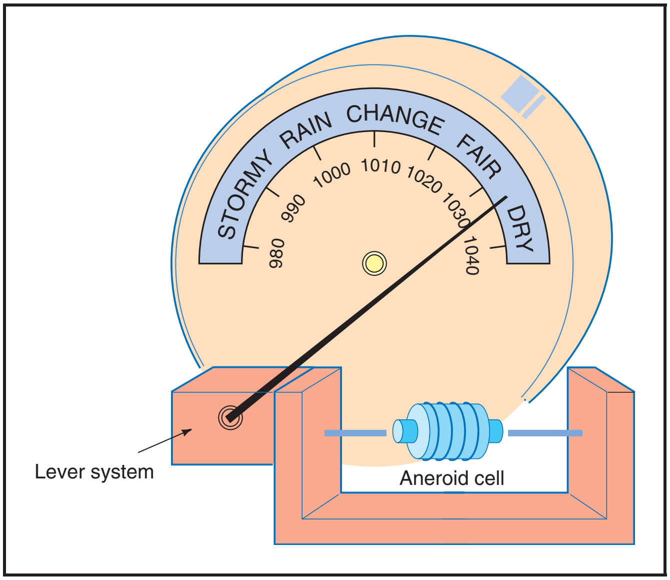
A recording barograph.

the inner cylinder. The diameter of the mouth of the funnel will be several times wider than the diameter of the inner cylinder. If the diameter of the mouth of the funnel is ten times the diameter of the inner cylinder, than the area will be one hundred times greater. Thus, when an inch of water accumulates in the inner cylinder, it indicates that one-hundredth of an inch of rain has actually fallen.

If you want to get highly precise measurements, you can purchase a rain gauge that records patterns of precipitation over time. There are numerous varieties of this type of device, such as weighing-bucket rain gauges and tipping-bucket rain gauges. They are each driven by different mechanisms, but the outcome is the same: The rainfall is recorded on a paper-covered rotating drum.

Your rain gauge should be situated far from trees and buildings. If possible, follow this rule: Do not place the rain gauge closer to an obstacle than a distance equal to four times the height of that obstacle. For example, the rain gauge should be set up at least sixteen feet away from a four-foot-tall shrub. To prevent your rain gauge from tipping over, dig a small hole (a few inches deep) in the ground that is the width of your container and set the rain gauge in this depression.

Snow is easier to measure than rain. Just stick a ruler down through the snow until it hits the ground and take a reading. For best results, record the average of several readings taken around your weather station. If you want to find how much new snow has fallen in a given time

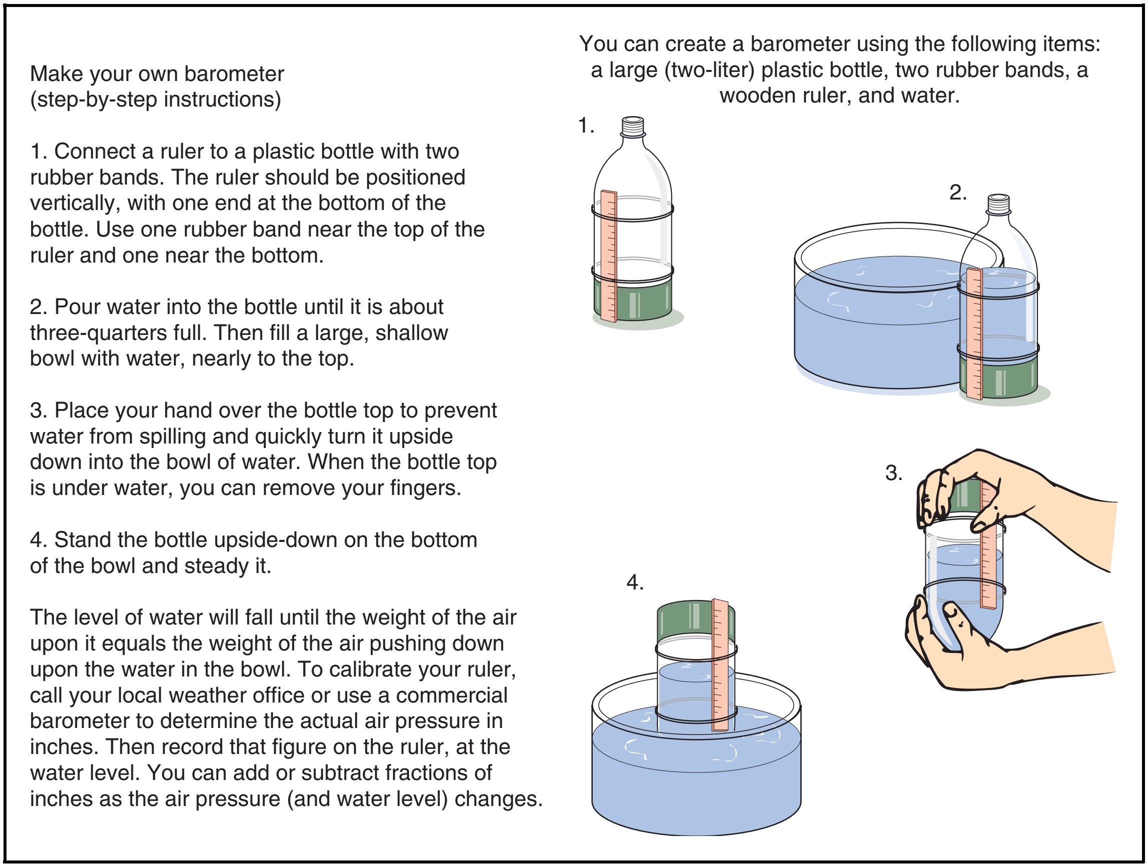


An aneroid barometer.

period, set a board on top of the old snow and measure the snow that falls on the board.

Meteorologists are also interested in the water content of snow, called the meltwater equivalent. There are various, somewhat complicated methods of finding the meltwater equivalent. Some require the use of a modified rain gauge and antifreeze. On average, ten inches of snow equals one inch of liquid water. This value varies greatly, however, depending on how cold and dry, or warm and wet, the snow is. In fact, very dry snow can be as little as be as one-thirtieth meltwater by volume and very wet snow can be as much as one-third meltwater by volume.

Recording observations Daily measurements that have been made over a long period are the most useful type of information about local weather conditions. Standard daily weather log sheets (such as those provided by the National Weather Service) may be quite detailed. They generally include columns for sky condition (type and amount of cloud cover); wind direction; wind speed; visibility (how far you can see due to presence or absence of haze or fog, which is just a cloud at ground level); relative humidity (recorded as wet-bulb and dry-bulb temperatures); maximum and minimum temperatures; snowfall; rainfall; soil temperatures at various depths; and hours of sunshine throughout the day. They also have



Make your own barometer.

space for notes about significant weather occurrences (such as a hailstorm) and general conditions of the day.

To record your observations, fashion your own log sheet, on which you can record the conditions you are able to measure. You do not want to create an impossible task for yourself. It is better to make once- or twice-daily recordings of a limited number of conditions than to make occasional recordings of many conditions.

Try to take your readings at the same time (or times) each day, ideally each morning and afternoon. Temperature should be consistently recorded either in degrees Fahrenheit or degrees Celsius. Readings of air pressure should include the current air pressure, the change in pressure since the last reading, and whether the pressure is rising or falling (pressure tendency).

Three wind vanes and an anemometer. FMA, INC.

Wind direction, to the nearest 10 degrees, should be measured with a compass. Wind speed can be recorded in miles per hour or kilometers per hour if you have an anemometer, otherwise use the Beaufort scale.

Visibility is a measure of how far you can see. The best way to assess visibility is to determine the distance to certain landmarks, and note each day which ones you can see from your weather station. Cloud cover can be noted as one of four categories: overcast (covering more than 90 percent of the sky); mostly cloudy (covering 50–90 percent of the sky); partly cloudy (covering 10–50 percent of the sky); or clear (covering less than 10 percent of the sky).

Your notes will be briefer and more orderly if you use international weather symbols to describe wind speed, current weather conditions, and clouds. Your weather journal should have plenty of room for notes, where you can record any general or specific weather observations for the day—such as the opening or closing of pinecones, the location of a rainbow (to the east or west) in the sky, the arrival of migrating birds, or the impact of the fall's first frost on a garden. It is also helpful to supplement your written notes with drawings or photographs of clouds, frost patterns on your windshield, or icicles dripping from trees, for instance.

Making forecasts The information you record at your home weather station will enable you to give a weather report of current conditions, but predicting the future is a more complex task. Before you try your hand at producing forecasts, it is best to just record daily observations until you have become familiar with the instruments and the methods of measuring specific conditions. It also helps to review your journal after several days or weeks, looking for any weather trends. Once you are comfortable with the whole process, you are likely to have greater success at forecasting.

A homemade forecast for one day in advance may include elements such as the expected cloud cover, precipitation, and what the minimum temperature for the night will be. While there are standard procedures for predicting these conditions, keep in mind that forecasting, as a whole, is greater than the sum of its parts. In other words, an overall description of what the next day's weather may bring takes more than plugging each measurement into some equation. It requires the ability to notice subtle changes in the natural world, as well as monitoring atmospheric conditions with your instruments.

Certain types of predictions and general assessments about the weather can be made by looking at your measurements or by taking note of general conditions. For example:

- Falling air pressure indicates that a storm may be moving in, while rising air pressure suggests skies will clear.

A rain gauge with a wind screen used to lessen the amount of catch (rain) missed due to rain streaming over the edge of the gauge. FMA, INC.

A key reference to: The Beaufort scale

In the early 1800s British Navy commander Sir Francis Beaufort developed a scale for estimating wind speed. The Beaufort Scale of Wind Force looks at the effect of the wind on water, trees, and other flexible objects on land. Beaufort's intention was to create a standard method of assessing wind speed, based on descriptions commonly used by sailors.

His scale was officially adopted by the British Navy in 1838 and became the international mariner standard in 1853. In 1926, the scale was modified so it could also be used on land. Many sailors still use the Beaufort method to measure wind speed.

The scale ranges from 0 to 12, with 0 for still conditions and 12 for hurricane-force winds. Try using the Beaufort scale provided here in various weather conditions to approximate the wind speed. Compare your results with the official wind speed reported by your local weather service.

- Feathery, high-level clouds are a sign that, while current conditions may be fair, a storm may be approaching. Thick, low-level clouds are a sign that precipitation is imminent.
- The appearance of a line of dark, middle-level clouds on the horizon indicates that precipitation is likely.
- Cloud formation is more likely when relative humidity is high than when it is low.
- Clear weather is likely forthcoming when fog burns off before noon, the percentage of cloud cover decreases, or "cracks" develop in a sheet of clouds.
- The air temperature will dip lower on a clear night than on a cloudy night, everything else being equal.
- The lowest nighttime temperatures occur when there are clear skies, light winds, and snow on the ground.
- When the dew point is below 32°F (0°C), you will get frost rather than dew.
- A veering wind (clockwise shift with height) is a sign of clearing skies and rising temperatures.
- A backing wind (counterclockwise shift with height) is a sign of stormy weather and falling temperatures.

To answer more complex questions about the weather, however, you must take into account a whole host of observations. Here are some examples of how to make general assessments and predictions about the weather by looking at several atmospheric conditions simultaneously.

Will it rain? Will it snow? A prediction of rain or snow is made by examining three specific atmospheric conditions: air pressure, sky conditions, and temperature. First, look at your last few readings of air pressure. Is it rising, falling, or staying the same? If it is rising or staying the same, precipitation is unlikely. Falling barometric pressure is often a signal of changing weather.

Beaufort Wind Scale

Wind Speed (mph)	Beaufort Number	Wind Effect on Land	Official Description
Less than 1	0	Calm; smoke rises vertically.	CALM
1–3	1	Wind direction is seen in direction of smoke; but is not revealed by weather vane.	LIGHT AIR
4–7	2	Wind can be felt on face; leaves rustle; wind vane moves.	LIGHT BREEZE
8–12	3	Leaves and small twigs in motion; wind extends light flag.	GENTLE BREEZE
13–18	4	Wind raises dust and loose papers. Small branches move.	MODERATE BREEZE
19–24	5	Small trees with leaves begin to sway; crested wavelets appear on inland waters.	FRESH BREEZE
25–31	6	Large branches move; telegraph wires whistle; Unbrellas become difficult to control.	STRONG BREEZE
32–38	7	Whole trees sway and walking into the wind becomes difficult.	NEAR GALE
39–46	8	Twigs break off trees; cars veer on roads.	GALE
47–54	9	Slight structural damage occurs (roof slates may blow away, etc.).	STRONG GALE
55–63	10	Trees are uprooted; considerable structural damage is caused.	STORM
64–72	11	Widespread damage is caused.	VIOLENT STORM
73 or more	12	WIdespread damage is caused.	HURRICANE

The next factor to examine is sky conditions. If skies are clear, clouds are few, or only smooth, low-level clouds exist, then chances of rain are small. However, the presence of dark, low-lying clouds or development of upper-level clouds to the west, in conjunction with falling air pressure, indicates that precipitation is likely.

To determine whether that precipitation will fall to the ground as rain or snow, check the temperature. If it is above 37°F (3°C), rain is likely. However, if the temperature is 37°F or below, you can expect sleet or snow.

How cold will it get tonight? This question is one people often ask when trying to decide whether it is safe to leave their pet or plants outside for the night. By checking a minimum thermometer in the morning, you can learn the previous night's low temperature. But predicting the upcoming night's low is a more involved process that requires checking the outdoor temperature twice after the Sun goes down, and using an equation to find the answer. Bear in mind that since cloud cover and wind distort the amount of heat lost at night, this method works only under clear, calm conditions.

The first step is to find out what time the Sun will set in the evening and rise the next morning. This information is published in most local newspapers. The time of your first temperature reading depends on the month. In December or January wait one hour after sunset; in October, November, or February wait one-and-a-half hours after sunset; and in any other month wait two hours after sunset. This rule only applies to the Northern Hemisphere.

You must wait a certain length of time before taking measurements, because once the Sun sets, heat from the ground begins to radiate upward, into space. After a given period, the temperature at the surface will fall at a constant hourly rate. The length of time it takes for the temperature to begin dropping at the constant rate is shorter in the colder months and longer in the warmer months.

Assume the month is September. Two hours after sunset, go out to your instrument shelter, read the thermometer, and record the temperature. One hour later, go back and record the temperature again. The difference between the two temperatures is the "hourly drop." Next, count the hours that remain until one hour before sunrise. Multiply that number by the hourly drop. Subtract that figure from your second temperature reading and you will get the night's likely minimum temperature.

Will dew or frost form? To answer this question you must determine the dew point and the night's predicted low temperature. The dew point depends on temperature and relative humidity. Specifically, the dew point is the temperature at which the air is saturated, resulting in the formation of dew or frost. Using wet-bulb and dry-bulb thermometers you can find the wet-bulb depression. Once you know the wet-bulb depression and the actual air temperature, you can find the dew point from the dew-point chart.

After you determine the dew point, two questions remain: Will the air become cold enough to reach the dew point and is the dew point above or below freezing? To answer the first question, use the method described above for determining minimum temperature. If the predicted minimum temperature is at or below the dew point, moisture will form on the ground. If the predicted minimum temperature is above freezing, the moisture will take the form of dew. However, if it is at or below freezing, you can expect frost.

Is the day hot or cold for the time of year? Imagine that it is March 1 and it is very cold outside. How do you know if it just *seems* colder than normal because you are tired of the long winter or if it really *is* colder than normal? Here is a way to find out.

To determine whether the day is hot, cold, or normal for the time of year, you must look at a number of factors. These include identifying the existing air mass; comparing the day's maximum temperature with the average maximum temperature for the time of year in your locality; and recording the current wind speed and sky conditions. Then you can plot all of these variables on a chart to find out how the day compares to the norm.

The first step is to determine what type of air mass is in your area. An air mass is a large body of air that has fairly consistent temperature and moisture content. There are several clues that will help you identify whether you are within a tropical air mass or a polar air mass. The first is the season. In the United States, tropical air masses tend to dominate in the summer and polar air masses tend to dominate in the winter.

Here are other clues: polar air masses range from cool to extremely cold. One may bring bitterly cold temperatures to Montana (–10°F, or –20°C), yet on the rare occasion when it moves as far south as Florida, it may warm up to 50°F (10°C). Tropical air masses, on the other hand, range from warm to very hot. In the winter, they are generally limited to the southern states. If a tropical air mass makes it to the northern United States, it brings unseasonably mild temperatures.

The second step is to record the maximum temperature for the day. Then you must find the average maximum temperature for your location at the particular time of year. This information can be found at your local public library or weather service office. Records are generally kept for ten-year periods. One you have taken a reading of the day's maximum temperature, compare it to the average maximum temperature. Note whether it is higher or lower than the average, and by how many degrees.

The next step is to observe today's weather: Is it overcast or partly-to-mostly sunny? Are the winds calm-to-light or strong?

Putting your weather observations to use One way to put your daily weather records to use is to become an official observer for the National Weather Service. This requires sending copies of your records to the NWS, where they will be added to the pool of data used by professional meteorologists. To learn how to do this, contact the weather service office in your area. Local radio and television stations also often receive reports from amateur observers.

State-of-the-art forecasting equipment

To complete the global atmospheric picture, a survey of the upper air is also necessary. Meteorologists rely on extremely sophisticated equipment

A radiosonde weather balloon being prepared for launch. Such balloons measure wind, temperature, and humidity to heights above 100,000 feet. FMA, INC.

to supply information about atmospheric conditions at various levels of the troposphere (the lowest part of Earth's atmosphere). This section will describe this equipment plus the supercomputers that analyze the mountains of data and produce forecasts at incredible speeds.

Weather balloons The very first upper air measurements were obtained by standing on mountaintops or by sending up instruments attached to kites. Then came the days when scientists would ride in hot air balloons and take readings. Pioneering balloonists risked their lives, ascending thousands of feet above ground where the air is dangerously thin and cold. Modern weather balloons filled with hydrogen or helium carry electronic instrument packages called radiosondes. These unpiloted balloons can safely climb to far greater heights than their piloted predecessors.

The instruments in radiosondes measure temperature, air pressure, and relative humidity as they ascend to a maximum of 20 miles (30 kilometers) above ground. Radiosondes are equipped with radio transmitters that continuously relay measurements to stations on the ground. Rawinsondes are radiosondes that emit a signal so that their location can be tracked by radar on the ground. From the path of a rawinsonde, one can determine how wind speed and direction changes with altitude.

About 1,000 radiosonde stations have been established worldwide, approximately 125 of them in the United States. About 500 radiosondes are launched at the same time around the world twice each day. These launches take place at noon and midnight Greenwich Mean Time, which is 7:00 AM and 7:00 PM Eastern Standard Time. A balloon takes forty-five to ninety minutes to reach its maximum height. At that point the balloon bursts.

In the United States, radiosondes are equipped with parachutes so they can reach the ground intact. Each one comes with a prepaid mail bag and instructions, so the finder can return it to the National Weather

Service. About one-third of all radiosondes launched are returned in this way and reused.

A variation on the radiosonde is the dropwindsonde. This instrument package is released at high altitude by an aircraft rather than being carried aloft by a balloon. It parachutes to Earth at a speed of 11 mph (18 kph), radioing back atmospheric measurements every few seconds. Dropwindsondes are used primarily over oceans, where there are very few surface stations for launching radiosondes.

Weather aircraft Weather aircraft also contribute to the collection of data in upper levels of the troposphere. They are used primarily to probe storm clouds, within which they measure temperature, air pressure, and wind speed, and direction. These airplanes have reinforced wings and bodies in order to withstand the hail, ice, and strong winds they encounter inside the clouds. The weather instruments are carried in pods beneath the plane's wings or attached to its nose cone. Weather aircraft are employed in small numbers by most of the world's leading meteorological agencies.

Weather aircraft have contributed greatly to our understanding of hurricanes and other tropical storms. In the fall of 1996 NOAA acquired a jet, called the Gulfstream IV-SP, specifically for studying hurricanes. The jet can cruise right through these storms at heights of up to 45,000 feet (8.5 miles or 14 kilometers). The NOAA jet contains sensors that measure air pressure, temperature, humidity, and wind speed at the edges and the core of the storm. It is just one of the eight types of research aircraft in use by NOAA.

The reason for upper-air hurricane research was explained by Commander Ron Philippsborn, one of four pilots to fly the NOAA jet, in the August/September 1996 issue of *Weatherwise* magazine: "We want to get almost to the base of the stratosphere if we can, up to the outflow

Who's who: Tom Kudloo, aerologist

Tom Kudloo operates a weather station in the Arctic, one of the thousands of weather stations across North America. He is an aerologist, someone who observes and gives reports of local atmospheric conditions. Kudloo uses weather balloons to take readings of upper-air conditions twice daily.

"I attach weather instruments and a tiny radio transmitter to the balloon," says Kudloo. "A cardboard box holds the radio transmitter and a sensor to measure air temperature, air pressure, and humidity. As the balloon rises, the sensor also measures the balloon's speed and direction. This helps me calculate the wind speed and direction. As the balloon goes up, the radio transmitter sends me information about the air masses above me."

This information is entered directly into a computer, which prints out a report. Kudloo analyzes this report and sends the results to forecast offices in several major cities.

He sends up balloons at 5:15 AM and 5:15 PM, local time, each day. These times coincide with balloon testing carried out at many other weather stations around the world. In this way, Kudloo's results can be coordinated to achieve a global picture of the atmosphere at particular times.

regions of the hurricane," said Philippsborn. "If we do that, we will finally be able to look at the entire air column throughout the environment of the hurricane, as well as the steering currents. This data will be fed into sophisticated computer models to improve forecasters' ability to figure out where these things are going to go."

The information collected by the jet is combined with readings taken at ground stations, in order to better assess where a hurricane is headed. In this way, it is possible to provide more advance warning to communities in the hurricane's path.

Other research platforms In addition to weather aircraft, NOAA also operates several other weather data-gathering systems. The NOAA ship the *Ronald H. Brown* is a state-of-the-art oceanographic and atmospheric research platform, sailing out of Charleston, South Carolina. It was commissioned in 1997, and as of 2007, is the largest vessel in the NOAA fleet. The *Ronald H. Brown* carries a wide variety of highly advanced instruments and sensors, and can travel worldwide supporting scientific studies to increase our understanding of the world's oceans and climate. NOAA also operates nineteen other vessels based in ports around the world, from which they conduct oceanographic and atmospheric research.

A NOAA P-3 Orion research plane flies toward a hurricane, ca. 1980s. AP IMAGES.

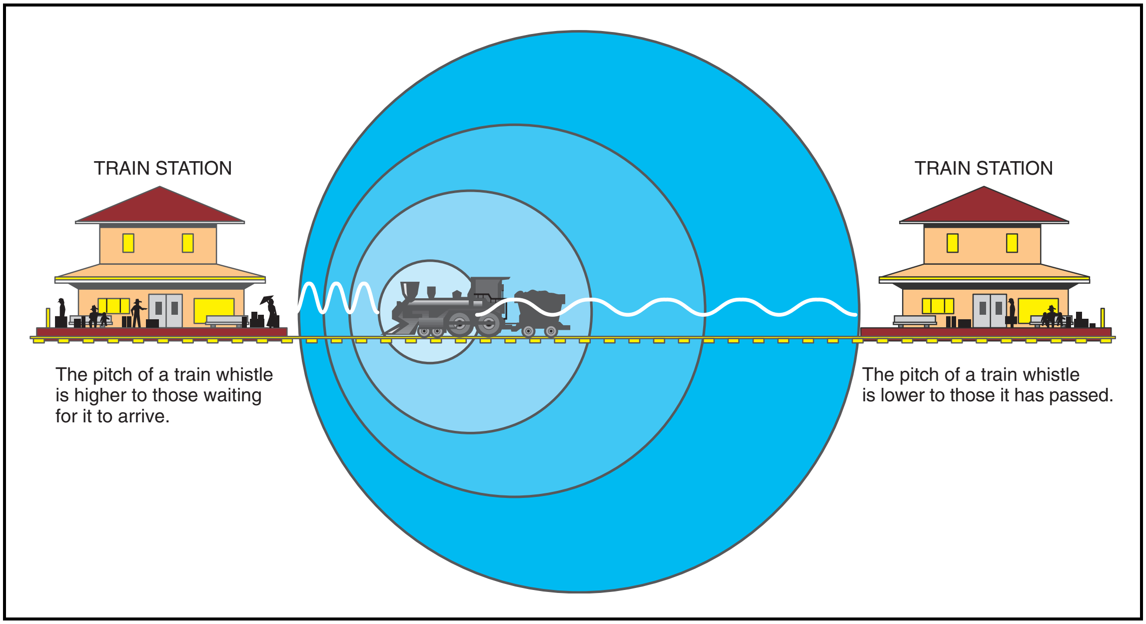
Radar Since its development during World War II (1939–1945), radar has become an indispensable tool for forecasting precipitation. Conventional radar (versus Doppler radar, discussed below) detects the location, movement, and intensity of precipitation, and gives indications about the type of precipitation present in a weather system. Since radar continuously scans a large region, it can detect isolated areas of precipitation that are often missed by instruments at widely spaced weather stations. For this reason, radar is particularly valuable for monitoring severe weather systems that are concentrated over small areas, such as thunderstorms. Radar is also valuable for assessing the intensity of larger severe weather systems, such as hurricanes.

The NOAA research ship Ronald H. Brown. *Scientists onboard are conducting an air pollution study in the Gulf of Mexico, 2006.* AP IMAGES.

Radar is an abbreviation for "**Ra**dio **D**etection **a**nd **R**anging." Conventional radar operates by emitting short-wavelength radio waves in the microwave portion of the radio spectrum. The microwaves are reflected by precipitation but not by the tiny droplets of water or ice that make up clouds. In this way, radar distinguishes between precipitation, which it "sees," and clouds, which it does not "see."

Precipitation scatters the microwaves, sending a portion of them—a "radar echo"—back to a receiver. The radar echo shows up as pulses on a cathode-ray monitor, which is similar to an older-style television screen. The radar continuously rotates, scanning a complete circle with a radius of up to 250 miles (400 kilometers) surrounding the station. It sends out and receives hundreds of signals each second.

Since radar waves travel at the speed of light, the distance of the precipitation from the radar station can be determined by the length of time between the emission and reception of a signal. The intensity of precipitation, or "echo intensity," is determined by the strength of the radar echo. This echo is portrayed on the monitor where intensities are color-coded. For example, large raindrops and hailstones, which have the greatest echo intensity, show up as red or purple, while light rain shows up as green.



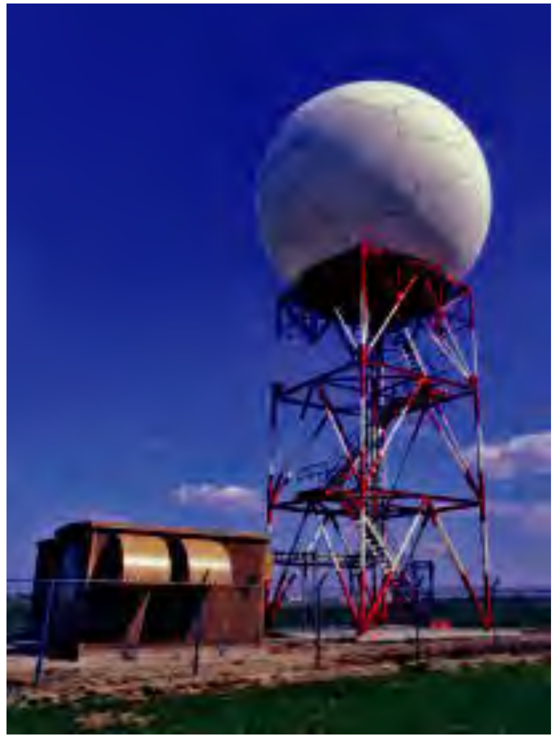
The Doppler effect.

In the mid-1970s a new, vastly improved type of radar, called Doppler radar, was developed. Doppler radar is based on the Doppler effect, discovered in 1842 by Austrian physicist Christian Doppler (1803–1853). The Doppler effect is the change in frequency of sound waves emitted from a moving source.

Waves bunch up as they approach their target and spread out as they move away from their target. An example of this effect is that the whistle of a train moving toward an observer sounds with a higher frequency than does the whistle of a train moving away from the observer. Similarly, a storm approaching a radar station reflects radar waves with a higher frequency than a storm moving away from a radar station.

Doppler radar can perform all of the functions of conventional radar plus it can determine the direction in which precipitation is moving, as well as wind speed and direction. Doppler can even estimate rainfall rates, which is important in foretelling floods. It can also locate fronts and wind shifts even in the absence of precipitation.

Doppler radar can look within a storm system and map out the air circulation patterns. This information allows forecasters to witness the earliest stages of a thunderstorm or tornado. While conventional radar can predict a tornado only two minutes before it is fully formed, Doppler radar gives twenty minutes's advance warning. Doppler radar gives a much sharper overall picture of precipitation and wind patterns than does conventional radar.



The Doppler radar tower at the National Weather Service in Wichita, Kansas. ©JIM REED/ CORBIS.

Aircraft pilots are particularly grateful for Doppler radar. Doppler radar can measure the velocity (speed and direction) of winds, giving advance warning of wind shear, which is a quick change in the direction or speed of the wind. A strong, downward wind that is the result of a wind shear, called a microburst, has been responsible for many plane crashes.

In the mid-1990s, the National Weather Service began replacing its conventional radars with Doppler radars. Between 1992 and 1997, 158 high-powered Doppler radars were installed. Each one can detect precipitation up to about 285 miles (460 kilometers) away and can measure winds up to about 150 miles (240 kilometers) away. These radars, which cover the continental United States, Alaska, Hawaii, Guam, and Korea, make up the NEXRAD (Next Generation Weather Radar) system, a joint project of the National Weather Service, the U.S. Air Force, and the Federal Aviation Administration. Additional Doppler radars known as Terminal Doppler Weather Radar (TDWR) were installed at major airports, specifically to watch for thunderstorms and microbursts.

Since Doppler radars have come into use, the success rate of identifying damaging thunderstorms and tornadoes has increased sharply. At the same time, the number of false alarms has been cut in half. The advance warning provided by Doppler radar has saved many lives.

Wind profilers A wind profiler is a specialized Doppler radar that probes the upper levels of the troposphere (the lowest part of Earth's atmosphere). Resembling a giant metal checkerboard, a wind profiler is a 40-foot-by-40-foot (12-meter-by-12-meter) wire mesh antenna mounted on Earth's surface. It is aimed straight up toward the sky and measures the speed and direction of winds aloft.

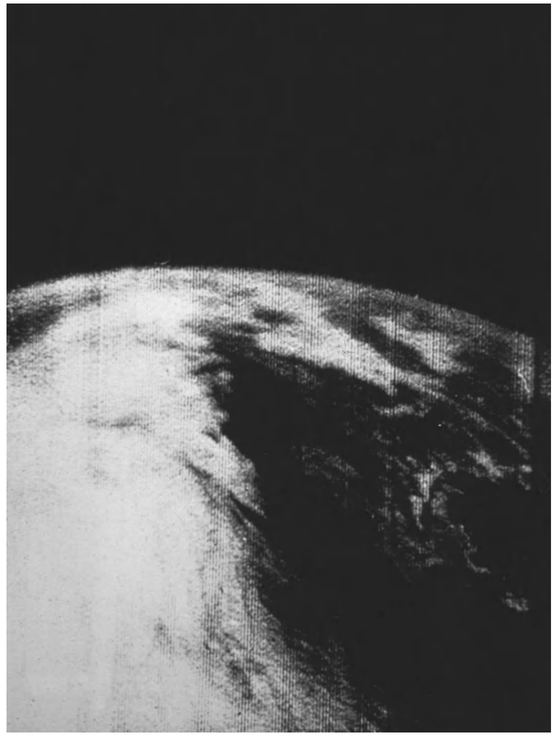
The technical name for a wind profiler is a "phased array antenna." It works by sending radar waves into the air. As the radio waves encounter changes in air density (caused by differences in temperature and humidity), they are reflected back to the antenna at varying intensities. A computer analyzes the data and calculates wind speeds and directions at seventy-two different levels of the atmosphere, to a maximum of 10 miles (16 kilometers) up. From that, average hourly wind speeds are calculated. This information is then sent to out to local offices of the National Weather Service and used in the creation of local forecasts.

The advantage of wind profilers over radiosondes or rawinsondes is that while rawinsondes take measurements only twice a day, wind profilers take readings every six minutes. Rawinsondes, however, measure temperature, air pressure, and humidity, as well as wind speed and direction. Wind profilers are used to complement the data collected by rawinsondes.

In 1992 the first network of twenty-nine wind profilers was erected in sixteen states throughout the Midwest. Scientists anticipated that the data they provided would assist in producing more accurate short-term weather forecasts. Up-to-the-minute information about winds aloft is particularly useful for plotting the course of a storm and for pilots who are planning flight paths. By 2004, thirty-five wind profilers had been installed in the central plains of the United States and Alaska.

Weather satellites The weather forecaster's most valuable tool for creating long-term forecasts is the weather satellite. Weather satellites make it possible to view storms from space and to monitor weather conditions continuously around the planet. Weather satellites also provide meteorologists with pictures and other information about hurricanes and tropical storms that occur over the oceans and points on land that are beyond the range of surface weather stations.

The first weather satellite, launched in April 1960, was *TIROS 1*. TIROS stands for Television Infrared Observation Satellite. It took twenty-three thousand pictures of global cloud cover over a period of seventy-eight days, exceeding the expectations of meteorologists. In September 1961, the value of weather satellites hit home with the images sent back of Hurricane Carla. That information resulted in the first widespread evacuation in the United States. About 350,000 people along the Gulf coast were removed from the path of the killer hurricane.



One of the first TIROS weather satellite pictures broadcast back from Earth orbit in 1960. COURTESY WALTER A. LYONS.

Today, several nations operate weather satellites. In addition to the United States, these include member nations of the European Satellite Agency, as well as Japan, India, and Russia.

Weather satellites do more than photograph clouds For most people, the words "weather satellite" conjure up images of swirling clouds seen from space. While weather satellites do produce such photos, their function is far more extensive. Weather satellites determine the temperature at various atmospheric levels, from cloud tops down to the land and oceans. They also measure humidity and wind speeds in the upper air and even track plumes (shifting regions) of invisible water vapor. In addition, satellites relay information from one ground station to another and pick up and transmit distress signals from vessels in the air and at sea.

Imaging equipment on board satellites is capable of receiving two types of radiation from Earth: visible and several channels of infrared. Visible radiation is reflected sunlight. Sensors on board satellites take what is essentially a black-and-white photo of the visible radiation. These pictures show cloud patterns as well as surface features larger than about a half-mile (a kilometer) across that are situated under clear skies. Therefore, it is possible to distinguish storm systems, fronts, thunderstorms, hurricanes, topographical landmarks, and even snow cover on land.

Infrared radiation is heat that is radiated by or reflected from Earth's surface. The picture produced by infrared sensors is essentially a road map of the temperatures of the cloud tops. Temperature varies with height—generally, the higher the cloud top, the lower the temperature. An infrared image also shows the location and intensity of thunderstorms. Thunderstorms are produced by towering clouds. The higher the cloud top, the greater the intensity of the thunderstorm.

The intensity of infrared radiation is also a measure of the amount of water vapor in the air. Since rising air carries moisture aloft, areas of vertical motion can be also be assumed to have high humidity. The presence of water vapor in the air, measured on what is known as the satellite's "vapor channel," has been recognized as an important factor in the development of thunderstorms at locations far from the vapor plume itself.

The instruments on board satellites analyze the visible and infrared radiation they receive and produce soundings. Soundings are analyses of temperature and humidity at different atmospheric heights. Satellites transmit these data by radio to weather forecasting centers several times daily.

Geostationary and polar-orbiting satellites The United States' fleet of weather satellites is operated jointly by NOAA and the National Aeronautics and Space Administration (NASA). Generally, weather satellites are either geostationary or polar-orbiting. Geostationary satellites orbit at an altitude above Earth's equator, about 22,300 miles (35,000 kilometers), that gives them the same orbital period as Earth's rotation period. Consequently, they appear to be "parked" above a given point on Earth's equator. Polar-orbiting satellites, on the other hand, travel north-south routes, crossing over both poles just 500 to 620 miles (800 to 1,000 kilometers) above Earth's surface. Together, geostationary and polar-orbiting satellites constitute a complete global weather monitoring system.

The current series of U.S. geostationary satellites is called Geostationary Operational Environmental Satellite (GOES). The first satellite in this series was launched in 1975. In late 2006, NOAA had four operational geostationary satellites. GOES-11 and GOES-12 are positioned to view the United States. Together, they provide complete scans every thirty minutes. GOES-10 has been positioned to scan much of South America. GOES-13 is operational, but has been placed in reserve (or storage) until needed.

Because of its high altitude, a geostationary satellite is able to scan nearly one-third of Earth's surface at a time, producing a picture of all of North America every thirty minutes. Most of North America is scanned by two different satellites, sometimes called GOES East and GOES West. Among other data collected by these satellites, they can detect developments in the atmosphere (which meteorologists call "triggers") that may lead to severe weather events, such as tornadoes, flash floods (sudden localized floodings), and hurricanes. Once the satellite detects a trigger, it tracks the storm's movements closely.

NOAA also operates several polar-orbiting satellites. The two oldest operational satellites are named NOAA-12 and NOAA-14. They were

The GOES meteorological satellite—an important part of the U.S. weather satellite program. FMA, INC.

launched in May 1991 and December 1994, respectively. While still operational, they are currently considered on standby status. Launched between 1998 and 2005, NOAA-15, 16, 17, and 18 are a newer and heavier design with enhanced capabilities.

Each satellite completes just over fourteen orbits in a twenty-four-hour period. Consequently, each satellite flies over a given point on Earth's surface approximately twice each day. Between the two satellites, every place on Earth is observed four times each day, twice in the morning and twice in the afternoon. Measurements of atmospheric conditions are therefore updated every six hours for each location. A lower flying polar-orbiting satellite collects highly detailed information from 100-mile-wide (60-kilometer-wide) sections of Earth's surface at a time. The polar-orbiters, in addition to monitoring temperature, cloud cover, and humidity, are equipped with ultraviolet sensors. These sensors measure ozone levels in the atmosphere and monitor the ozone hole, where ozone gets low in the upper atmosphere, that develops over Antarctica each fall.

The most recent entry in the fleet of polar-orbiting satellites is NOAA-18, which was developed by NASA for NOAA. It collects information about Earth's atmosphere and environment to improve weather prediction and climate research across the globe. NOAA-18 has the capability to detect severe weather and report to it the National Weather

Service, which broadcasts the findings to the global community. Early warning can mitigate the effects of catastrophic weather.

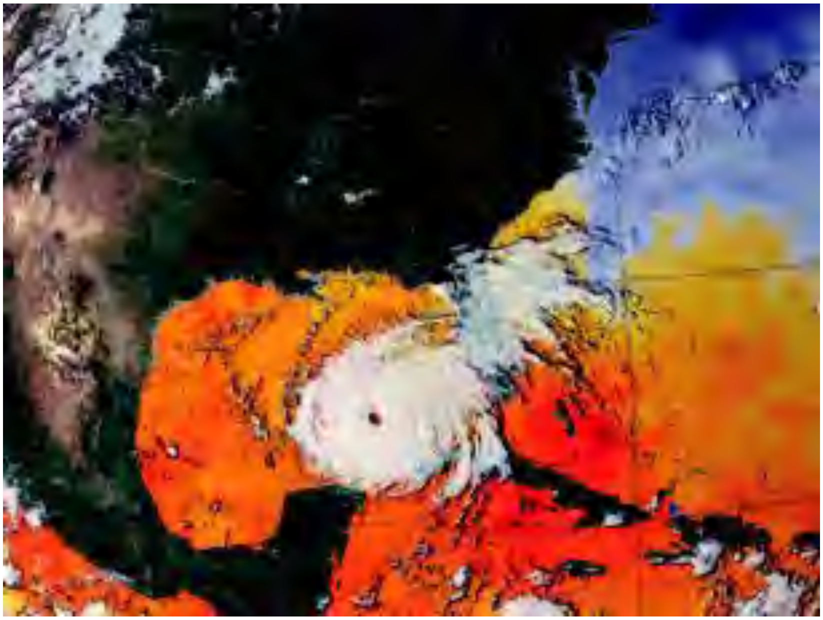
NOAA-18 also has instruments to support an international search-and-rescue program. The Search and Rescue Satellite-Aided Tracking System transmits to ground stations the location of emergency beacons from ships, aircraft, and people in distress around the world. The program, in place since 1982, has saved about eighteen thousand lives. NOAA-18 is also the first in a series of polar-orbiting satellites to be part of a joint cooperation project with the European Organization for the Exploitation of Meteorological Satellites.

Oceanographic satellites NOAA at one time also operated satellites specifically designed for surveying the oceans. The first of these, called Seasat, was launched in June 1978. After just one hundred days of operation, it ceased operation due to a power failure. While in orbit, Seasat used radar wave, visual, and infrared sensors to determine water surface temperature, wind speed, wind direction, wave height, and weather conditions on the seas.

The data collected by Seasat was used in the creation of the next oceanographic satellite, called the Ocean Topography Experiment, or TOPEX. (Topography is the shape and height of Earth's surface features.) The U.S. TOPEX, together with the French satellite Poseidon, was launched in 1992. The TOPEX/Poseidon data was used to create near-perfect maps of ocean topography, complete with ice floes (chunks of floating ice), wind, and waves.

In December of 2001, TOPEX/Poseidon was operationally replaced by Jason-1, a joint program of NASA and the French Centre National d'Etudes Spatiales. Jason-1 has vastly improved understanding of ocean circulation and its effect on global climate. This new system completed its fifth year in orbit on December 7, 2006. From its vantage point 860 miles (1,330 kilometers) above Earth, Jason-1 has provided measurements of the surface height of the world's oceans to an accuracy of 1.3 inches (3.3 centimeters).

Computer forecasting models Due to the complex and partly chaotic nature of weather forecasting, the National Weather Service has come to depend on computers to store and analyze the vast quantities of data received from surface weather stations, weather balloons, aircraft, radar, wind profilers, and satellites.



This visualization of Hurricane Rita shows the sea surface temperature from September 17–21, 2005. Temperatures in the Gulf of Mexico remained one to two degrees warmer (areas in yellow, orange, and red) than the 82 degree minimum needed to sustain a hurricane. ©NASA/CORBIS.

Before the use of computers in forecasting, which began in the mid-1950s, day-to-day forecasts could be made only thirty-six hours in advance. Now that computers have been developed to perform numerical forecasting, daily forecasts can be made for six to ten days in advance. Numerical forecasting is the use of mathematical equations and computer models to predict the weather.

The National Weather Service has contracted with IBM to provide supercomputer facilities to aid in hurricane forecasting through 2012. The computer system is a cluster of forty-four IBM eServer p690 servers located in Gaithersburg, Maryland. All together the system is capable of 7.3 trillion calculations per second. This improved forecasting was put to a severe test during the 2005 hurricane season, but it aided the NWS in making accurate landfall predictions for hurricanes Katrina and Rita. It also revealed gaps in our basic understanding of the forces controlling hurricanes.

NOAA and the NWS continue to upgrade and develop computer systems to improve the range and accuracy of forecasts. A wide variety of computer systems are used to run a variety of different numerical and dynamical models to provide local, aviation (for pilots), marine (for sailors), and other forecasts.

WORDS TO KNOW

occluded front: a front formed by the interaction of three air masses: one cold, one cool, and one warm. The result is a multi-tiered air system, with cold air wedged on the bottom, cool air resting partially on top of the cold air, and warm air on the very top.

ozone hole: the region above Antarctica where the ozone concentration in the upper atmosphere gets very low at the end of each winter.

ozone layer: the layer of Earth's atmosphere, between 25 and 40 miles (40 and 65 kilometers) above ground, that filters out the Sun's harmful rays. It contains a higher concentration of ozone, which is a form of oxygen that has three atoms per molecule.

polar front: the region or boundary separating air masses of polar origin from those of tropical or subtropical origin.

polar orbiting satellite: a weather satellite that travels in a north-south path, crossing over both poles just 500 to 625 miles (800 to 1,000 kilometers) above Earth's surface.

precipitation: water particles that originate in the atmosphere (usually referring to water particles that form in clouds) and fall to the ground.

psychrometer: an instrument used to measure relative humidity. It consists of a dry-bulb thermometer and a wet-bulb thermometer. Also called hygrometer.

radar: an instrument that detects the location, movement, and intensity of precipitation, and gives indications about the type of precipitation. It operates by emitting microwaves, which are reflected by precipitation. It is an abbreviation for **Ra**dio **D**etection **a**nd **R**anging. Radar may be called conventional radar to distinguish it from Doppler radar.

radiosonde: an instrument package carried aloft on a small helium- or hydrogen-filled balloon. It measures temperature, air pressure, and relative humidity from the ground to a maximum height of 19 miles (30 kilometers).

rain gauge: a container that catches rain and measures the amount of rainfall.

rainbow: an arc of light, separated into its constituent colors, that stretches across the sky.

refraction: the bending of light as it is transmitted between two transparent media of different densities.

relative humidity: a measure of humidity as a percentage of the total moisture that a given volume of air, at a particular temperature, can hold.

shower: a brief spell of localized rainfall, possibly heavy, that only occurs in warm weather.

sling psychrometer: an instrument that measures relative humidity. It consists of a dry-bulb thermometer and a wet-bulb thermometer mounted side by side on a metal strip, which rotates on a handle at one end.

In addition, NOAA is developing an extensive system for storing and analyzing data. Two NOAA sites began using the system, called the Comprehensive Large Array-data Stewardship System (CLASS), in

2004. It provides researchers and policy-makers access to NOAA environmental data and products, obtained either from spacecraft or ground-based observations.

These national and global forecasts and maps are then handed down to local weather agencies and private meteorologists in the media and at airlines. Local weather forecast offices use this information, in combination with other data, to produce basic public forecasts (including warnings of hazardous weather such as floods, thunderstorms, thick fog, or high winds) and aviation reports. Weather offices on the coasts also provide marine forecasts.

Who's who: Lewis Fry Richardson, forecaster by the numbers

British mathematician Lewis Fry Richardson (1881–1953) introduced the use of mathematical equations in forecasting with his 1922 report "Weather Prediction by Numerical Process." It took Richardson many months to devise a set of calculations that could represent the behavior of the various atmospheric processes necessary to create a sample twenty-four hour forecast. Although his calculations were far from perfect and his results quite inaccurate, he had set the stage for the development of the computer models which generate our forecasts today.

Richardson demonstrated that an enormous number of calculations would have to be made very quickly to produce accurate numerical predictions. In fact, he estimated that the creation of forecasts by his numerical process would require the efforts of sixty-four thousand mathematicians with calculators working around the clock every day of the year. Only with the advent of microcomputers did numerical prediction become feasible. With today's sophisticated equations that more closely model the behavior of the atmosphere, numerical prediction using computer models continues to produce increasingly reliable forecasts.

Understanding forecasts

The final product of the measurement is a weather forecast. The basic elements of a professional, local forecast are presented in a straightforward way that can easily be understood. Rather than page after page of data, daily forecasts use a type of shorthand consisting of internationally recognized weather symbols and weather maps. Learning this weather "language" makes it possible to understand professional forecasts, and will also be a handy tool to use in a weather journal.

What a forecast says A typical local forecast found in a newspaper, on the radio, television, or on the Internet will include information on at least the following conditions: temperature, humidity, air pressure, winds, sky conditions, and precipitation. On particular days, or in certain locations, forecasts may include additional information, such as storm warnings, marine advisories, aviation forecasts, and air quality reports. Forecasts may also give the times of sunrise and sunset and tell the phase (how much of the Moon is visible from Earth; how "full" it is) of the Moon.

Temperature In addition to giving the current temperature, most weather forecasts include the high and low temperatures for the preceding twenty-four hours. By way of comparison, they also include the normal high and low temperatures, as well as the record high and low temperatures, for that location on that date.

In winter or in cold climates, where the danger of frostbite (freezing skin) exists, weather forecasters include an index called the windchill equivalent temperature (WET), or windchill index, or just windchill. It is a measure of how cold the air feels, due to the interaction of wind and temperature. The WET is the temperature at which the body would lose an equivalent amount of heat if there were no wind. For instance, if it were 30°F (–1°C) with winds blowing at 15 mph (24 kph), the WET would be 9°F (–13°C).

During winter, or in any place where it is cold enough to require home heating, local weather forecasts may include a measurement called heating-degree-days. A degree-day is the number of degrees' difference between the day's mean (average) temperature and a temperature selected to represent the temperature at which most people set their thermostats. By tallying the total number of degree-days throughout a season officials can get a good idea of how cold the period has been and, consequently, how much heating fuel has been consumed.

To calculate the mean temperature, add together the day's high and low temperatures and divide by two. For example, say the high temperature for the day is 50°F (10°C) and the low is 20°F (6°C). The mean temperature is 35°F (50°F + 20°F, divided by 2). Now assume that in an average home the thermostat is set at 65°F (18°C). For this particular day, subtract the mean temperature, 35°F, from 65°F and come up with 30 degree-days. The colder the climate and the more severe the winter, the greater the number of heating-degree-days for the season.

Humidity What is referred to as "humidity" in forecasts is actually the relative humidity. It is expressed as a percentage of the amount of moisture in the air compared to the total moisture the air is capable of holding at that temperature. This measurement will not necessarily tell how wet or muggy the air will feel, since that is greatly dependent on temperature. For instance, 85 percent relative humidity will feel much more uncomfortable when it is 90°F (32°C) than when it is 50°F (10°C).

One way to determine "mugginess" is to look at the wet-bulb temperature. A wet-bulb thermometer will always give a reading that is lower than the actual air temperature except when the outside air has 100 percent relative humidity. When it is hot out, the lower the wet-bulb reading, the faster sweat evaporates, and the less muggy it feels. As the wet-bulb temperature approaches the air temperature, the slower sweat evaporates and the muggier it feels.

The temperature at which the wet-bulb temperature equals the actual air temperature is the dew point. The dew point, the temperature at which moisture condenses out of the air (because the air is saturated), can be used as a measure of mugginess or comfort. In general, if the dew point is below 40°F (4°C), the air feels dry. If it is between 40°F and 59°F (15°C), the air feels comfortable. If the dew point is higher than 59°F, the air feels muggy.

Air pressure Measurements of air pressure always include the pressure itself (which may be given in a variety of different units) and whether the pressure is rising or falling. The latter piece of information is more significant than the former, since it is the change in air pressure that gives clues about weather patterns. Recall that rising pressure generally means fair weather and falling pressure means changing weather.

There are no set values defining "high pressure" and "low pressure," since these are meaningful only when two pressures are compared to one another. That is, air pressure is "high" only if it is higher than an adjacent system or "low" if it is lower than an adjacent system.

At sea level, the average air pressure is 29.92 inches (1013 millibars). While it is tempting to categorize anything above that as "high" and anything below that as "low," consider this: The air pressure at one location may be 30.12 inches (1020 millibars) adjusted to sea level, considerably higher than average. Yet that location may be situated within a high-pressure belt where the average pressure is 30.25 inches (1024 millibars). In light of this information, is that air pressure "high" or "low"?

Winds Most weather forecasts provide two pieces of data about the wind: speed and direction. The speed describes current conditions, while the direction is most valuable as an indicator of what is to come.

Here is a general guideline for categorizing how windy a day is: From 0 to 10 mph (0 to 16 kph) the wind is somewhere between still and gentle; from 10 to 20 mph (16 to 32 kph) the wind is moderate or "breezy"; from 20 to 30 mph (32 to 48 kph) the wind is strong; and anything above 30 mph (48 kph) is a gale-force wind.

	Air temperature (°F)	Relative humidity (%) 10	20	30	40	50	60	70	80	90	100
Uncomfortably warm	104	90	98	106	112	120					
	102	87	95	102	108	115	123				
Pleasant	100	85	92	99	105	111	118			Unbearably hot	
	98	82	90	96	101	107	114				
	96	79	87	93	98	103	110	116			
	94	77	84	90	95	100	105	111			
	92	75	82	87	91	96	101	106	112		
	90	73	79	84	88	93	97	102	108		
	88	70	76	81	85	89	93	98	102	108	
	86	68	73	78	82	86	90	94	98	103	
	84	66	71	76	79	83	86	90	94	98	103
	82	63	68	73	76	80	83	86	90	93	97
	80	62	66	70	73	77	80	83	86	90	93
	78		63	67	70	74	76	79	82	85	89
Crisp	76		60	63	67	70	73	76	79	82	85

The humiture index.

Wind direction often provides a clue as to what type of weather is coming, although the specifics vary from location to location. See if you can draw a connection between wind direction and weather patterns in your area by examining trends in your weather journal.

Sky conditions This section of the forecast includes information on the amount and type of cloud cover, as well as fog and haze, when relevant. It also includes changes in conditions, such as "increasing cloudiness," "decreasing cloudiness," "clearing," or "fog lifting before noon." In general, increasing cloudiness indicates a greater chance of precipitation while decreasing cloudiness and lifting fog indicate that fair weather is in store.

Precipitation This category contains information on the amount of rain or snow that has fallen within the previous twenty-four hours and amount predicted to fall during the coming twenty-four hours. In the United States, rainfall and snowfall are generally measured in inches. Any rainfall over one-half inch (about one centimeter) in one day is considered heavy. It takes about five or six inches (about fifteen centimeters) of snow to be considered a heavy snowfall. Snow occupies roughly ten times the volume of its meltwater equivalent although this varies with temperature. The warmer and wetter the snow, the higher the meltwater equivalent, and the colder and drier the snow, the lower the meltwater equivalent.

Most forecasts state that there is a certain percent chance that rain or snow will fall during the coming twenty-four hours. Alternatively, the probability of precipitation may be characterized by terms such as "chance of rain" or "slight chance of snow."

The percentages are determined by examining ten days in the past which had weather conditions comparable to the present day. The first step is to tally up how many of those ten days had at least 0.01 inch of rainfall or the meltwater equivalent of snowfall. Then that number is divided by ten and multiplied by 100 percent. Thus, if precipitation occurred on four out of ten similar days, there is a 40 percent chance of precipitation for the present day.

Many forecasters prefer to use phrases to describe the chance of rain or snow. Here is a key to understanding those phrases, as well as some other forecasting language relating to precipitation:

- slight chance of precipitation—10 or 20 percent chance
- chance of precipitation—30 to 50 percent chance
- occasional precipitation—over 50 percent chance (but will last less than half of the forecast period)
- showers—localized, brief rainfall ("snow showers" refers to snowfall)

A key reference to: The humiture index

The humiture index, also known as the "temperature-humidity index," is another way to measure how hot and muggy it feels and consequently how stressful outdoor activity will be. The index is based on the same principle as the wet-bulb temperature, namely that the faster water (or sweat) evaporates, the less muggy it is (and the cooler people feel), and vice versa.

The humiture index is most useful during the hottest part of the day. The value for any given set of conditions can be determined by solving a rather complex equation for given values of temperature and relative humidity. Fortunately, there is a chart that serves the same purpose. The lower the humiture index, the more comfortable the air feels. Any value over 89 on the chart is in the "uncomfortably hot and muggy" range.

Most television and newspaper weather forecasts include some form of humiture index when conditions are so hot and muggy that people are in danger of suffering heat stroke. This index may be listed as a "heat-stress index" or "apparent temperature." It generally includes one of the following four danger categories: caution, extreme caution, danger, or extreme danger.

- rain—steady rainfall covering a wider area
- isolated showers—showers that fall on less than 10 percent of the forecast area
- scattered showers—showers that fall on 10 to 50 percent of the forecast area
- numerous showers—showers that fall on the majority of the forecast area
- periods of rain (or snow)—on-and-off rain (or snow) throughout the whole area, for the duration the forecast period
- snow squall—very heavy, brief snowfall
- snow flurries—very light snowfall that results in little or no accumulation
- heavy snow—snow that is accumulating at a rate of at least 1 inch per hour, with visibility less than 5/16 of a mile

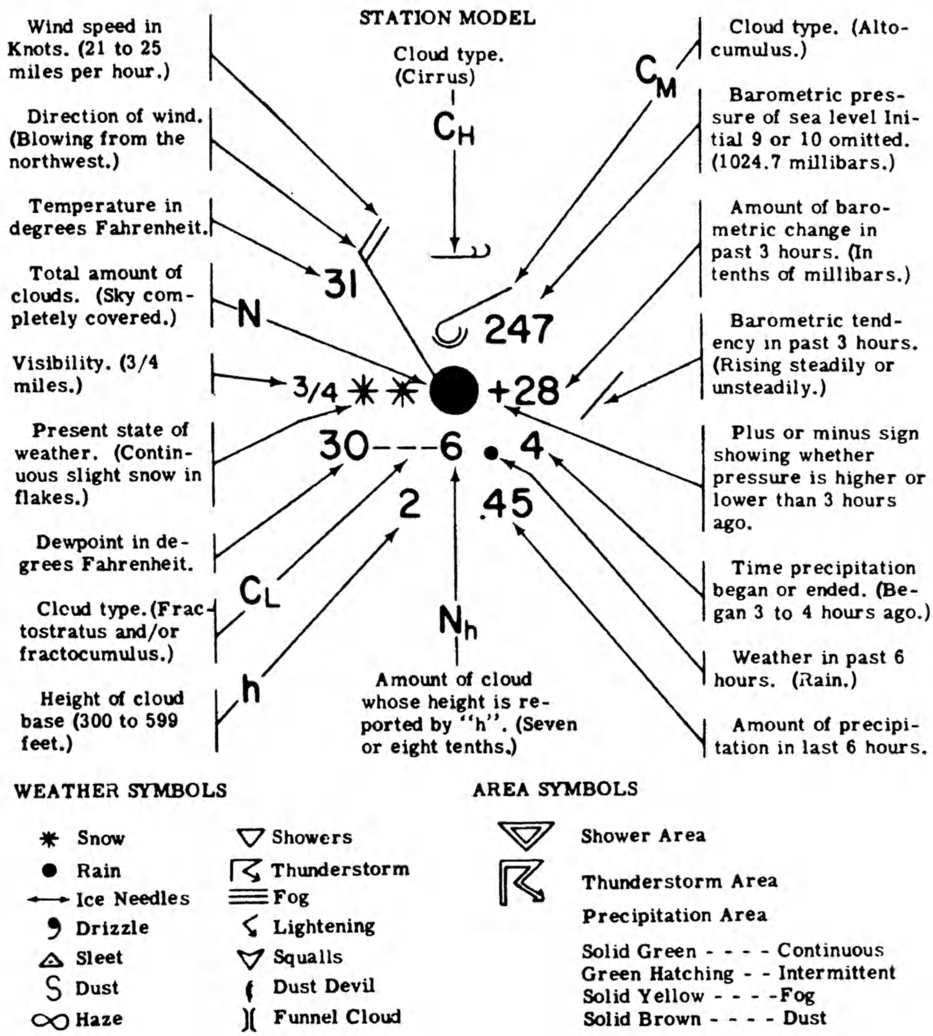
International weather symbols The set of weather symbols in use today was developed as a way to standardize the data collected by the thousands of weather stations around the globe. Using this universal shorthand, a weather station can describe many conditions—winds, temperature, visibility, present weather conditions, dew point, cloud cover, precipitation, and air pressure—for each time period (usually every three hours) in a space the size of a postage stamp. Forecasters also use symbols for fronts, pressure highs and lows, and regions of equal pressure, in the creation of weather maps. A weather station entry, sometimes called a station circle, is the form in which information is summarized by each individual weather station and sent to regional offices. A forecaster, by glancing at a station circle, can quickly discern the overall conditions at a given station.

Weather maps A weather map, also called a surface analysis, is created by national or regional weather agencies and is intended for use by forecasters. Weather maps generally encompass an entire nation or group of nations. In North America, the basic map before weather patterns are added shows state/provincial borders, large cities, major rivers, and other important topographical features.

Station circles are plotted on the map at their appropriate locations. The collection of local data is then examined for patterns of air pressure and temperature. From this, meteorologists can determine the locations of fronts, regions of high and low pressure, the dividing line between

EXPLANATION OF WEATHER STATION MODEL AND SYMBOLS

At Weather Bureau offices, maps showing conditions at the earth's surface are drawn 4 times daily or oftener. The location of the reporting station is printed on the map as a small circle. A definite arrangement of the data around the station circle, called the station model, is used. The station model is based on international agreements. Thru such standardized use of numerals and symbols, a meteorologist of one country can use the weather maps of another country even though he does not understand the language. An abridged description of the symbols is presented below.

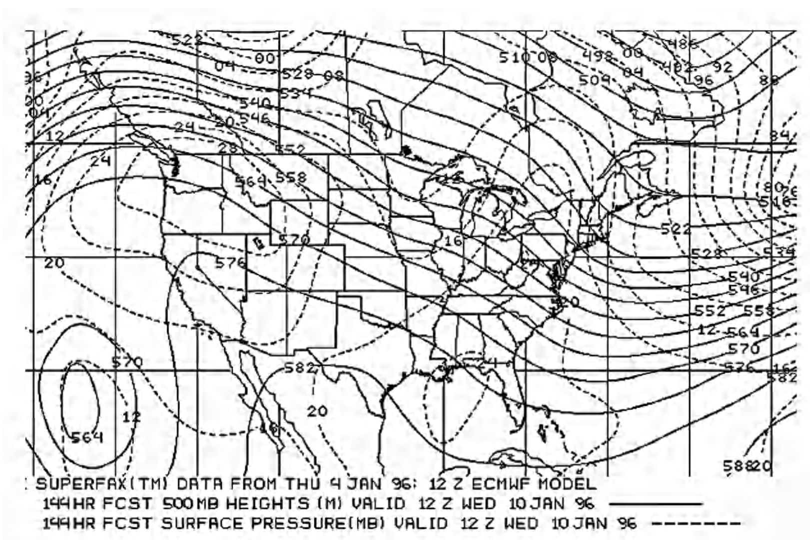


A weather station journal entry.

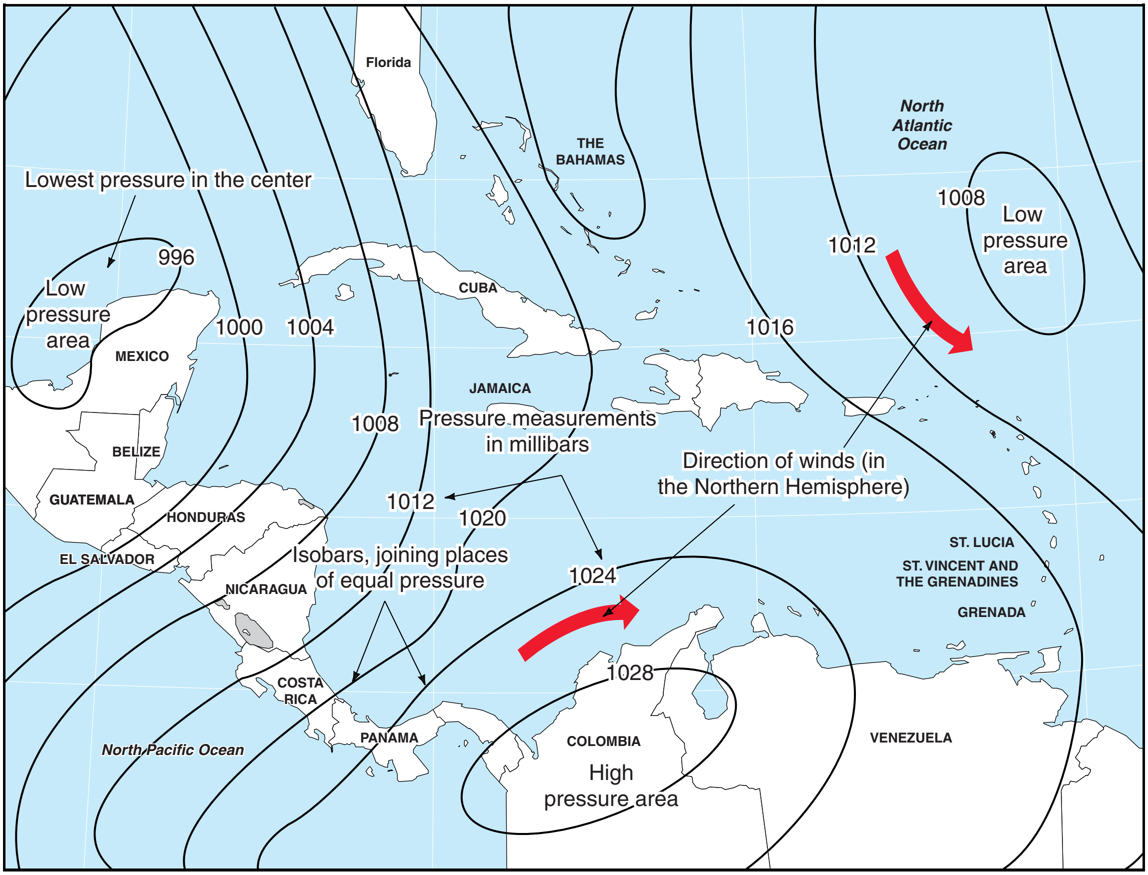
temperatures below freezing and above freezing, and the movement of storm systems. Each of these patterns is labeled on the map using symbols. The weather maps on television or in the newspaper are greatly simplified versions of the type used by forecasters.

A set of features found on many weather maps is a series of lines known as isobars. Isobars are lines that connect points of equal air pressure. On some maps, an air pressure value is tagged on each isobar. Closed isobar curves represent centers of high and low pressure. These areas are usually marked on a map with a capital "H" or "L." The isobars in the figure form concentric circles of increasingly high pressure. Between the high pressure areas are isobars of low pressure, where the lowest pressure is along the circle at the center.

Isobars are also guides to wind speed and direction. First, the closer the isobars are to one another, the steeper the pressure gradient and hence, the stronger the winds. Second, remember that winds do not flow into the center of high- and low-pressure areas, but around them. In the Northern Hemisphere, winds flow counterclockwise around the lows and clockwise around the highs. Isobars are generally closer together as they approach low-pressure areas, where winds also tend to be strong. Conversely, isobars are generally farther apart as they approach high-pressure areas, where winds are relatively calm.



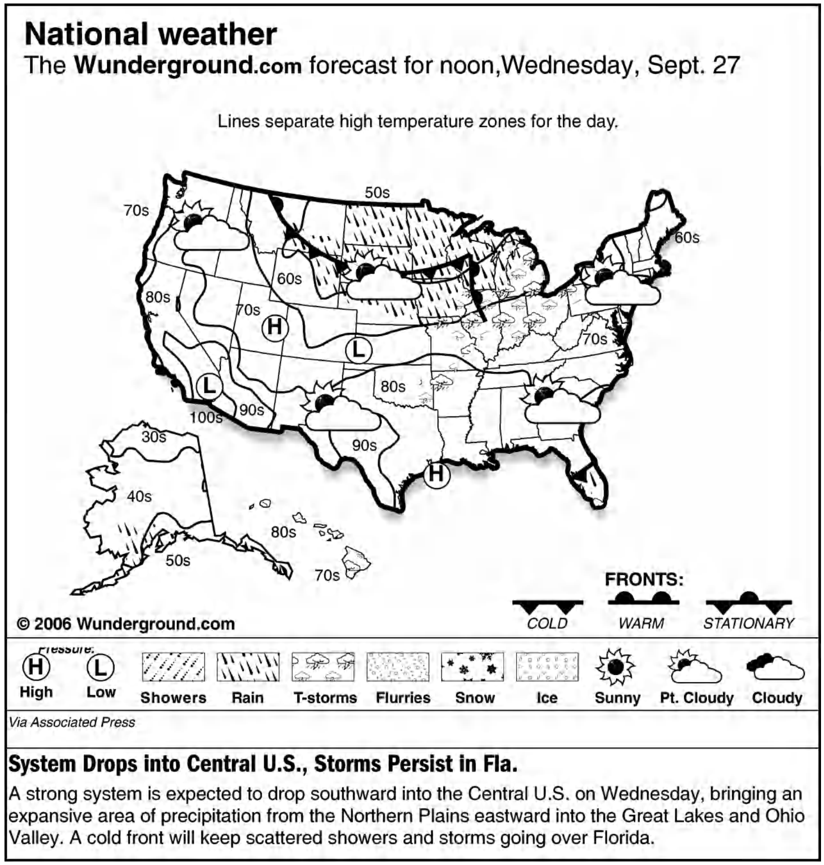
An atmospheric weather map. COURTESY WEATHER SERVICE INTERNATIONAL CORPORATION.



Isobars are lines connecting areas of equal pressure.

Fronts, the boundaries between relatively warm and cold air masses, are also labeled on a weather map. The locations of fronts are determined by using both surface data and satellite images. Clues to the position of a front are found in surface readings for wind direction, dew point, sky conditions, and precipitation. The locations of temperature differentials on satellite images also help identify where air masses begin and end.

As illustrated in the national weather map, a line with triangles represents a cold front and line with half-circles represents a warm front. The triangles and half-circles point in the direction the air mass is heading. A line with triangles on one side and half-circles on the other represents a stationary front (the line between a cold and a warm air mass,



A U.S. weather map showing many of the international weather symbols. AP IMAGES.

neither of which is moving) and a line with triangles and half-circles both on the same side represents an occluded front (a front formed by three air masses).

Satellite and radar images also indicate where precipitation is falling. These areas are marked on weather maps with certain colors or gray shading, or are superimposed with diagonal lines. The maps also indicate temperature by applying different shades of gray or colors to areas that fall within given temperature ranges.

Weather maps are also created for the upper levels of the atmosphere, using information provided by radar, weather aircraft, weather satellites, and radiosondes. These maps differ from surface maps in that they are constructed along an imaginary surface of equal pressure (i.e., 500 millibars, where the atmosphere is at half its sea-level pressure). Air pressure varies with altitude, primarily due to temperature differences. Air pressure drops with altitude at a faster rate in cold air masses than it does in warm air masses.

People can also discern the pattern of upper-air winds from upper-air maps. This information is valuable because the motion of winds aloft is a key component in the development of weather patterns at the surface.

Forecasting in the media

What most people know about the weather is based solely on reports they see on television, read in the newspaper, hear on the radio, or find on the Internet. These reports include general information about the nation's weather as well as more detailed analyses and predictions for the local area.

Television weathercasts Television is the medium from which most people today get their weather information. Weather is an element of practically every local and national television news show, and the true weather fanatic with cable television can tune in to it twenty-four hours a day.

In addition to providing the basic information that helps people decide how to dress in the morning, TV weather can be quite educational. Television weathercasts have featured lessons on the dynamics of frontal systems, jet streams (the fastest upper-air winds), El Niño (strong episodes of Pacific warming), highs and lows, hurricanes, tornadoes, and other phenomena.

Weather reports first appeared on television in the early 1940s. The original broadcasts were extremely primitive, even laughable by today's standards. To assure some measure of professionalism in TV forecasts, the American Meteorological Society began issuing its Seal of Approval in 1959 to those weather shows it deemed trustworthy. A similar system of offering credentials was adopted by the National Weather Association in 1982.

In the early years, television weathercasters drew fronts, highs and lows, and other information by hand, or placed stick-on symbols onto large maps, as they gave their reports. In the early 1980s these methods were replaced by computer-generated color graphics. Coupled with images provided by geostationary satellites, which first began appearing on TV screens in the mid-1970s, television weathercasts became an impressive visual presentation.

The five-minute weather presentation seen during a TV news show may appear simple, but producing the segment is actually quite a laborious task. It begins about five hours before the broadcast, when the weather reporter pores through the stacks of computer-generated forecasts

A meteorologist explains weather patterns. ©SW PRODUCTIONS/ BRAND X/CORBIS.

provided by the National Weather Service, as well as radar and satellite images. It is the weather reporter's task to make sense of it all, condense it into a short report, and choose satellite images to go along with it.

Next comes the creation of weather graphics, including maps, forecasts, and animated satellite images. These animated images are actually a string of satellite pictures shown in quick succession, so it looks as if they are moving. While many television stations rely on private weather graphics firms to design the visuals for their weather shows, some stations, including The Weather Channel, design their own computerized graphics.

Then, just before the show, the weather reporter must get all the information in order, check for any last-minute changes in conditions, and rehearse the report. Finally, it's show time—five minutes later, it is over.

Newspaper weathercasts There is no such thing as a standard newspaper weather report. Newspaper weather pages are often colorful, with easy-to-understand symbols (such as pictures of sun and clouds), and they contain a great variety of information presented in many different ways. For instance, newspapers may feature a large weather map of the entire nation, a local map, or both.

Regardless of the differences, some basic ingredients show up in one form or another in weather pages of most newspapers, particularly large ones. These include a weather map, a local report, national and local forecasts, a list of high and low temperatures for select cities in the North America, and, in some cases, around the world. Most weather maps include fronts and pressure systems. While many weather maps display isobars, an even greater number display isotherms, which are bands representing areas of similar temperature.

Most weather pages contain information that goes beyond the basic report. The specifics of those supplements generally depend on the economic, geographic, and recreational interests of the inhabitants of the locality. For instance, a weather page may contain a ski report, a marine forecast, a farm and garden report, or an air quality index. Some weather pages also contain sections for children, including pictures, activities, or "fun facts." Others may contain satellite photos, an analysis of the jet stream, or a tally of heating-degree-days.

Weather report: Wooly Lamb—the first weather reporter

The very first televised weather report was shown on October 14, 1941, on WNBT (later WNBC) in New York City. The report was presented by a cartoon character named "Wooly Lamb." The little lamb began each report by first looking at the sky through a telescope, then facing the camera and singing this song: "It' hot, it's cold. It's rain, it's fair. It's all mixed up together. But I, as Botany's Wooly Lamb, predict tomorrow's weather." ("Botany" referred to the show's sponsor, Botany's Wrinkle-Proof ties.) A written forecast for the next day's weather then appeared on the screen. Even more amazing than the notion of a cartoon lamb presenting the weather, is the fact that Wooly Lamb kept its job for seven years!

Radio weathercasts Without the aid of weather maps and other visuals, weather reporting is quite challenging. Thus, most commercial and public radio stations present only general current weather information and what listeners may expect over the next twenty-four hours. Other information, such as shipping reports or agricultural reports (generated especially for farmers), are broadcast in locations where they are relevant.

One source of extensive, local weather information on the radio, available all across the United States, is provided by the National Oceanic and Atmospheric Administration. NOAA Weather Radio is transmitted on seven different high-band FM frequencies, ranging from 162.400 to 162.550 megahertz. To hear this transmission, listeners may need a special receiver called a "weather radio." In some places, NOAA Weather Radio comes in on special radio bands such as the weather band, citizens' band, and some automobile, aircraft, and marine bands. In a few areas the transmission can be picked up on standard AM/FM radios.

NOAA Weather Radio continuously broadcasts the latest weather information, twenty-four hours a day. Reports are usually four to six

A key reference to: The marvelous chroma key

Television weather reporters do not see what viewers see. The colorful weather map so familiar to TV audiences, to which the reporter appears to point as he or she describes the weather, does not show up in the studio. Instead, the background seen by the reporter is a single color, typically green or blue. The reporter relies on monitors on either side of the screen to determine the position his or her hands or body relative to the map.

The color images viewers see on a TV weathercast are produced by a process called "chroma key," or "color-separation overlay." A computer in the station's control booth electronically superimposes single-color portions of a graphic on top of one another, producing a full-color image. When the forecaster gives a verbal cue or when the color of the screen behind the reporter (the "chroma key") changes, a new graphic is appears.

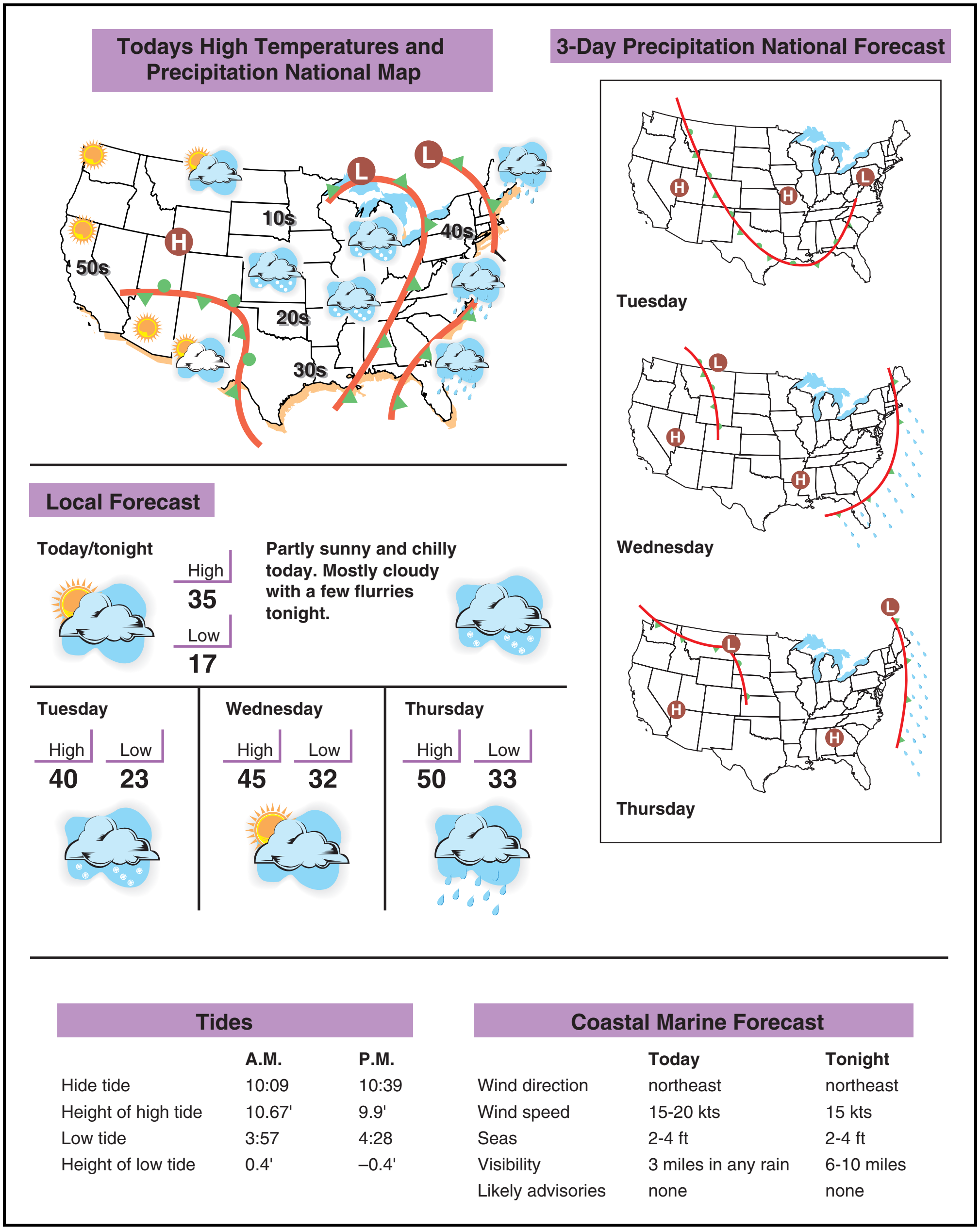
minutes long and are updated about every one to three hours. Reports are changed more frequently during rapidly changing or severe weather.

In response to hazardous weather, NOAA Weather Radio will sound an alarm that alerts listeners to turn up the radio and stay tuned. Some receivers are programmed to turn on whenever a hazardous-weather alarm is activated. NOAA Weather Radio also broadcasts reports from local weather service offices that are relevant to the region. For instance, one may offer marine reports while another offers agricultural reports and climatological forecasts.

NOAA Weather Radio broadcasts are prepared by local offices of the National Weather Service (NWS) and sent out from four hundred transmitters throughout the United States, Puerto Rico, Guam, and Saipan. Each station transmits to a radius of only 40 miles (64 kilometers), an area covered by the report. Presently, NOAA Weather Radio can be received by 80 to 95 percent of the U.S. population, provided they have a radio.

Weather on the Internet The Internet serves as a link between the general public and just about every type of weather information imaginable. It is a valuable resource for professional meteorologists, the media, and weather enthusiasts alike. On the Internet, users can find satellite and radar images, photos of storms and storm-related damage, the predicted courses of hurricanes and inland storms, detailed forecasts for particular regions, reports tailored to specific interest groups (e.g., mountain climbers, boaters, and skiers), and much more.

National Oceanic and Atmospheric Administration The most extensive and most reliable source of weather information on the Internet is from the National Oceanic and Atmospheric Administration. Much more than weather information is available: NOAA also covers fisheries, navigation, and other topics related to the oceans. It does, however, give



Tides

	A.M.	P.M.
Hide tide	10:09	10:39
Height of high tide	10.67'	9.9'
Low tide	3:57	4:28
Height of low tide	0.4'	–0.4'

Coastal Marine Forecast

	Today	Tonight
Wind direction	northeast	northeast
Wind speed	15-20 kts	15 kts
Seas	2-4 ft	2-4 ft
Visibility	3 miles in any rain	6-10 miles
Likely advisories	none	none

Newspaper weather maps including national and local forecasts and marine forecast.

WORDS TO KNOW

stationary front: the dividing line between two stationary air masses. It occurs when a cold air mass comes in contact with a warm air mass, with neither air mass moving.

sunspot: an area of magnetic disturbance on the surface of the Sun, sometimes referred to as a sun storm.

thermograph: an instrument consisting of a thermometer and a needle that etches on a rotating drum, continually recording the temperature.

thermometer: an instrument used to measure temperature. It consists of a vacuum-sealed narrow glass tube with a bulb in the bottom containing mercury or red-dyed alcohol. Also called dry-bulb thermometer.

thunderstorm: a relatively small but intense storm system, that produces moderate-to-strong winds, heavy rain, and lightning, sometimes with hail and tornadoes.

topography: the shape and height of Earth's surface features.

tornado: a rapidly spinning column of air that extends from a thunderstorm cloud to the ground. Also called a twister.

veering wind: a wind that shifts direction, turning clockwise as it moves higher.

warm front: the line behind which a warm air mass is advancing, and in front of which a cold air mass is retreating.

warning: a severe weather advisory that means that a storm has been sighted and may strike a specific area.

watch: a severe weather advisory that means that while a storm does not yet exist, conditions are ripe for one to develop.

weather: the set of conditions of temperature, humidity, cloud cover, and wind speed at a given time.

weather aircraft: aircraft that carry weather instruments and collect data in the upper levels of the troposphere. They are primarily used to probe storm clouds, within which they measure temperature, air pressure, and wind speed and direction.

weather forecast: a prediction of what the weather will be like in the future, based on present and past conditions.

weather map: a map of a large geographic region, on which weather station entries are plotted. By looking at a weather map, a meteorologist can determine the locations of fronts, regions of high and low pressure, the dividing line between temperatures below freezing and above freezing, and the movement of storm systems. Also called surface analysis.

weather satellite: a satellite equipped with infrared and visible imaging equipment that provides views of storms and continuously monitors weather conditions around the planet.

wind sock: a cone-shaped cloth bag open on both ends, through which wind flows that is used to determine the direction and estimate the speed of the wind.

wind speed: the rate at which air is moving relative to the ground.

windchill equivalent temperature: the temperature at which the body would lose an equivalent amount of heat, if there were no wind. Also called windchill index.

in-depth information on satellites (weather and others) and provide a link to the National Weather Service, which is a branch of NOAA.

Using forecasts

Most people listen to or read a forecast to decide how to dress the next day or whether to set up their party indoors or outdoors. But forecasts take on much greater significance when the weather is severe. Warnings of an approaching storm are intended to give local inhabitants time to take safety precautions and, if possible, secure their property. Forecasts take on economic significance for people who make their living outdoors or at sea.

Improving on forecasts Understanding the basics of weather enables one to make greater use of forecasts. With knowledge of how the landscape (mountains, valleys, lakes, buildings, trees, etc.) affects weather conditions surrounding a locality, a local forecast can be customized to fit. For instance, in a city, the temperature, on average, may be a few degrees warmer than at the airport weather station. Large buildings block the wind, making it slower than what is reported.

Knowing how weather works, ordinary people can check the accuracy of a forecast. Remember that weather reports sent out through the media are generally based on information that is at least two hours old, and the weather is notorious for its quick changes. A cold front, for example, may advance more rapidly or more slowly than predicted, or a completely new weather system may develop quickly.

Severe weather warnings One of weather forecasters' most important duties is to alert the public to approaching severe weather. In recent years, the amount of time between the warning of a potential disaster and its actual occurrence has greatly increased. This improvement is due primarily to better computer forecasting models. In fact, major storms such as hurricanes, blizzards (the most severe type of winter storm), and heavy rains can now be predicted by computer even before the weather conditions they produce are detected by weather stations.

Tools such as computer modeling, Doppler radar, and weather satellites have significantly improved the accuracy with which the course of severe storms can be predicted. This process is important because forecasters do not want to initiate evacuations of people who are not really in a storm's path. Evacuations, which are often carried out in advance of a hurricane, are very expensive. People spend money boarding up their houses and purchasing supplies. Businesses lose money when they are forced to close. More importantly, when people are evacuated without reason, they tend to lose faith in weather warnings. The next time a warning is issued, they may decide there is no reason to leave, even though that time they may really be in harm's way.

Far more challenging than predicting when a major storm will strike is predicting the approximately ten thousand violent thunderstorms and one thousand tornadoes that occur in the United States each year. In recent years, only modest gains have been made in this area. One reason why it is much more difficult to forecast small-scale storms than it is to forecast large-scale storms is that small, localized patterns are usually not predicted by computer models. The warning signs of tornadoes and thunderstorms must be picked up at weather stations before any type of advisory can be issued—and then there is usually not much time before the storm strikes.

Thanks to Doppler radar, recent improvements have been made in determining when thunderstorms become severe, as well as assessing the course of tornadoes. This technology, which gathers information from the heart of the storm, is responsible for increasing the warning times for violent thunderstorms, as well as halving the number of false alarms.

Meteorologists make use of two main categories of severe weather advisories: watches and warnings. A "watch" means that while a storm does not yet exist, conditions are ripe for one to develop. A "warning" is more serious. This message indicates that a storm has been sighted and may strike a given area. While numerous subsets of these categories are issued for each type of storm, these two words alone provide important clues about the status of a storm and how to respond appropriately. It is important to stay tuned to forecasts and heed all warnings. While some storms are merely exciting spectacles that cause little damage, others may create life-threatening conditions.

Specialized forecasts Specialized forecasts are generated for particular geographic areas and are tailored to the interests of specific groups of people, such as pilots, boaters, travelers, and farmers.

Aviation reports provide information on the height of clouds, visibility, and storm systems. In response to reports of storms or poor visibility, a pilot may change his or her course and fly around a storm. Reports of poor conditions at an airport may force a pilot to delay landing or to proceed to a different airport. The National Weather Service operates a toll-free telephone information line to help keep pilots informed.

Marine forecasts are issued for areas along the coastlines of North America. Such forecasts are of interest to the nearly two-thirds of the population who live within 50 miles (80 kilometers) of a coast. These forecasts give projections of the times of high and low tides, wave heights, wind speed and direction, and visibility. When rough weather is brewing over the water, the NWS issues small-craft advisories and other warnings that may affect fishermen and other boaters, as well as workers on oil rigs.

Agricultural reports include current temperature, precipitation, and wind speed and direction, as well as predictions of temperature and precipitation for the days to come. One example of how farmers use this information is in deciding when to apply pesticides. The temperature projections help a farmer determine which insects will likely pose a threat to which crops. If a pesticide is deemed necessary but rain is predicted, a farmer will delay applying chemicals since rain will wash the chemicals off before they take effect. The farmer also takes into account the current wind information, as a safety measure, before spraying.

Another element of an agricultural forecast is a frost warning, which is issued to warn farmers of the danger to their crops. Decisions about when to irrigate, obviously, are also dependent on predicted rainfall. So is cutting hay, since fresh hay needs at least two days to dry once it has been cut.

Travelers' reports tell what the weather is like at a traveler's destination. Some TV or newspaper weather sources regularly include forecasts for popular vacation spots, while others list temperature highs and lows and general conditions for major cities around the world. Some travelers' reports indicate whether or not airlines are operating on schedule at airports in major travel destinations.

Ski reports, which describe conditions of interest to skiers, generally list forecasts for popular ski destinations.

The future of forecasting

In the early 1960s Edward Lorenz demonstrated that it may never be possible to predict the weather with perfect accuracy; just how close to perfection forecasting can come is still not known. However, the meteorological community is determined to push the success rate of forecasting to the theoretical limit, whatever that may be. With that goal in mind, meteorologists are pursuing various strategies, including achieving a greater understanding of the forces at work in creating weather, obtaining higher quality observational data, and improving computer capabilities.

Weather report: Marine forecast

The following is an example of a marine forecast taken from NOAA on March 7, 2007: "Point Arena, California: Tonight: west winds 5 to 10 knots switching northwest late. Wind waves 1 to 2 feet with swell 4 to 6 feet at 11 seconds. Thursday: northwest winds 10 knots. Wind waves 1 to 2 feet with swell 5 to 7 ft at 10 seconds." A marine forecast for Plymouth, Massachusetts, on the same day reads follows: "SMALL CRAFT ADVISORY IN EFFECT FROM THURSDAY MORNING THROUGH THURSDAY EVENING. Tonight: west winds 15 to 20 knots. Seas 2 to 4 feet. A slight chance of snow showers after midnight. Light freezing spray after midnight with visibility 1 to 3 nautical miles. Thursday: west winds 20 to 25 knots, becoming northwest 25 to 30 knots. Seas 4 to 6 feet. Light freezing spray. A chance of snow showers in the morning. Visibility 1 to 3 nautical miles."

Toward a greater atmospheric understanding

During the World War I era (1914–1918), the discovery of fronts, air masses, and upper-air patterns revolutionized how we look at weather. It sparked the rapid development that the field of meteorology continues to enjoy to this day. Along with increased knowledge of how weather works, however, has come the realization that there is still much to learn.

New facets of atmospheric science are continually being discovered and probed. Some topics currently under study include interaction between the ocean currents and temperatures and atmospheric circulation; the role of the stratosphere (the layer of Earth's atmosphere above the troposphere); the effect of plumes of water vapor in the air; the effect of ice particles in thunderstorm clouds, and lightning above the clouds, on the global electrical circuit; and the interaction of winds and clouds in the formation of storms.

As meteorologists learn how these factors fit with other pieces of the atmospheric puzzle, they can incorporate them into computer forecasting models. While technological advances in recent years have greatly improved the abilities of computers to process information, in the end, a computer merely does what it is programmed to do. The quality of the results depends on the sophistication of the program. The sophistication of the program, in turn, is a reflection of the programmer's understanding of atmospheric processes.

More and better observations Another way that meteorologists are working to improve the accuracy of weather forecasts is by collecting more detailed data, with greater frequency. If they start out with incorrect, incomplete, or out-of-date data, it does not matter how good their computer model is—the results will be skewed. When more precise and current data are entered in a computer model, more accurate forecasts are produced.

One problem that forecasters are working to overcome is that in some parts of the world, such as sparsely populated lands and the oceans, observations are scant. An increase in the number of automated weather stations and weather satellites, anticipated to become operational over the next several years, will help remedy this shortfall.

The quality of observational instruments is also being improved. Older equipment is undergoing modernization and greater numbers of newer, high-tech instruments (particularly Doppler radar, wind profilers, and satellites) are being deployed.

Improving computer capabilities Along with improvements in data collection, the future will also see more effective computers. The National Weather Service's supercomputers will certainly be replaced with newer, faster, and more powerful models that are capable of processing an increased volume of data. They will be programmed with more complex and sophisticated models and will produce forecasts with greater range and accuracy.

Another important criterion in a computer's performance is resolution. Resolution refers to the number of squares that make up the computer's grid system. The entire area under study, such as the continental United States, is divided into squares. The computer produces one forecast for each square in the grid by averaging conditions at all points throughout that square.

The number of squares in a grid is inversely proportional to the size of each square. The greater the number of squares, the smaller each square is. Likewise, as the square size decreases, the resolution increases and the more precise the forecast becomes.

Consider a low-resolution grid in which each square is 100 miles (161 km) across. Conditions can vary greatly over this 100-square-mile (260-square-kilometer) area. For example, temperatures may differ by 15°F (8°C)or more. Thus, a forecast based on average conditions will not be relevant for many points within the square.

Meteorologists have a goal to increase resolution so that each square within a grid is as small as 4 square miles (10 square kilometers). In that way, the variation of conditions within a square will be much lower and forecasts will become more accurate for every point within the square.

Ensemble forecasting Meteorologists are currently experimenting with a new method of forecasting called ensemble forecasting. This method takes into account the predictability of the behavior of the atmosphere at the time a forecast is made. If the atmosphere shows signs of stability, the forecast is more likely to be correct than when atmospheric conditions are showing signs of rapid and erratic change.

The predictability of the atmosphere can be determined by running a series of computer simulations, starting with slightly different atmospheric variables each time. If the forecasts generated for ten days in advance in each simulation are similar to one another, then the atmosphere is in a predictable phase. However, if the forecasts start to differ from one another by day three, then the atmosphere is unpredictable.

The predictability of the atmosphere influences how accurate a forecast will be beyond a few days. Thus, using the ensemble method, a forecaster can determine the probability that his or her forecast will be correct. When the atmosphere is unpredictable, a forecaster may decide to limit a forecast to three days ahead. However, when the atmosphere is predictable, a ten-day forecast could be made with confidence.

[*See Also* **Climate; Clouds; Human Influences on Weather and Climate; Hurricane; Precipitation; Weather: An Introduction**]

For More Information

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Climate Change and Global Warming

Climate is the weather experienced by a given location, averaged over several decades. A region's climate tells how hot or cold, wet or dry, windy or still, and cloudy or sunny it generally is. Climate is determined not only by average weather conditions, but also by seasonal changes in those conditions and weather extremes. Thus, for example, a climate can be described as hot and wet year-round, frigid and dry year-round, or warm and rainy in the summer and cold and dry in the winter.

Climate has been an important factor in determining where groups of people choose to settle. While humans are resourceful enough to survive almost anywhere on the planet, most population centers are in areas where temperature and rainfall are adequate to sustain some form of agriculture. There are fewer settlements in regions of extreme dryness or cold, such as deserts or the arctic. Climate also influences how people live. It largely defines choices of architecture, clothes, food, occupation, and recreation.

The climates of the world are distinguished by several factors, including latitude (distance north or south of the equator), temperature (the degree of hotness or coldness of an environment), topography (the shape and height of land features), and distribution of land and sea.

Climate is not a fixed property. The global climate has changed continuously and dramatically over the 4.6 billion years since the Earth was formed. It continues to change today, and it will in the future. Understanding climate change and its causes will help us to anticipate future climates.

Elements of Climate

The two factors that are most significant in defining climate type are temperature and precipitation. These criteria, in turn, are influenced by a number of atmospheric, oceanographic, and topographic factors.

WORDS TO KNOW

air pollutant: any harmful substance that exists in the atmosphere at concentrations great enough to endanger the health of living organisms.

Cenozoic era: the historical period from sixty-five million years ago to the present.

deforestation: the removal of all or most of the trees from an area.

desert climate: the world's driest climate type, with less than 10 inches (25 centimeters) of rainfall annually.

desertification: the process by which semiarid lands turn to desert (also called land degradation). It is caused by prolonged drought, during which time the top layers of soil dry out and blow away.

drought: an extended period during which the amount of rain or snow that falls on an area is much lower than usual.

eccentricity: a measure of how much an orbit deviates from a circle. A circular orbit has zero eccentricity. An ellipse has eccentricity between zero and one.

ecosystem: a community of plants and animals, including humans, and their physical surroundings.

El Niño: means "the Christ child" in Spanish. A period of unusual warming of the Pacific Ocean waters off the coast of Peru and Ecuador. It usually starts around Christmas, which is how it got its name.

equinoxes: the days on which the Sun appears to cross Earth's equator in its yearly motion.

flood: the inundation of normally dry land with water.

food chain: the transfer of food energy from one organism to another. It begins with a plant species, which is eaten by an animal species; it continues with a second animal species, which eats the first, and so on.

fossil fuels: coal, oil, and natural gas—materials composed of the remains of plants or animals that covered Earth millions of years ago and are today burned for fuel.

global warming: the observed global increase in atmospheric temperature. Also called global climate change.

Temperature Climate is affected by annual mean (average) temperature and annual temperature range. High mountain deserts such as in central Asia and the high mountain plateaus of South America may experience extreme temperature variation, with daytime temperatures exceeding 100°F (38°C) and nighttime temperatures plunging below freezing. At the opposite extreme, regions in the tropics may have little daily or yearly variation in temperature.

The annual temperature range is found by subtracting the year's lowest average monthly temperature from the year's highest average

WORDS TO KNOW

greenhouse effect: the warming of Earth due to the presence of greenhouse gases, which trap upwardly radiating heat and return it to Earth's surface.

greenhouse gases: gases that trap heat in the atmosphere. The most abundant greenhouse gases are water vapor and carbon dioxide. Others include methane, nitrous oxide, and chlorofluorocarbons.

heat wave: an extended period of high heat and humidity.

Holocene: the most recent part of the Cenozoic era, from ten thousand years ago to the present.

ice age: a period during which significant portions of Earth's surface are covered with ice.

interglacial period: a relatively warm period that exists between two ice ages.

Maunder minimum: a period of time from 1645 to 1715, during which sunspot activity was almost nonexistent.

Mesozoic era: the historical period from 225 million years ago to 65 million years ago, best known as the age of the dinosaurs.

Milankovitch theory: the theory stating that the three types of variation in Earth's orbit, taken together, can be linked with warm and cold periods throughout history. These variations include: the shape of Earth's orbit, the direction of tilt of its axis, and the degree of tilt of its axis.

obliquity: the angle of the tilt of Earth's axis in relation to the plane of its orbit.

ocean current: the major routes through which ocean water is circulated around the globe.

paleoclimatologist: a scientist who studies climates of the past.

Paleozoic era: the historical period from 570 million years ago to 225 million years ago.

precession of the equinoxes: the reversal of the seasons every thirteen thousand years. This occurs because Earth spins about its axis like a top in slow motion and wobbles its way through one complete revolution every twenty-six thousand years.

season: a period of the year characterized by certain weather conditions, such as temperature and precipitation, as well as the number of hours of sunlight each day.

monthly temperature. The annual temperature range reveals whether or not a location experiences different seasons, which is just as important as the annual average temperature in identifying climate type.

Average annual sea-level temperatures plotted on a map roughly correspond to latitude. That is, temperatures are highest at the equator, decline with increasing latitudes, and are lowest at the poles. This is due to the uneven heating of Earth by the Sun due to the varying angle of the Sun's rays.

An imaginary line connecting locations with the same temperature is called an "isotherm." Because water takes longer to heat up and retains

Comet Ikeya-Zhang, 2002. AP IMAGES.

heat longer than does land, isotherms veer where landmasses meet the sea. Ocean currents, which are the major routes that carry warm water toward the poles and cold water toward the equator, also cause the bending of isotherms along the coasts.

Precipitation In addition to temperature, precipitation (water in any form falling out of the air) is the other factor determining climate. Both the total precipitation and the distribution of precipitation throughout the year have an impact. For example, a city that receives all of its precipitation during a few torrential rainfalls during the hottest summer months might have an arid climate, while a city that receives the same amount of precipitation distributed evenly through the year might have a climate able to support trees and grasses.

Wet and dry regions are scattered across the globe. However, there are some general trends corresponding to global air circulation patterns. Around the equator, where the trade winds (dominant surface winds that blow from east to west) converge and air rises, precipitation is relatively high. Precipitation is also high around 60° latitude, in the middle latitudes, where the warm westerly air currents rise as they meet the cold polar easterlies.

In the subtropical regions, around 30° latitude, conditions are much drier. It is there that most of the world's deserts exist. The polar regions are also characterized by dryness. However, these latitudes are not fixed. As Earth makes its yearly revolution around the Sun the amount of sunlight received at each latitude changes, causing northward and southward shifts in "wet" and "dry" latitudes.

History of Climate Change

Throughout Earth's 4.6-billion-year existence, the global climate has changed continuously. Most of what scientists know of the history of climate change is based on the most recent 10 percent of Earth's history—the last 500 million years or so. There are fewer clues about the climate in the more distant past. However, by using the clues that do exist plus drawing conclusions from more recent data, scientists have been able to construct a climatic picture spanning the entire existence of Earth.

There have been times when Earth has been alternately warmer or colder than it is today. There have also been several periods during which significant portions of the planet's surface have been covered with ice. These are popularly known as ice ages. Each ice age has brought about the extinction of numerous species of plants and animals as well as dramatic shifts in the distribution of plant and animal species, which means that the process by which plants and animals have evolved has not been a smooth one. Rather, it has been halted many times and begun anew with each new warm period.

Comets

Another theory of the origin of Earth's atmosphere suggests that the atmospheric gases were deposited at least in part by comets colliding with Earth. Debris from comets is known to have carbon dioxide and nitrogen in roughly the same proportion as found in the early atmosphere. There are numerous impact craters on Earth from past collisions with asteroids, comets, and other objects from space. The role of comets in the formation of Earth's early atmosphere and life remains an area of vigorous scientific debate.

The geologic history of Earth is conventionally divided into six main eras: Hadean, Archaean, Proterozoic, Paleozoic, Mesozoic, and Cenozoic.

Precambrian era (Hadean, Archaean, Proterozoic) The Precambrian period begins with the formation of Earth around 4.6 billion years ago, along with the rest of our solar system, and ends 570 million years ago. Earth began its existence as a ball of molten liquid rock. Within about 900 million years, its surface cooled and solidified. Earth's atmosphere was first produced from gases of volcanoes and possibly with additional gases from comets, which are chunks of rock and ice that orbit the Sun. These gases included nitrogen compounds, water vapor, carbon dioxide, sulfur dioxide, and argon.

At first, the atmosphere contained a lot of water vapor. The water vapor condensed into rain, which fell to the surface forming vast oceans. The rain washed most of the carbon dioxide and sulfur dioxide out of the atmosphere. The carbon dioxide and sulfur dioxide eventually formed into limestone rocks. This left primitive Earth with an atmosphere composed of nitrogen, argon, water vapor, and a small amount of carbon dioxide. The small amount of carbon dioxide and other gases produced a modest greenhouse effect, which is the warming of Earth due to the presence of gases that trap heat, making the planet capable of supporting life. However, there was no free oxygen in Earth's early atmosphere. Since there was no free oxygen, there was also no ozone in Earth's upper atmosphere.

Soon after the formation of the early atmosphere, the first forms of life appeared. Geologists mark this as the beginning of the Archaean era. Since there was no free oxygen in Earth's atmosphere at this time, the organisms were probably some form of anaerobic bacteria known as Archaeans. (Anaerobic means capable of living without oxygen.) Archaeans of today are known to thrive in extremely harsh conditions—they were first discovered in the hot springs of Yellowstone National Park—so they were likely to be capable of thriving in the high temperatures and methane-rich environment of early Earth.

About 3.5 billion years ago, the first photosynthesizing organisms appeared. Photosynthesis is the process in which an organism combines water and carbon dioxide to form a simple sugar, driven by the heat of the Sun. Oxygen is given off as a byproduct.

Over time, oxygen accumulated in the atmosphere. By 2 billion years ago, it accounted for 1 percent of its present concentration; by 700 million years ago, it accounted for 10 percent; and by 350 million years ago, the concentration of oxygen in the atmosphere reached its present value of 21 percent. Oxygen molecules (O_2) then combined with free oxygen atoms, which were formed when oxygen molecules broken apart by sunlight, to form ozone (O_3). The ozone formed a separate atmospheric layer, 25 to 40 miles above ground, that filters out the harmful ultraviolet rays. Together with the protection provided by the ozone layer, the oxygen in the atmosphere encouraged the burst of biological diversity that marked the end of the Precambrian era.

Paleozoic era The Paleozoic era, lasting from 570 to 225 million years ago, began with a dramatic increase in the number of marine animal species. The Paleozoic era saw dramatic temperature changes. Much of the time it was significantly warmer than the Precambrian era, but there were two glacial periods. The first was relatively short and began around 430 million years ago. At the end of this cold period, around 400 million years ago, plants began to take hold on land.

The first land plants were little more than rigid stems. They reproduced by releasing spores, the same reproduction mechanism used today by ferns and mushrooms. Within fifty million years, however, plants had begun producing seeds, which are capable of being dispersed over far greater distances than spores.

The spread of plants across the land had a significant impact on climate. Primarily, it reduced the albedo (reflectivity) of Earth's surface by 10 to 15 percent. As a result, more sunlight was absorbed, which raised the planet's surface temperature. The second cold period occurred during the last portion of the Paleozoic era, from 330 to 225 million years ago.

Around 250 million years ago, Earth's two supercontinents, called Laurussia (containing Greenland, North America, Scandinavia, and most of Russia) and Gondwana (containing most of the rest of the landmass), joined together. The newly formed supercontinent, Pangaea, extended from the North Pole almost all the way to the South Pole.

Mesozoic era The Mesozoic era, which is often known as the age of the dinosaurs, lasted from 225 to 65 million years ago. In the latter half of this era, Pangaea split into two continents, Laurasia and Gondwana. Laurasia included North America, Europe, and Asia. Gondwana included most of the southern continents. About 100 million years ago, these land masses further subdivided, roughly into the present continents. However, the landmasses were still situated very close together.

Throughout the Mesozoic era, temperatures everywhere on Earth were, on average, 11 to 18°F (6 to 10°C) warmer than they are today. They were also relatively uniform across the planet. This was most likely due to the efficient distribution of heat from the equator to the poles by ocean currents and global winds. Land masses, even by the end of the Mesozoic era, were not as widely dispersed across the globe as they are today. Thus, ocean currents (the major routes through which ocean water is circulated around the globe) and winds had a relatively clear path between the equator and poles.

The Mesozoic era experienced a number of temperature swings, culminating in a sudden, brief ice age. This coincided with the extinction of about 70 percent of Earth's life forms, including dinosaurs. One theory is that the ice age was brought about by the collision of an asteroid with Earth that created a dust cloud that blocked out the Sun's rays.

Cenozoic era The Cenozoic era began sixty-five million years ago and continues to the present. Throughout this era, the continents have continued to drift apart, moving to their present configuration. The process of supercontinent formation and breakup will likely repeat several

The Muir Glacier at Glacier Bay National Park in Alaska is retreating. ©TOM BEAN/ CORBIS.

more times as the continental plates continue to move. This era is also characterized by the emergence of mammals, including humans, as the dominant animal group.

The early part of the Cenozoic era was warmer than it is today, and there were no polar ice caps. Beginning around fifty-five million years ago, a long cooling trend began. This cooling occurred both gradually over time, and through a series of extremely cold periods. One of these cold spells took place about fifty million years ago, and another about thirty-eight million years ago. The most recent was about fifteen million years ago, the results of which can still be seen in the polar ice caps and the glaciers nestled in protected areas of tall mountains.

Over the last 2.4 million years there have been two dozen ice ages (periods during which the global temperature plummeted). At seven different times over the last 1.6 million years, up to 32 percent of Earth's surface has been covered with ice. Scientists estimate that throughout the Cenozoic era, new ice ages have occurred about every one hundred thousand years and have been interspersed with warmer, interglacial periods, each lasting at least ten thousand years.

The most recent ice age peaked about twenty thousand years ago, when there were glaciers up to 10,000 feet (3,000 meters) thick over most of North America, northern Europe, and northern Asia, as well as the southern portions of South America, Australia, and Africa. The sea level fell, exposing large areas of land that are currently submerged, such as the Bering land bridge, which connected the eastern tip of Siberia with the western tip of Alaska.

This era was followed by a warm period, beginning around fourteen thousand years ago. By eight thousand years ago, most of the ice had melted, and between seven and five thousand years ago, the world was about 5°F (3°C) warmer than it is today. The sea level rose and the current shape of continents emerged.

Holocene epoch The most recent division of the Cenozoic is called the Holocene epoch. It began approximately ten thousand years ago and continues to today. Extensive climatic data exist for this time period. The history of modern civilization begins during this postglacial period, about six thousand years ago.

About five thousand years ago, when Earth was slightly warmer and wetter than it is today, agriculture was developed, and the earliest cities were established in Egypt and Mesopotamia, which is part of modern Iraq. There was a relatively cool period that began around 900 BCE and lasted until about 500 BCE, which resulted in crop failures. There are also indications that, beginning around 800 CE, there was a prolonged drought, or period of extreme dryness, which may have contributed to the decline of the great Mayan civilizations in Mexico and Central America.

In the Middle Ages (500 to 1500 CE), the global climate was similar to today. During that time, the civilizations of Europe flourished and the Vikings colonized Iceland and Greenland. However, the end of the thirteenth century saw the beginning of a cold spell. Summer after summer was cold and wet, which caused famine throughout Europe.

Conditions were more moderate during the fifteenth century and then became colder again between about 1500 and 1850, a period referred to as the "Little Ice Age." Rather than being continuously cold, the Little Ice Age consisted of a series of cold spells, each up to thirty years long, separated by warmer years. For the most part, this period was characterized by bitterly cold winters and cold, wet summers. The canals of Holland, as well as the Baltic Sea and the River Thames in England, were often covered with layers of ice several inches thick. Food became scarce throughout Europe, the mountain glaciers grew, and the colonists in Greenland and Iceland perished.

After the Little Ice Age, temperatures warmed. In the years since 1850, however, significant fluctuations have occurred in global temperatures. About a dozen cool periods have alternated with warmer periods. From 1900 to the present, there has been a 1°F (0.5°C) increase in global temperature. Scientists now think that this increase is not merely a natural part of Earth's continually changing climate, but rather constitutes part of a trend of human-influenced global warming, or temperature increase.

There are various ways of looking at the Holocene epoch. Some consider it a "warm period," since ice exists only at the polar regions, covering 10 percent of the planet. Others believe the world is still in the

This Dutch painting from the 1700s illustrates how during the "Little Ice Age" rivers in Europe that were usually ice-free froze over. THE ART ARCHIVE / GALLERIA SABAUDA TURIN / DAGLI ORTI (A).

final stages of the most recent ice age. What many scientists do agree on, however, is that another ice age is in store for the future.

Reasons for Climate Change

In an attempt to find some order in the series of climatic shifts that describes the history of Earth, scientists have sought to define a pattern of warm-cool cycles that repeat after a given period of time. However, they have been largely unsuccessful. The proposed cycles either do not apply to all times in the past or do not hold true for all parts of the world.

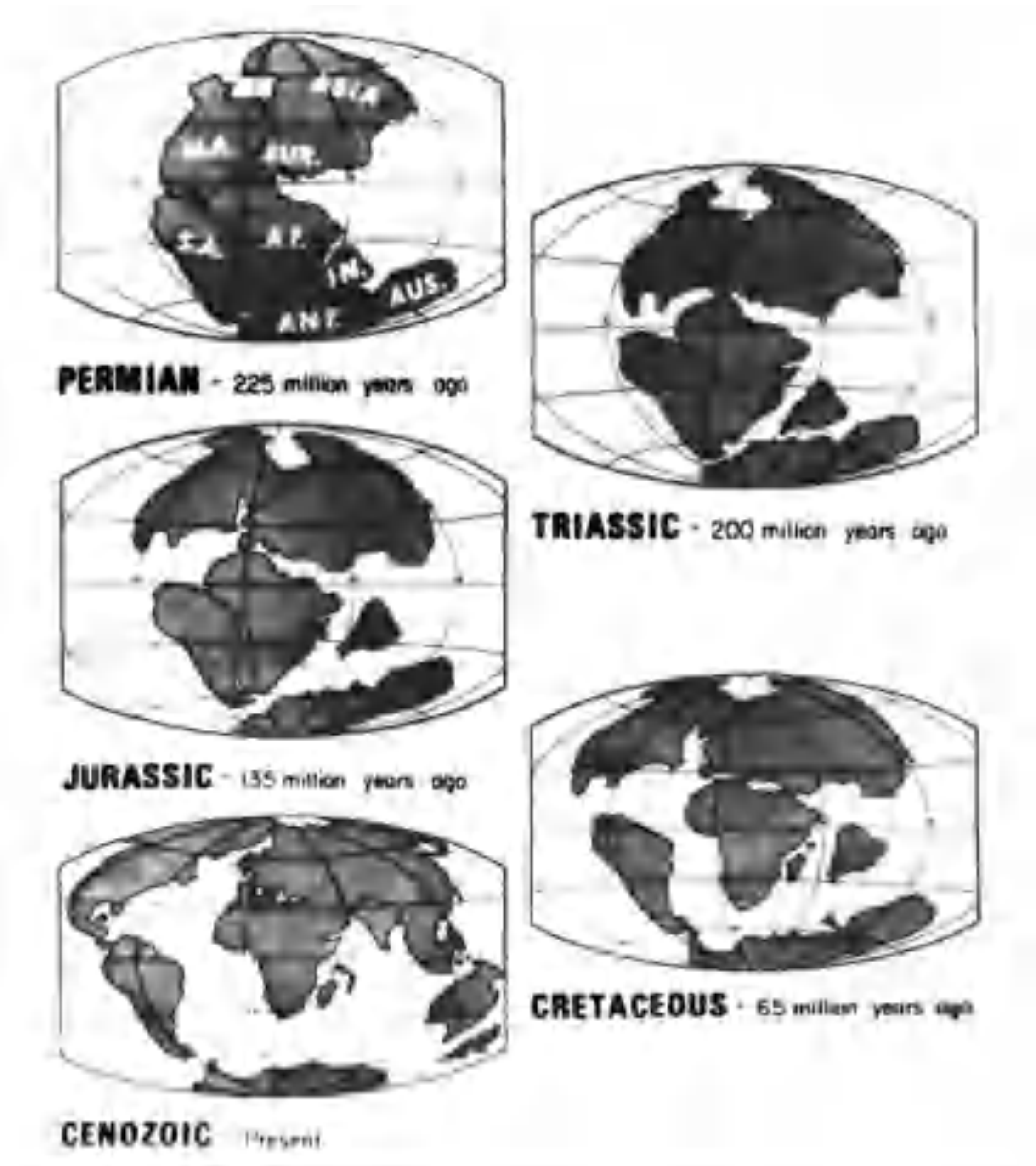
One problem in determining patterns of climatic change is that many factors are involved. Some of those factors affect Earth's climate for millennia while others affect it only for decades. In addition, some factors, such as Earth's shifting orbit around the Sun, are predictable and regular, while others, such as collisions with large objects in space, are not.

Human activity constitutes a whole category of factors affecting climate change in the very recent past, present, and future. Among the possible agents of climate change are deforestation, which is the removal of trees; the burning of fossil fuels, such as coal, oil, and natural gas; acid precipitation, which is rain and snow that are made more acidic when carbon, sulfur, and nitrogen oxides in the air dissolve in the water; and smog, a layer of hazy, brown air pollution at Earth's surface caused by industrial emissions. Though the impact of human activity on climate change has be the subject of much debate in recent years, a February 2007 report by the United Nations' Intergovernmental Panel on Climate Change made one of the strongest arguments yet that recent sharp rises in global temperature, also known as global warming, are a direct result of human actions. The Intergovernmental Panel on Climate Change was established in 1988 to study the global climate. Its 2007 report stated that "most of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic (human-generated) greenhouse gas concentrations."

There are a handful of forces that have affected Earth's climate throughout its history: continental drift, shifts in Earth's orbit, volcanoes, asteroids and comets, and solar variability. Another phenomena that is currently being studied as a possible factor in long-term climate change is El Niño /Southern Oscillation (ENSO).

Continental drift The theory of continental drift was first suggested by German meteorologist Alfred Wegener (1880–1930) in 1915. That theory states that 200 to 250 million years ago, all land on Earth was

Growth of traffic congestion and the popularity of automobile transportation in developing nations such as China, the world's second-largest vehicle market, may hinder efforts to reduce greenhouse gas emissions. ©CLARO CORTES IV/ CORBIS.



Global maps showing continental drift. AP IMAGES.

joined together in one supercontinent that Wegener named Pangaea. Then, over the years, the supercontinent broke up and the pieces drifted to where they are today. Although there was substantial evidence supporting the theory of continental drift, Wegener could not suggest a mechanism causing the breakup and drift of the continents. The theory was not considered for decades. Then, in the late 1950s and early 1960s, a new theory incorporating the ideas of continental drift was developed. This new theory, plate tectonics, explained the motion of the plates as being due to convection currents (the transfer of heat by the mass movement of heated particles into an area of cooler fluid) in Earth's upper mantle, the layer beneath the crust, which is the planet's thin outer-most layer.

Evidence of continental drift can be found in the fossils of dinosaurs and other mammals that migrated across once-connected land masses, and in the fossilized remains of tropical plants beneath polar ice sheets. Another piece of evidence that land masses were once connected is that shapes of the continents fit together like pieces of a jigsaw puzzle. The Atlantic coastlines of Africa and South America are the most striking examples of this phenomenon. In addition, satellites today are able to record the subtle, extremely slow movements of the continents.

Continental drift is believed to affect both the climates of individual continents and the climate of the entire planet. The climates of the individual continents have been altered by their gradual, but radical, change in position around Earth. For instance, parts of Europe and Asia that once sat on the equator are now at high latitudes in the Northern Hemisphere. India moved to its current low-latitude Northern Hemisphere position from deep in the Southern Hemisphere. Glaciers once covered parts of Africa, and Antarctica gradually slid from warmer latitudes to the South Pole.

On a global level, the position of land masses affects how the heat from the Sun is distributed around Earth. When the continents were joined together, ocean currents and global winds produced a different pattern of global heat distribution than they do at present. Global climatic conditions 200 to 250 million years ago were more uniform than they are today. As the continents separated and moved out around the globe, greater extremes in climatic conditions began to appear around the world.

Another consequence of continental drift has been the formation of mountain ranges. When land masses come together, the land is forced upward. Examples of mountain ranges formed in this way are the Rocky Mountains, the Andes, the Himalayas, and the Kunlun and Qilan

A cape of clouds forms as warm, moist air rises up the windward slope of a mountain in New Zealand. ©JASON HOSKING/ZEFA/CORBIS.

mountain ranges bordering the Tibetan Plateau. Mountain ranges affect temperatures, winds, and rainfall over limited areas. Very tall ranges, particularly those with north-south configurations, can influence air circulation patterns over very large areas.

The Tibetan Plateau is a prime example of this phenomenon. Called "the roof of the world," it was formed fifty million years ago by the collision of the Indian and Asian continents and is one of the world's tallest and widest plateaus. It affects wind patterns across the entire Northern Hemisphere. Fossil records show that almost immediately following the formation of the Tibetan Plateau, the climate of the Northern Hemisphere cooled and large glaciers formed. The presence of glaciers led to further cooling. Snow accumulates on the ice, which reflects sunlight rather than absorbing it.

Another aspect of continental drift that affects global climate is the distribution of land masses at various latitudes. For instance, as land moved away from the tropics and toward the poles, tropical oceans replaced the land. These bodies of water absorbed huge amounts of incoming heat, which led to global cooling. Also, the movement of continents into polar regions provided a surface on which ice layers could accumulate.

Earth's orbit In the 1930s, the Yugoslavian astronomer Milutin Milankovitch (1879–1958) proposed another theory to explain changes in

Earth's climate. He listed three factors that could affect the planet's climate: the shape of Earth's orbit and the angle and direction of Earth's axis.

The shape of Earth's orbit around the Sun changes over long periods of time. At times, the orbit is almost circular. At other times, it has a more elliptical shape. The eccentricity of Earth's orbit changes in a regular cycle—from circular to elliptical to circular again—that takes about one hundred thousand years.

When the orbit is circular, there is less variation in the levels of solar energy received by Earth throughout the year than when it is elliptical. At present, the orbit is in a stage of low eccentricity, meaning that it is nearly circular. Earth receives only 7 percent more solar energy in January, when Earth is closest to the Sun, than July, when it is farthest from the Sun. In contrast, when the orbit is highly eccentric, the solar energy received at points closest to and farthest from the Sun differ by up to 20 percent. In addition, a more elliptical orbit means the relative lengths of the seasons are different. Springs and falls are shorter, while a particular hemisphere might have a long summer and short winter, or vice versa.

The second orbital factor that affects climate is the wobble in Earth's axis of rotation. This effect is what causes the Northern and Southern Hemispheres to receive different amounts of sunlight throughout the year.

Earth spins like a top in slow motion, so that its axis follows a cone-shaped path. It wobbles its way through one complete revolution every twenty-six thousand years, a phenomenon called the precession of the equinoxes. Equinoxes are the days on which the Sun appears to cross Earth's equator in its yearly motion, and "precession" refers to the motion of Earth's axis of rotation. The precession of the equinoxes means that every thirteen thousand years the seasons gradually reverse. Eventually, unless the calendars are adjusted to compensate, the Northern Hemisphere will experience winter in July and the Southern Hemisphere, in January. Precession also influences Earth's distance from the Sun at different seasons. When it is winter in the Northern Hemisphere in July, Earth will also be at its closest point to the Sun in that month.

The third variable affecting Earth's climate is the angle of the tilt of Earth's axis compared to the plane of its orbit. This angle is called obliquity. Over the course of forty-one thousand years, this angle fluctuates between 21.5 degrees and 24.5 degrees. It is currently 23.5 degrees. When the angle is smaller, sunlight strikes various points on Earth more evenly and the seasonal differences are smaller, bringing milder winters and cooler summers. Yet when the angle is larger, there is a greater variation in the level of solar radiation received across Earth and seasons are more pronounced.

The smaller angle of tilt tends to favor the formation of glaciers in polar regions. The reason for this effect is that when winters are warmer, the air holds more water and snowfall is heavier. That snow then has a greater probability of remaining on the ground during the cool summer.

Evidence has been found in deep ocean sediments that strongly support Milankovitch's theory. By analyzing the chemical composition of these sediments, scientists have deduced that glaciers have advanced and retreated in roughly one-hundred-thousand-year cycles over the last eight hundred thousand years. Within those cycles, glacier formation occurs in secondary cycles, reaching peaks every twenty-six thousand and forty-one thousand years. These time intervals correspond to the cycles of the three types of orbital variation described here. However, there are many difficulties in correlating climatic change to the Milankovitch cycles, which remains an active field of scientific inquiry.

Volcanoes In the early stages of Earth's history, thousands of volcanoes dotted the surface. These volcanoes underwent frequent, large eruptions, which had a significant impact on the climate. In addition to releasing gases that rose up and formed Earth's atmosphere, these eruptions sometimes spewed out ash and dust so thick that they nearly blocked out the Sun. Volcanic eruptions have probably been the catalysts for some periods of glaciation.

While volcanic eruptions still occur today, they are far less frequent and intense than they once were. A very large volcanic eruption today affects global climate only for a few years. For example, in 1815 the Indonesian volcano Mount Tambora erupted. Dust from the eruption was carried around the world by upper-air winds. In conjunction with smaller eruptions of other volcanoes over the preceding four years, the Tambora event led to a decrease in global temperature. A severe cold spell in 1816 earned that year the nickname "the year without a summer."

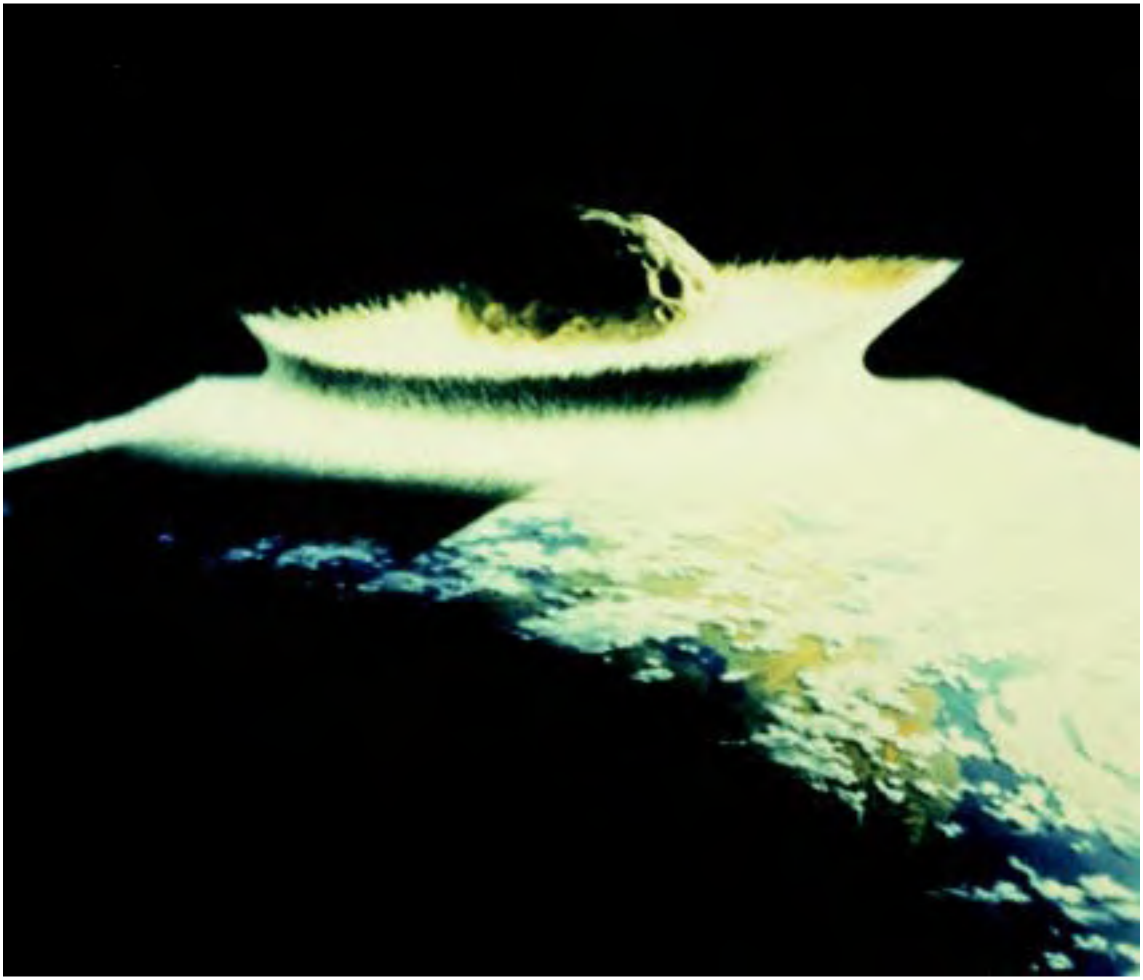
The eruptions with the gravest climatic consequences are those rich in sulfur gases. Even after the ash and dust clears from the atmosphere, sulfur oxides continue to react with water vapor to produce sulfuric acid particles. These particles collect and form a heavy layer of haze. This layer can persist in the upper atmosphere for years, reflecting away a portion of the incoming solar radiation. The result is a global decrease in temperature.

Mount St. Helens in Washington erupts in March, 2005. AP IMAGES.

Asteroids Throughout Earth's history, there have been at least five abrupt, dramatic changes in global climate, occurring 500 million years ago, 430 million years ago, 225 million years ago, 190 million years ago, and 65 million years ago. One possible explanation for these changes is that a large body from space, such as an asteroid or a comet, crashed into Earth. Many scientists think that the extinction of the dinosaurs, which occurred around 65 million years ago, was caused by a collision with an asteroid.

The impact of an asteroid at least 6 miles (10 kilometers) across, traveling at a speed of at least 12 miles (20 kilometers) per second, would produce a crater about 95 miles (150 kilometers) in diameter. It would release energy equivalent to that of four billion atomic bombs such as those dropped on Hiroshima, Japan, during World War II, heating the atmosphere near the impact to temperatures of 3,600 to 5,400°F (about 2,000 to 3,000°C). Another result of this energy release would be the production of huge concentrations of nitric and nitrous acids. These acids would react with and destroy the ozone layer. They would fall to the ground as highly acidic rain, destroying plants and animals.

If the asteroid were to fall on land, a thick dust cloud would rise and could block out all sunlight for several months. Following an early wave of wildfires caused by the high temperatures, any surviving plants and animals would die during a long, dark winter.



An artist's creation of an asteroid crashing into Earth. An impact of a large asteroid or comet could cause catastrophic climate changes. ©PREMIUM STOCK/CORBIS.

It is more likely that an object from space would fall into the ocean, since oceans cover almost three-quarters of Earth's surface. In this case, the impact would stir up carbonate-rich sediments and produce vast quantities of carbon dioxide. Increase of carbon dioxide in the air traps reradiated infrared radiation from Earth's surface, leading to an increased greenhouse effect.

The possibility of such an asteroid impact happening within our lifetimes is remote. However, it has become more of a concern following the July 1994 crash of fragments of Comet Shoemaker-Levy into Jupiter.

These collisions, which occurred over several days, caused disturbances on an Earth-sized area of the giant gaseous planet's atmosphere. Had the same impact occurred on Earth, the results would probably have been disastrous.

Solar variability It has long been understood that the amount of energy emitted by the Sun varies slightly over the years. In recent years, scientists have made correlations between changes in cycles of solar output and particular weather patterns. While there have been several theories linking solar variation to long-term climate change, many more years of data collection will be necessary before such links can be proven. However, the evidence collected thus far presents a compelling case for the link between solar variability and climate change—at least climate change on the scale of decades.

Astronomer Keith Pierce measures sunspots at the McMath-Pierce Solar Telescope in Arizona, 1990. ©ROGER RESSMEYER/ CORBIS.

The variation in solar output is primarily based on cycles of sunspot activity. Sunspots are dark areas of magnetic disturbance on the Sun's surface. When the number and size of sunspots is at a maximum, which occurs roughly every eleven years, the Sun's energy output is highest. This heightened solar output is due to an increase in bright areas, called faculae, which form around the sunspots.

Measurements taken by special instruments called radiometers on board satellites have shown that 0.1 percent, and possibly up to 0.4 percent, more solar energy reaches Earth during a sunspot maximum than during a sunspot minimum. The length of sunspot cycles varies over time, from seven to seventeen years. There is a growing body of evidence supporting a link between the length of sunspot cycles and temperature patterns around the world. It has been shown that over the last century, global temperatures, in general, are higher during shorter sunspot cycles than during longer sunspot cycles. In addition, a reduction in the amount of sea ice around Iceland, another sign of warming, has been noted during shorter sunspot cycles.

Another piece of evidence linking sunspots and global temperatures is that the period of lowest sunspot activity in several centuries coincided with the coolest period in several centuries. Between 1645 and 1715, the stretch of years known as the Maunder minimum (named for the British solar astronomer E. W. Maunder who discovered it in the late 1880s), sunspot activity was at a very low level. It is even possible there were no sunspots at all during this period. The period also coincides with the coldest part of the Little Ice Age.

Ways to Measure Climate Change

A paleoclimatologist, a scientist who studies climates of the past, uses many methods. The first step in learning about climates of the past is to discover objects that were formed long ago and to determine an accurate date for those objects. Then the problem is to extract information from the objects that describe the climate at that time.

There are many types of materials, both on Earth's surface and embedded far underground, that have been preserved over thousands and millions of years that provide clues about Earth's past. Paleoclimatologists use these materials in a variety of ways.

Rocks and rock formations The oldest exposed rocks on Earth are found in northwestern Canada near Great Slave Lake. They are about 4.0 billion years old. These rocks are the only objects that still exist from the earliest period in Earth's history, the Precambrian era. Thus, scientists must rely entirely on rocks to learn about the climate of that time.

To determine the age of rocks, paleoclimatologists use a technique called radiometric dating, which was developed in the late 1800s. This can be used for rocks that contain radioactive elements, such as uranium, radium, and potassium. Radioactive nuclei exist in an unstable configuration and emit high-energy particles (alpha particles or positrons) over time, to achieve greater stability. When the parent nuclei shed alpha particles, or "decay," they transform into daughter nuclei (in the case of a uranium parent, the daughter is lead).

The age of a sample is determined by comparing the percentage of parent nuclei to daughter nuclei. Since scientists know the rate at which radioactive elements decay, they can determine how long ago the sample was entirely made of parent atoms; in other words, when the sample was formed.

Once scientists have established the age of a sample, they can study it for clues about the climate at that time. First, the shape of a rock tells them about the medium in which it once existed. For example, rocks with rounded surfaces probably once existed in a body of water, and rocks with eroded (worn-away) surfaces were probably once covered by glaciers.

To take this a step further, if rounded rocks from the same time period are found all over Earth, it can be assumed that the average temperature at that time was above freezing. The presence of surface water also indicates the existence of some form of atmosphere, without which water would quickly evaporate. By the same token, if eroded rocks of the same age are found at far-flung locations, this signals that an ice age was in progress.

Evidence of primitive organisms begins showing up in rocks dated about 4.0 billion years ago. Studying fossils provides information not only about the progression of life forms at different time periods, but also about the climate. For instance, rocks formed during cooler times, such as ice ages, have little or no fossils embedded within them. In contrast, rocks that were formed during warmer times contain fossils in far greater numbers.

A particularly valuable source of evidence of climate change is rock formations made from layers of particles, deposited incrementally and hardened over time. An analysis of samples of each layer of a rock formation provides information about Earth's climate at that time. Of particular interest are the fossils within each layer, which make up a timeline of the emergence of various species.

The presence of marine animals in a given layer indicates that the region was once covered with water. By studying the chemical composition of fossilized shells, which are primarily composed of calcium carbonate, it is even possible to determine the relative warmth of the water. Oxygen in calcium carbonate exists in two forms: oxygen-16, which is by far the most plentiful, and oxygen-18 (the number refers to how many neutrons the atom possesses). It has been found that during periods of glaciation, the concentration of oxygen-18 increases in the oceans. Thus, the ratio of oxygen-18 to oxygen-16 in fossilized shells can be used to estimate water temperature.

Ice cores Ice cores drilled into the 2-mile-thick (3-km-thick) polar ice caps provide unique insights into climates of the past. The ice has been accumulating in layers, one year at a time, for thousands of years. Though individual layers of ice can be counted for the last 50,000 years in Greenland, patterns can be discerned from this ice that yield information as far back as 250,000 years. In Antarctica precipitation is so meager that annual layers of ice cannot be distinguished from one

A round sample of an ice core taken from the Greenland ice sheet, shown under polarized light. ©ROGER RESSMEYER/ CORBIS.

another. However, information contained in the thick layer describes conditions from as far back as 500,000 years ago.

The layers of ice contain many types of climatic evidence, all perfectly preserved. For instance, the thickness of a layer tells how much precipitation fell during a given year. That, in turn, yields information about temperature, since greater levels of precipitation fall during warmer times.

Chemicals detected within the ice are also clues as to the air temperature at the time the precipitation fell. The approximate temperature during a particular period can be determined by comparing ratios of oxygen-16 and oxygen-18 present in a given medium.

By determining the nature of the dust contained within ice cores from the North Pole, it is possible to determine the origin of that dust. That, in turn, provides information about the wind patterns at that time. This type of evidence is not useful in South Pole ice cores, since Antarctica is surrounded by oceans, and is a great distance from all other land masses.

In addition, air bubbles in ice can be analyzed for the composition of the atmosphere. In addition, the timing of volcanic eruptions can be guessed at based on the presence of high levels of acidity in the ice. When volcanoes erupt, they emit dust and gases that are highly acidic.

Ocean and lake sediments The sediments collected from the bottoms of oceans and lakes contain information about the global climate dating back millions of years. The sediment accumulates in layers, much the same as rock formations and ice. The age of sediment layers is determined using chemical analysis.

The fossils of tiny marine organisms that have evolved and become extinct over time are embedded within the layers of sediment. Each species was adapted only to a narrow range of water temperatures. Therefore, the presence of a species in a given layer of sediment reveals the ocean temperature at that time.

Pollen has also settled in layers on ocean and lake floors. Pollen provides clues to past conditions because every plant species requires a particular set of conditions for survival. The first step in pollen analysis is to identify the pollen species. The next step is to determine its age by finding the age of the surrounding sediment. Studying the times in which particular plant species inhabited a given location teaches scientists about that location's climatic history.

For example, a study of a bog in northern Minnesota identified pollen of fourteen plant types dating back eleven thousand years. In the oldest layer, the greatest pollen concentration was spruce. Since spruce trees inhabit cold climates, it could be inferred that at that time conditions were cold. The next layer yielded primarily pine pollen. Since pine trees grow in warmer regions than do spruce, conditions must have been warmer then. In the next layer, dated eighty-five hundred years ago, oak pollen was widespread. Oak grows in drier conditions than does either spruce or pine, which means that conditions must have been drier at that time. By examining the pollen within each layer, it was possible to construct a climatological history of the bog.

Tree rings Dendrochronology, the study of the annual growth of rings of trees, is another important component of paleoclimatology. Trees are the oldest living entities on Earth. Some bristlecone pines that are still alive today are more than 4,700 years old.

A core sample of sediment taken from Chesapeake Bay, 1979. ©LOWELL GEORGIA/ CORBIS.

A cross-section of a cedar tree stump shows growth rings. FIELD MARK PUBLICATIONS.

As trees grow, they add new cells to the center of their trunk each year. These cells force the previous years' growth outward, forming concentric rings with the oldest ring on the outer edge. A tree's woody material acts like a library of climatic data, creating a record for each year of its lifetime. This information can be found in living trees, dead (but not rotten) trees, and tree stumps.

Dendrochronologists measure the width of a given year's growth ring in order to assess the overall conditions of that year. In warm, wet years, trees grow more (and therefore have wider growth rings) than in cool, dry years. Therefore, the difference in the width of growth rings is an indicator of climate.

In order to separate the effect of temperature from that of precipitation, it is necessary to examine trees growing at the edge of their temperature or rainfall range. An example of this is the fir trees growing at the edge of the subpolar zone in Canada. Since temperatures are quite cold every year, an increase in growth from one year to the next would be due almost entirely to precipitation. To study temperature, consider the case of Joshua trees in the heart of a North American desert. There, rainfall is continuously very light, so variations in the width of tree rings would be caused by temperature changes.

Global warming

Global warming is the name given to the recently observed phenomenon of rising global temperatures believed to be caused by human, not natural, activities. A better name is "global climate change," because some places on Earth may actually experience lower temperatures during a period of global warming. According to many atmospheric and planetary scientists, the rapid rise in global temperatures is primarily due to the corresponding rapid increase of gases in Earth's atmosphere called "greenhouse gases." The most important greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, and methane. Nitrous oxide and chlorofluorocarbons are also greenhouse gases but they contribute an insignificant amount to the global greenhouse effect.

The rapid increase of carbon dioxide in the atmosphere during the nineteenth and twentieth centuries is thought to be the main reason for global warming. Although this remains an area of vigorous scientific debate, the February 2007 report "Climate Change 2007" issued by the United Nations Intergovernmental Panel on Climate Change, which incorporates the input of hundreds of scientists from around the world, offered strong evidence that human-generated pollution is indeed the primary cause of global warming. Carbon dioxide is produced by burning fossil fuels, such as coal, fuel oil, gasoline, and natural gas, and is emitted into the air from homes, factories, and motor vehicles. During the last century, the amount of carbon dioxide in the atmosphere increased by 30 percent. During that same period, the planet has become, on average, slightly more than 1.0°F (0.5°C) warmer.

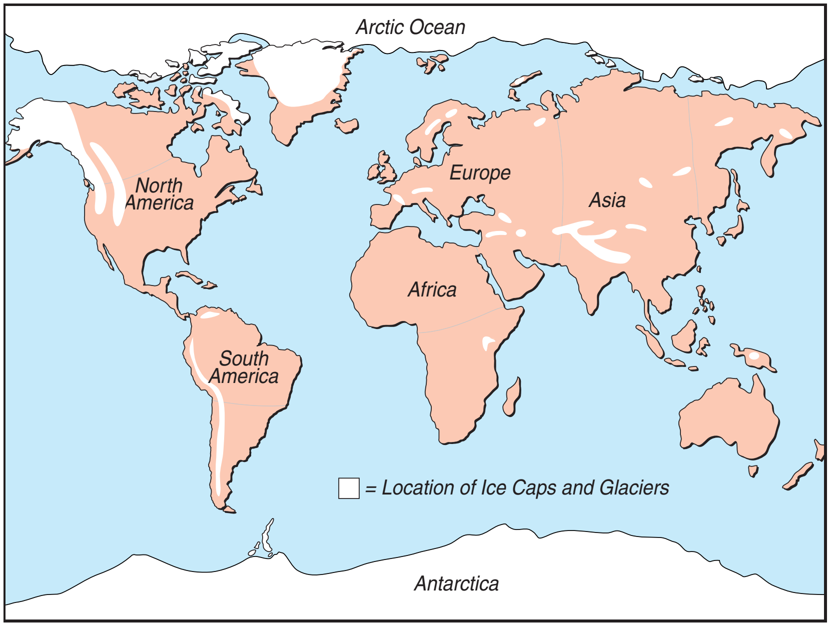
Watch this: *An Inconvenient Truth*

Former vice president Al Gore's 2006 film *An Inconvenient Truth* explores the political and environmental consequences of unchecked global warming, and calls on viewers to take immediate action to learn how they can help reverse destructive climate trends. The film won an Academy Award for best documentary feature.

Since 1880, when accurate temperatures were first recorded around the world, the years 1998 and 2005 were on record as the world's warmest years, and every other year from 1995 to 2005 were among the warmest years on record. In fact, tree rings and sea coral growth indicate that the 1990s was the hottest decade in the last one thousand years and the twenty-first century looks to be even warmer. (Trees and sea corals grow outward from the center, depositing concentric rings every year; each ring yields information about rainfall and temperature for that year.)

In the November 6, 2000, issue of *U.S. News & World Report*, David Rind, a researcher with National Aeronautics and Space Administration's Goddard Institute for Space Studies, commented that warming in the twentieth century was "a magnitude of change that has not been seen for thousands of years." According to a February 2007 United Nations report, if present trends continue, we can expect an average global temperature increase, heat waves and droughts to become more persistent and severe, and tropical cyclones (hurricanes and typhoons) to become more intense and destructive. Some scientists studying global warming using sophisticated computer programs predict that Earth's climate will undergo as great a change in the next century as it has in the last ten thousand years.

Global warming is a significant concern because it has the potential to disrupt ecosystems—entire communities of plants and animals,—and contribute to the extinction of numerous species. Many scientists blame global warming for the increasing number of severe storms. It may also be



Map showing the location of ice caps and glaciers around the globe.

a contributing factor to global extremes of droughts and floods. Rising sea levels, another consequence of global warming, threaten to put island nations and coastal cities underwater.

Rising sea levels Because of global warming, ocean levels have increased 4 to 10 inches (10 to 25 centimeters) since 1900. The rate at which the sea level is rising is expected to increase in the coming century. Current projections have ocean levels climbing as much as 2.5 feet (0.8 meter) by the year 2100. Such an increase would put many coastal areas underwater.

The primary reason for rising water levels is that ocean water becomes less dense and expands as its temperature increases. Water from melting glaciers in Greenland, Alaska, and Antarctica, as well as in the Rockies, Urals, Alps, and Andes mountain ranges, also contributes to rising sea levels.

"The melting of glaciers is emerging as one of the least ambiguous signs of climate change," wrote science writer Fred Pearce in the March 31, 2000, *Independent* of London. "Amid arcane arguments about the meaning of yearly fluctuations in the weather, it is hard to argue with the wholesale melting of some of the largest glaciers in the world. Mankind, it seems, has hit the defrost button."

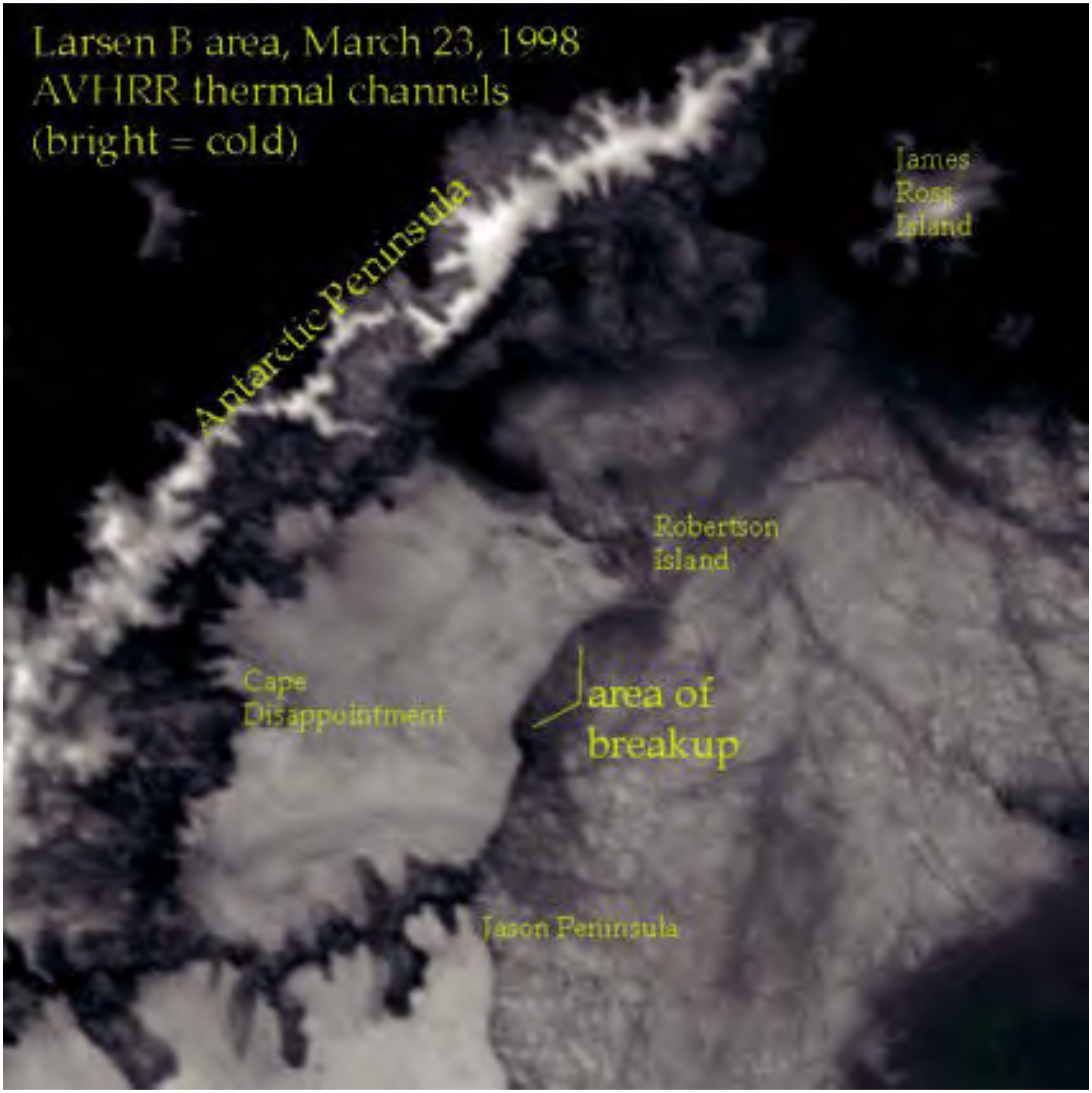
Melting in Antarctica The melting of the West Antarctic ice sheet, which is an enormous glacier in Antarctica, poses the greatest threat to coastal cities and island nations. At its thickest point, the ice sheet is 9.75 miles (15.7 kilometers) deep—ten times the height of the tallest skyscraper in the United States. Since the ice sheet sits on land below sea level, ocean waters lap at its edges and make it vulnerable to melting.

If the West Antarctic ice sheet were to collapse and pour into the sea, it would raise global sea levels by 13 to 20 feet (4 to 6 meters). A sea-level rise of that size would flood coastal regions, including much of Florida and New York City. Global warming experts, however, believe that it would take five hundred to seven hundred years for the West Antarctic ice sheet to collapse if global warming continues at its present rate.

Melting in Greenland The melting of Greenland's ice sheet, the world's second largest expanse of ice after all of Antarctica's ice, is also a grave concern. The Greenland ice is 2 miles (3.2 kilometers) thick on average and covers 708,000 square miles (1.84 million square kilometers)—almost all of Greenland.

Studies conducted by the National Aeronautics and Space Administration (NASA) between 1993 and 1999 show that Greenland's ice is thinning on about 70 percent of its margins—in some places by 3 feet (1 meter) per year. In total, more than 2 cubic miles (8.2 cubic kilometers) of Greenland's ice melts each year. That amount of melting accounts for about 7 percent of the yearly rise in sea levels. If Greenland's entire ice sheet were to melt, ocean levels would rise by about 25 feet (7.6 meters), and there would be massive flooding in many parts of the world.

Melting in the Himalayas The Himalayan Mountains, one-sixth of which are covered with glaciers, contain more snow and ice than any other place in the world except for the polar regions. (The Himalayas cover 1,500 miles [2,340 kilometers] across northern India, Nepal, and Tibet.) In the summer of 1999, researchers from Jawaharlal Nehru University in Delhi, India, announced their findings that the Himalayan glaciers are melting faster than anywhere else in the world. Their study showed that the Gangotri glacier, situated at the head of the Ganges River—a 1,550-mile-long (2,418-kilometers-long) river flowing southeast from the Himalayas into the Bay of Bengal—is shrinking at a rate of approximately 90 feet



This satellite photo shows a 75-mile chunk of ice shelf on the Antarctic Peninsula that snapped off in 1998. ©AP PHOTOS/ NATIONAL SNOW AND ICE DATA.

(27 meters) per year. If melting in the Himalayas continues at present levels, those glaciers could disappear by the year 2035.

The meltwater from the Himalayan glaciers has formed dozens of lakes, many of which are in danger of bursting through their natural dams.

These dams consist of walls of debris that were deposited by retreating glaciers over the last three hundred years. As the water level in these lakes continues to rise, it puts pressure on the natural dams. Eventually, the force of the water will grow too great, and the dams will give way, causing walls of water to surge down the mountainsides. Such catastrophes used to occur about once every ten years, but for the last decade they have been occurring once every three years. Geologists anticipate that by 2101, lake-bursts in the Himalayas will be annual events.

The worst lake-burst in recent history took place in 1985 in the Khumbal Himal region of Nepal. A wall of water 50 feet (15 meters) high swept downstream, killing villagers and destroying a hydroelectric plant. In 1994 a lake-burst in northern Bhutan killed twenty-seven people and ruined buildings and farmland. Tsho Rolpa, a lake at the edge of the Trakarding glacier, northeast of Katmandu, is also in danger of bursting. Engineers for the Tsho Rolpa Hazard Mitigation Project have installed a hazard warning siren on the lake that can be heard far down the valley and is linked to satellite communications. In addition, engineers cut a slot in the natural dam and installed a sluice gate to allow controlled discharge of the meltwater. However, there are many other glacial lakes in India, Nepal, Pakistan, and Tibet that are in imminent danger of collapse that feature no such warning systems.

The increased melting of the Himalayan glaciers also threatens to disrupt the region's supply of water for drinking and crop irrigation.

Snow-covered Himalayan peak, India. ©RIC ERGENBRIGHT/CORBIS.

Residents of the tiny island nation of Tuvalu may be forced to abandon their homes due to rising sea levels. AP IMAGES.

Glacial meltwaters supply two-thirds of the flow of the Ganges River and other nearby waterways. If the glaciers melt entirely, those rivers will shrink and cease to supply the region. If that happens, almost five hundred million people in India would be at risk of starvation.

Island nations in trouble The effects of the swollen seas are already being felt by small island nations. On the South Pacific islands of Kiribati and Tuvalu, for example, rising waters have destroyed roads and bridges and washed out traditional burial grounds. Many residents of those islands have had to move to higher ground. In Barbados, rising ocean levels have caused salt water to contaminate fresh-water wells near the coasts. The salination (process of making salty) of drinking water is a grave concern in Barbados, where drinking water is already in short supply.

At the global warming summit held in The Hague, the Netherlands, in November 2000, representatives of thirty-nine small island nations expressed their frustration at rising sea levels. They described the threat that rising waters pose to tourism and agriculture, which are concentrated on the coasts and are primary sources of income for island nations. "These are serious issues of economics and livelihood—issues that can disrupt the social fabric of countries," stated Leonard Nurse, a representative from Barbados in a news report of November 17, 2000.

Nurse and other delegates from island nations responded angrily to suggestions made that they should cope with rising sea levels by building surge barriers and storm drains. They blamed industrialized nations, foremost among them the United States, for emitting large amounts of carbon dioxide into the air and accelerating global warming. Those sentiments were underscored by Yumie Crisostomo of the Marshall Islands, who stated to the press: "Whoever caused the problem has to clear up the problem."

What causes global warming? It is likely that global warming is partially the result of natural processes. For example, Earth could be still recovering from the most recent ice age. However, the rate of global warming is higher now than at any time in Earth's geologic history. This suggests some abnormal cause, such as the recent rapid increase of greenhouse gases in the atmosphere.

While the term "greenhouse effect" has a negative popular connotation because of its association with pollution and global warming, Earth's natural greenhouse effect keeps Earth at a suitable temperature for life on Earth. Without a modest greenhouse effect, the planet's average surface temperature would be about 0°F (–18°C).

How the greenhouse effect works The greenhouse effect is so-named because of the resemblance of the heat-trapping function of Earth's atmosphere to that of a greenhouse. However, the similarity is

Rising sea levels due to global warming may cause the island chain of Tuvalu in the South Pacific to disappear. ©MATTHIEU PALEY/ CORBIS.

only superficial. In a greenhouse, the glass panels allow solar radiation to pass through. The plants and other objects in the greenhouse absorb the radiation and heat the surrounding air. Since the warm air cannot escape, the air in the greenhouse can become quite warm when the Sun is shining. This is the same phenomenon that can cause the interior of an automobile to become blistering hot in the summertime.

Earth's greenhouse effect is a different process. Solar radiation is primarily visible light. This shorter-wavelength radiation passes through Earth's atmosphere and reaches the surface. Some is reflected back to space by clouds and by Earth's surface itself. The rest is absorbed by the surface and by plants. As the surface warms, it begins to emit infrared radiation. Infrared is longer wavelength than visible light, and Earth's atmosphere does not allow infrared to pass. Consequently, much of this outward-bound radiation is either absorbed by the atmosphere or reflected back to the surface, raising the temperature even further. Eventually, Earth achieves heat balance, with as much energy radiated by the surface as is absorbed, but the presence of greenhouse gases in the atmosphere means heat balance is achieved at a higher temperature.

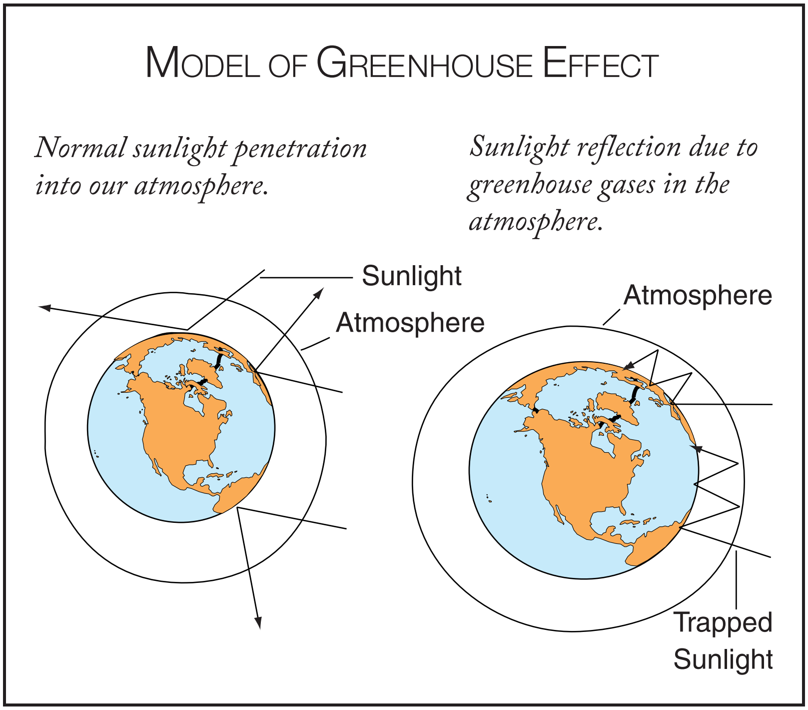
The most plentiful, and most effective, greenhouse gas is water vapor. Nighttime temperatures in winter often do not drop as low when there is a cloud cover. All other things being equal, the surface temperature remains higher on cloudy nights than it does on clear nights. On clear, dry nights, most of the reradiated heat can escape and the surface temperature can drop to low temperatures. This happens in the high deserts of Asia and South America, where daytime temperatures can soar to over 100°F (40°C) during the day and plummet below freezing at night. Since clouds block incoming solar radiation, they have a cooling effect on the surface during the day.

Why melting icebergs don't contribute to rising sea levels

Many people are under the false impression that melting of icebergs and the floating ice cap that covers the waters around the North Pole are contributing to the rise in sea level. In fact, the melting of floating ice has no effect on the sea level. Ice, with its crystalline configuration of molecules, takes up more space than liquid water. Ice floats because it displaces a weight of water equal to the weight of the ice. When the ice melts, it becomes water with the same weight and volume as the water it was displacing. Consequently, there is no change in water level. The following experiment demonstrates this principle.

1. Take a large clear bowl and fill it half way with water.
2. Empty a tray of ice cubes into the water and measure the height of the water.
3. Wait for the ice to melt, and then measure the height of the water again.

So why do scientists say melting ice caps will cause a rise in sea level? If ice sheets melt, ice and snow covering the polar regions will no longer have anything holding them in place. If Antarctic ice, for example, slides into the ocean and melts, then the sea level will rise.



An atmosphere with natural levels of greenhouse gases (left) compared to an atmosphere of increased greenhouse effect (right).

Why has the greenhouse effect has been getting so much negative publicity in recent years, when it is necessary to sustain life? The answer is that too much of a good thing, in this case the warming of Earth, can be harmful. The natural systems on Earth exist in a delicate balance and require a specific temperature range. If the heat is turned up, the balance is disrupted. The concentration of some greenhouse gases has increased rapidly in recent years, meaning that more heat is being trapped and returned to Earth. This condition is technically called enhanced greenhouse effect, but is commonly known as global warming.

Carbon dioxide and global warming A majority of planetary and atmospheric scientists now agree that an increase in the amount of carbon dioxide in the atmosphere is almost certainly the primary reason for the enhanced greenhouse effect and the resulting global warming. Carbon dioxide is an industrial byproduct that has been accumulating in the atmosphere since the start of the Industrial Revolution (around 1760–1830). Carbon dioxide is produced by the burning of coal, oil, gas, and wood, and is emitted by factory smokestacks and motor vehicles.

Levels of carbon dioxide, measured at the Mauna Loa Weather Observatory in Hawaii, rose from about 315 parts per million (ppm) in 1960 to about 350 ppm in 1990. During the twentieth century, the level of carbon dioxide in the air rose by 25 percent. In 2001, the rate of increase of carbon dioxide in the atmosphere was about 0.5 percent. Since then, the rate of increase has steadily grown. Atmospheric carbon dioxide levels were 381 ppm in March 2006. Measurements show that 2005 saw one of the largest increases on record, 2.6 ppm, which is a rate of 0.75 percent per year.

Another reason why levels of carbon dioxide are increasing is deforestation, which is the removal of the forests. Deforestation affects the atmosphere in two ways. First, trees naturally absorb carbon dioxide by converting it to oxygen through the process of photosynthesis. With fewer trees, less carbon dioxide is absorbed. Second, in clearing forests to allow for other land use (such as farming), many trees are burned; this places large amounts of carbon dioxide into the atmosphere.

Other greenhouse gases Carbon dioxide is not the only pollutant responsible for enhancing the greenhouse effect. Concentrations of other greenhouse gases, such as chlorofluorocarbons (CFCs), nitrous oxides, and methane, are also on the rise. While the concentrations of each of these other gases is substantially smaller than the concentration of carbon dioxide, these gases are much more efficient than carbon dioxide at absorbing infrared radiation.

Chlorofluorocarbons are similar to hydrocarbons, except that some or all of the hydrogen atoms have been replaced by chlorine or fluorine atoms. CFCs can be liquids or gases. They are used in refrigerators and air conditioners; as propellants in aerosol spray cans (such as deodorants, spray paints, and hairsprays) and foam-blowing canisters; and in some cleaning solvents.

Nitrous oxides, like carbon dioxide, are emitted from industrial smokestacks and car exhaust systems. They are also components of some fertilizers sprayed on agricultural fields.

Methane is a product of anaerobic (in the absence of oxygen) decay of organic matter. Some sources of methane are swamps, rice paddies, garbage dumps, and livestock operations. Approximately 60 percent of atmospheric methane is the result of human activity. Of that portion, most is due to livestock. By growing rice for millions of people, dumping refuse in landfills, and raising livestock, humans contribute to a rising concentration of methane in the atmosphere. Since methane only survives fifteen to twenty years in the atmosphere, and is twenty times more potent than carbon dioxide as a greenhouse gas, reducing methane emissions could be an effective means of reducing climate warming in a relatively short time.

Consequences of global warming Recent findings by scientists on the Intergovernmental Panel on Climate Change (IPCC) and others about the trend in global warming maintain that within the next century the world may reach its warmest point in the history of civilization. The effects, according many scientists, could be far-reaching. One consequence of global warming, as discussed above, is an increase in ocean levels around the world. The warmer weather is also expected to alter rainfall patterns, increase the severity of storms, and have negative effects on human health. By many accounts, global warming has already harmed certain animal species. A review of 866 scientific studies in the journal *Annual Review of Ecology, Evolution and Systematics* finds that many species of frogs are becoming extinct, and cold-dependent animal species such as penguins and polar bears are also threatened.

Drought, floods, and storms Global warming is expected to increase the amount of rainfall in the tropics and produce drought throughout temperate regions (for example, the northern three-quarters of the United States, southern Canada, and much of Europe). In places suffering from a lack of rainfall, crop yields would be lower, and natural vegetation would suffer. Grazing animals would either have to migrate to find food and water or would die off.

Climatologists (scientists who study climate) point to the occurrence, over the last two decades, of two of the most extreme El Niños on record as further evidence of global warming. El Niño is the extraordinarily strong episode of the annual warming of the Pacific waters off the coast of Peru.

Some scientists also assert that global warming has been responsible for recent, unusually severe, weather such as strong blizzards, hurricanes, tornadoes, heat waves (extended periods of high heat and humidity), and wildfires. They warn that these weather disasters will intensify as global warming increases. Other scientists dispute the effect of global warming on the weather, pointing out that there has been no increase in the number of major hurricanes in recent decades.

Risks to human health By many accounts, global warming is bad for human health. A group of researchers in the United States warns that

The retreating Arctic ice pack is affecting wildlife in the region. Scientists have documented multiple deaths of polar bears off Alaska, where they likely drowned after swimming long distances in the ocean. ©GREENPEACE/HANDOUT/EPA/CORBIS.

the number of U.S. residents dying of heat stress may double by the year 2075 (presently two thousand to three thousand people per year die from heat stress). Sustained rains, predicted for warm regions, may produce flooding that causes drinking water to be contaminated with sewage; people drinking the contaminated water would become sick. Warmer air also increases ground-level ozone pollution (smog), which aggravates symptoms of asthma and other respiratory ailments.

Disruptions to animal life Many scientists are also concerned about the harm global warming causes to wildlife. "Global climate change has the potential to wipe out more species, faster, than any other single factor," stated Patty Glick, coordinator of the Climate Change and Wildlife Program at the National Wildlife Federation, in a November/December 2000 *International Wildlife* interview. The World Wildlife Fund estimates that 20 percent of species in northern regions, from New England to the North Pole, could die out by the year 2100 because of the loss of habitat brought about by global warming.

As reported by the World Wildlife Federation in June 1999, tropical fish have been forced to migrate to colder waters in search of food. Animals that depend on fish for sustenance, such as sharks, sea lions, and marine birds, have also been forced to migrate or face starvation.

The reason for the migration is that the warming of ocean waters in recent years has led to a reduction of the fishes' food source, ocean

Antarctic penguin species declining

An animal species suffering from higher temperatures in recent years is the Adelie penguin. The Adelies live on the Antarctic continent and on the great sheets of off-shore pack ice. They survive on krill, tiny shrimplike animals that live in the icy waters. The krill, in turn, feed on the algae that bloom within the layers of sea ice and are released into the water as the ice melts.

The Adelies' reproductive cycle is tied to the changing of the seasons. They give birth just at the start of the Antarctic summer, when algae fill the water and krill are plentiful. If the temperature is too high and the thawing begins too early, however, the algae are scattered far and wide (as are the krill) at the time the chicks are born. In that case, the Adelie parents are forced to travel great distances to gather food for their young, all the while leaving their young unattended. A study found that Adelies were spending sixteen hours a day to gather food, up from previous years' average of six hours a day. As a consequence, the young may not get enough food or may fall prey to predatory birds.

Over the last twenty-five years, Adelie penguin populations in areas under study by American researchers have declined dramatically. Numbers of breeding pairs in five large colonies dropped from 15,200 to 9,200, and several small colonies were entirely wiped out. In the last two years alone, the Adelie population in the study area dropped by 10 percent. The decline in Adelies corresponds to an increase in temperature over the last fifty years, during which time Antarctica has become warmer by 3 to 5°F (1.7 to 2.8°C) in the summer and 10°F (5.6°C) in the winter. Seals, whales, and other species of penguins are also threatened by dwindling krill supplies near Antarctica. For example, an average blue whale eats 4 to 6 tons (3.6 to 5.4 metric tons) of krill each day.

plankton, in waters where plankton have traditionally thrived. Plankton are microscopic plants (phytoplankton) and animals (zooplankton) that occupy the bottom rung of the food chain, in which food energy is transferred from one organism to another one as each feeds on another species. Plankton are the beginning of the chain. Off the west coast of North America, plankton populations have decreased by 70 percent since 1977. As a result of that change, there has been a 90 percent decline in seabird populations since 1987.

Effects on arctic wildlife The effects of global warming on wildlife are seen most vividly in the arctic. In parts of that far northern region, temperatures increased 7 to 10°F (4 to 5.6°C) in the thirty-five-year span from 1965 to 2000. During the 1990s the number of salmon in Alaska's rivers decreased dramatically, as did the numbers of Stellar sea lions and harbor seals in the Bering Sea and Gulf of Alaska. More than one million

The habitat of king penguins, who live in the subantarctic regions, is quickly changing as glaciers in the area are melting. ©MOMATIUK-EASTCOTT/CORBIS.

seabirds starved to death in the Bering Sea in the years 1997 and 1998 alone, because of dwindling food supplies in the warmer waters.

The warmer weather also triggered much heavier snowfalls in Alaska. For some animals, such as the Peary caribou, the large quantities of snow make it difficult to get to buried food. This factor has led to a reduction in the numbers of this species of small caribou from 24,500 in 1961 to only about 1,000 in the year 2000.

The human factor Since global warming was identified as a problem in the 1970s, there has been vigorous debate over what role, if any, human activity plays in the trend. Since 1995, however, many global climate scientists agree that increased carbon dioxide levels and other forms of atmospheric pollution are a major factor in contributing to global warming, and that immediate action is necessary. Scientists from a variety of public and private agencies recommend that governments regulate greenhouse gas emissions now, instead of waiting until the problem is worse and the remedy more costly. They warn that even if the emission of pollutants were curbed today, it would take many years for the global warming trend to stop (primarily because heat, stored in the oceans, would continue to be slowly released). There is also debate over the projections of how fast climate changes will occur in the future and the effects of those changes.

Is global warming a natural phenomenon? Some scientists and others remain skeptical that humans are the primary cause of global warming. They point out that annual average temperatures in the continental United States have varied from decade to decade, with no significant upward or downward trend throughout the century. It was relatively cool from the beginning of the century until 1920; warmed up in the 1920s through the 1950s; cooled down in the 1960s and 1970s; and began warming again in the 1980s. One theory suggested to explain the warm 1990s is that the heat given off by the Sun has increased. In recent years, however, a growing number of corporations have abandoned the position that global warming is not a social problem.

Earth Summit addresses global warming The debate over the role of human activity in global warming has been carried out all over the world. The first international meeting to address the problem of global warming was held in June 1992 in Rio de Janeiro, Brazil. Formally called the United Nations (U.N.) Conference on Environment and Development, but better known as the Earth Summit, the 1992 meeting was attended by representatives of 178 nations, including 117 heads of state.

One outcome of the Earth Summit was the drafting of a document called the Declaration on Environment and Development, also known as the Rio Declaration. The document spelled out twenty-seven guiding principles of environmentally friendly economic development. Conference attendees came to an informal agreement on the need to change energy policies in order to halt global warming.

The Kyoto conference In December 1997, representatives of 166 nations gathered in Kyoto, Japan, for the U.N. Framework Convention

Global warming and the United States

In June 2000, a report commissioned by the U.S. Congress painted a grim picture of the effect of global warming on the United States. The national assessment report, compiled by scientists from both within and outside of the government, gave a detailed summary of what will likely occur if average temperatures rise 5 to 10°F (2.8 to 5.6°C) over the next century. While recognizing the "significant uncertainties in the science underlying climate-change impacts," the study concluded that "based on the best available information, most Americans will experience significant impacts" from global warming.

The report predicts that as temperatures rise, entire ecosystems will move northward. For instance, as New England warms, that region's sugar maple forests will die off, to be replaced by forests in Canada. Salmon currently inhabiting the Columbia River (in the Pacific Northwest) will be unable to survive in the warmer water, while other warmer-water fish species will move in. The report also warned that rising sea levels may cause coastal marshes and wetlands to spread inland, completely submerging the barrier islands off the coast of the Carolinas.

Among the report's other projections were sweltering heat waves in urban areas, frequent droughts in the Midwest, the conversion of forests in the Southeast into grasslands, the reduction of water levels in the Great Lakes (because of increased evaporation), and damage to roads and buildings in Alaska due to the thawing of the ground.

on Climate Change. The conference focused on the growing problem of global warming and ways to reduce greenhouse emissions.

Delegates to the meeting produced the Kyoto Protocol, a document that called upon industrialized nations (relatively wealthy nations, such as those in North America and western Europe) to take the lead in reducing emissions of greenhouse gases. The protocol specifically directed thirty-six industrialized nations to reduce greenhouse-gas emissions between the years 2008 and 2012 to 5.2 percent below 1990 levels. These nations are the largest producers of greenhouse gases. The United States, for instance, is responsible for 25 percent of global carbon dioxide emissions—more than any other nation. Poorer, developing nations (in Africa, Latin America, parts of Asia, and the Middle East) were spared the treaty's requirements. Conference participants agreed that it would pose too great an economic burden on developing nations to greatly reduce greenhouse emissions.

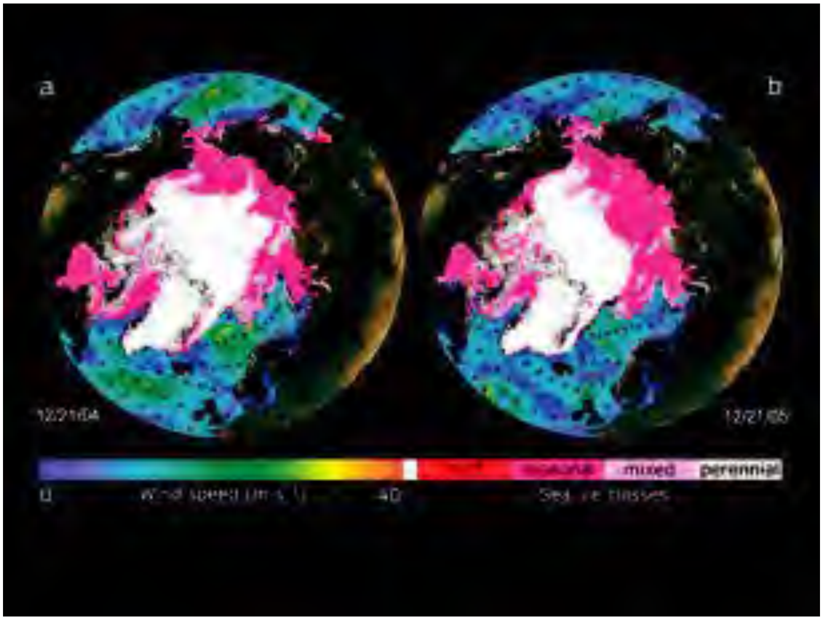
In November 1998 the administration of President Bill Clinton endorsed the Kyoto Protocol. The signing of the document, however, was largely symbolic since the Senate did not give its approval. (The U.S. Constitution states that all treaties are subject to ratification by two-thirds of the Senate.) Given the treaty's certain defeat in the Senate, President Clinton chose not to put it to a vote.

Senate leaders made their concerns about the Kyoto Protocol clear in a 1997 resolution, passed by a vote of 95–0 shortly after the convention. Senators vowed to oppose the agreement unless it required developing countries to reduce greenhouse emissions during the same time period as mandated for industrialized nations. They pointed out that developing nations, especially India and China, are rapidly increasing their use of fossil fuels.

Despite the United States' refusal to participate in the Kyoto Protocol, it has been signed by 169 countries and other governmental entities and became part of the United Nations Framework Convention on Climate Change on February 16, 2005.

Talks in The Hague end in stalemate In November 2000, delegates from more than 180 countries met in The Hague, the Netherlands, with the goal of implementing the Kyoto accord. They sought to develop a method for monitoring greenhouse gas emissions and to devise penalties for countries that did not reduce their emissions.

The two-week-long meeting, however, ended without an agreement. The talks broke down over a demand by the United States and some other



The area of sea ice over the Arctic has shrunk dramatically in the last few years. AP IMAGES.

industrialized nations to receive credit for carbon dioxide "sinks," which are areas covered with vegetation that naturally absorb carbon dioxide, such as forested land and farmland. The credits would have partially offset the amount by which those nations were required to cut their emissions.

The future of global warming

If global warming continues at the current rate, dramatic changes in the global climate are likely. Forests in the U.S. Southeast could be converted to grasslands. Deserts might spread around the globe at middle latitudes. The tropics might become virtually uninhabitable. Paradoxically, some areas might become cooler. For example, if the Gulf Stream (a warm water circulation pattern in the North Atlantic) is diverted to the south by meltwater from the Arctic ice, the British Isles could experience much colder weather.

At the same time, much of the frozen north would thaw and become habitable. The great coniferous forests of Asia, Europe, and North America could be converted to agriculture. The polar regions themselves might be habitable. This would lead to much conflict in areas such as Antarctica, where land would be at a premium. Whatever the ultimate consequences, it is clear that unchecked global climate change will have a profound effect on Earth.

[*See Also* **Climate; El Niño; Flood; Forecasting; Human Influences on Weather and Climate; La Niña; Weather: An Introduction**]

For More Information

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Human Influences on Weather and Climate

Human activity affects weather, climate, and the environment. Some human activity is harmless, but much human activity degrades the environment. While the environment can absorb some abuse without long-term effects, much harmful human activity exceeds the environment's ability to recover. The most significant way that humans damage the environment is by emitting harmful chemicals into the air and water. This activity has wide-ranging results, such as increasing the temperature of the planet, lowering the quality of the air we breathe, and killing forests and aquatic animals. (Global warming, the worldwide increase in atmospheric temperature, is discussed in detail in "Climate Change and Global Warming".) Other environmental consequences include air pollution and smog, acid rain, and ozone depletion. Each of these have multiple effects and there is mounting evidence that they result in increased impact on the environment over the last few years. The search for solutions to these environmental problems has yielded some results, including promising research on alternative energy sources.

Air pollution

Air pollution is the presence of high concentrations of undesirable gases and particles in the air. Although some air pollution is caused by natural processes, such as volcanic eruptions and wildfires, much is the result of human activity and is emitted by smokestacks and car exhaust systems. According to the U.S. Centers for Disease Control, air pollution contributes to between 50,000 and 120,000 deaths in the United States (primarily due to asthma, heart disease, and bronchitis) each year. Estimated yearly costs of treating illnesses in the United States triggered by air pollution are between $40 and $50 billion. In addition to posing a hazard to the health of humans and all other living things, air pollution creates unpleasant odors and diminishes the planet's natural beauty.

WORDS TO KNOW

acid precipitation: rain and snow that are made more acidic when carbon, sulfur, and/or nitrogen oxides in the air dissolve into water. Also known as acid rain.

active solar collector: system for gathering and storing the Sun's heat that uses pumps and motors. Is often used for heating water.

air pollutant: any harmful substance that exists in the atmosphere at concentrations great enough to endanger the health of living organisms.

Air Quality Index (AQI): measurement of air quality, based on concentrations of surface ozone averaged over an eight-hour period for specific locations.

chlorofluorocarbons (CFCs): compounds similar to hydrocarbons in which one or more of the hydrogen atoms are replaced by fluorine or chlorine.

Clean Air Act: set of environmental regulations limiting pollutants emitted by cars, factories, and other sources. First enacted by the U.S. Congress in 1970 and updated several times since then.

Environmental Protection Agency (EPA): government agency charged with implementing the provisions of the Clean Air Act.

fossil fuels: coal, oil, and natural gas—materials composed of the remains of plants or animals that lived on Earth millions of years ago and are today burned for fuel.

fuel cell: device that generates electricity by combining hydrogen and oxygen; it emits water vapor as a by-product.

global warming: the observed global increase in atmospheric temperature. Also called global climate change.

greenhouse effect: the warming of Earth due to the presence of greenhouse gases, which trap upwardly radiating heat and return it to Earth's surface.

While air quality has improved in the last three decades, half of all U.S. citizens live in counties where air pollution exceeds national health standards. Every large city in the world currently experiences some degree of air pollution. In a report released in 2004, the American Lung Association reported that particulate matter (fine particles suspended in the air) is an especially difficult problem. According to the report:

- 81 million Americans live in areas with unhealthy short-term levels of particulates
- 66 million Americans live in areas with unhealthy year-round levels of particle pollution
- 136 million Americans live in counties with unhealthy levels of ozone

greenhouse gases: gases that trap heat in the atmosphere. The most abundant greenhouse gases are water vapor and carbon dioxide. Others include methane, nitrous oxide, and chlorofluorocarbons.

ozone days: days on which the smog threshold is surpassed.

particulates: small particles suspended in the air and responsible for most atmospheric haze. Particulates can irritate the lungs and cause lung disease with long exposure.

passive solar collector: system for collecting and storing the Sun's heat that has no moving parts and is generally used for home heating.

photochemical smog: a hazy layer containing ozone and other gases that sometimes appears brown. It is produced when pollutants that are released by car exhaust fumes react with strong sunlight.

photovoltaic cell: light-sensitive device containing semiconductor crystals (materials that conduct an electric current under certain conditions) that convert sunlight to electricity. Also called solar cells.

phytoplankton: tiny marine plants that occupy the lowest level of the food chain.

skin cancer: a disease of the skin caused primarily by exposure to the ultraviolet rays in sunlight.

smog: common name for photochemical smog—a layer of hazy, brown air pollution at Earth's surface comprised of ozone and other chemicals.

smog threshold: the level of smog allowed by law and set by the Environmental Protection Agency at 80 parts per billion (ppb) of surface ozone.

unhealthy air days: days on which surface ozone levels reach 80 parts per billion—a concentration considered unhealthy to children, people with respiratory problems, and adults who exercise or work vigorously outdoors.

wind farm: a large group of interconnected wind turbines.

wind power: power, in the form of electricity, derived from the wind.

wind turbine: a windmill designed to convert the kinetic energy of wind into electrical energy.

- 159 million Americans live in counties with one of the three conditions: unhealthy levels of ozone, unhealthy short-term levels of particulates, or unhealthy year-round levels of particulates
- 46 million Americans live in counties where all three levels are unhealthy

In a report published in 2001, the World Health Organization estimates that 1.5 billion city dwellers face levels of outdoor air pollution that are above the maximum recommended levels. According to the report, about half a million deaths each year can be attributed just to particulate matter and to sulfur dioxide in outdoor air. While air pollution is usually considered a problem of developed countries, as a result of their high level of industrial activity and vehicle use, more than 70 percent

A factory emitting chemical pollutants into the atmosphere. ©GEORGE LEPP/CORBIS.

of deaths from outdoor air pollution occur in the developing world. In developing nations, populations tend to be larger and pollution standards often are less strict than in the more developed nations.

Air pollution in history Air pollution by humans is as old as the discovery of how to make fire. Air pollution first emerged as a public concern around the twelfth century, when legislation was passed in England restricting coal burning. By the mid-1600s, coal burning had noticeably worsened the quality of the air, particularly in London. By the mid-1800s, London's air was so thick with soot and smoke it was described as "pea soup."

London's air pollution was not only unsightly, it was deadly. In two incidents, one in 1873 and the other in 1911, the "pea-soup fog," sometimes called smog (combining the words "smoke" and "fog"), claimed nearly two thousand lives. It was not until a five-day bout of smog killed nearly four thousand Londoners in 1952 that legislation was passed to curb the pollution. The Clean Air Act of 1956 was an act of the Parliament of the United Kingdom in response to the Great Smog of 1952. The act banned the burning of peat and soft coal, which are relatively cheap and easy to obtain, but produce excessive amounts of soot and smoke. Instead, households were encouraged to burn gas, oil, or hard coal (anthracite), or convert to electrical heat.

Air pollution is not limited to Britain. The problem exists worldwide, especially where industrialization is coupled with lax, unenforced, or ineffective environmental regulations.

The United States has had a problem with air pollution for the last century or more. The soot from burning coal blanketed St. Louis, Missouri, and Pittsburgh, Pennsylvania, in the first half of the twentieth century. This type of pollution has given way in many large cities to photochemical smog, which is formed by the interaction of sunlight with unburned hydrocarbons from industrial process, gas stations, petroleum processing, and automobile exhaust. The problem is not limited to urban areas; polluted air blankets many beautiful natural areas as well. Big Bend National Park in far west Texas is plagued each summer by haze that may come from as far away as the petroleum processing facilities along the Texas Gulf Coast.

Air pollution An air pollutant is any harmful substance that exists in the atmosphere at concentrations great enough to endanger the health of

Smog hangs over farmland outside of Beijing, China, 2006. AP IMAGES.

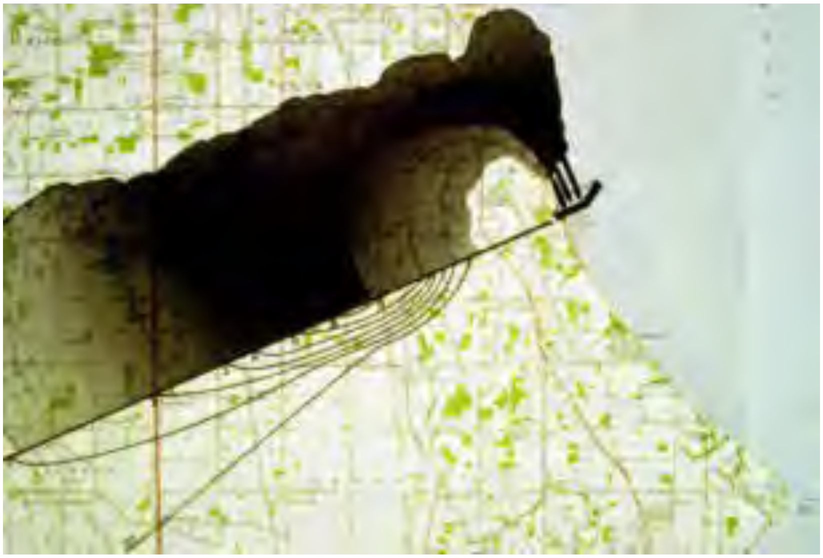
living organisms. An air pollutant may take the form of a gas, a liquid, or a solid (such as particulates). When a pollutant is emitted directly into the air, it is called a primary air pollutant. A primary air pollutant may undergo chemical reactions with water, sunlight, or other pollutants, and produce additional pollutants, called secondary air pollutants.

Some substances that exist naturally in the air in small concentrations, such as carbon monoxide and sulfur dioxide, are considered pollutants at higher concentrations. Other substances that do not occur naturally, such as benzene, can cause damage to organisms even at very low concentrations.

Pollutants make their way into the air either through natural processes or by human activities. Examples of natural processes that put pollutants in the air include forest fires, dispersed pollen, wind-blown soil, volcanic eruptions, and organic decay.

The primary human-related cause of air pollution is motor vehicle emissions. Other examples of human-created pollution include: the combustion of fuel for generating heat and electricity in "stationary" sources such as houses, power plants, and office buildings; industrial processes such as paper mills, oil refineries, chemical production plants, and ore smelting; the breakdown of organic waste at landfills; and crop dusting with pesticides or insecticides.

The amount of air pollution produced in the United States is difficult to calculate accurately. The best estimates are that in 2001, somewhere

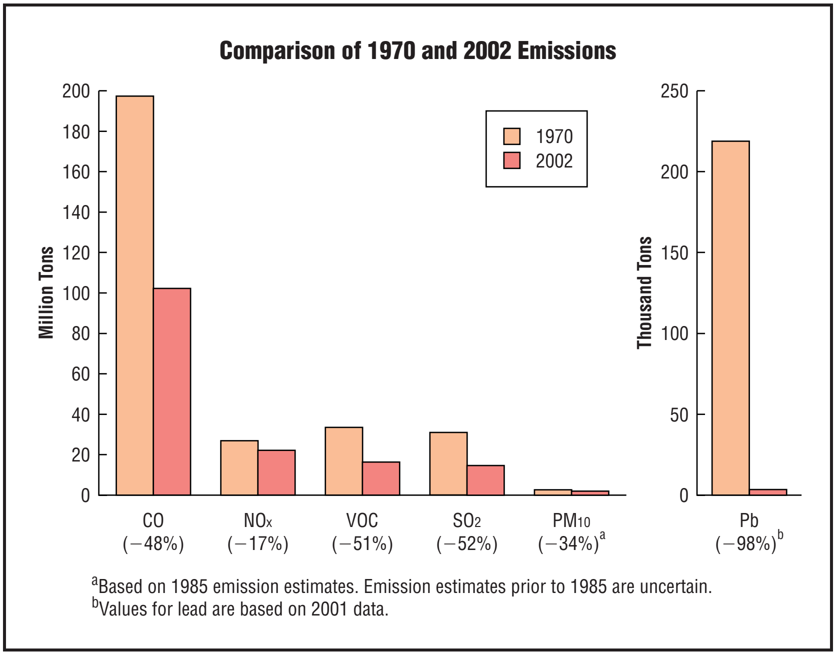


A computer model of power plant pollution. FMA, INC.

between 150 million and 300 million tons (130 to 270 million metric tons) of air pollutants were produced, an average of around 0.5 to 1.0 tons (0.45 to 0.89 metric tons) per year for every man, woman, and child living in the United States. About 63 million tons (56 metric tons) of pollutants were produced by motor vehicles alone. Due in part to federal and state regulations designed to reduce air pollution, total emissions of select air pollutants in the United States decreased by 25 percent between 1970 and 2001.

Categories of major air pollutants and their effects There are several different categories of air pollutants. One major category includes particulate matter, which are solid or liquid particles that are tiny enough to be suspended in the air. Air pollution created by particulate matter is the most visible type of air pollution. Some forms of particulate matter, such as dust, smoke, and pollen, are irritating to humans, but not toxic. Other types of particulate matter, such as asbestos fibers, arsenic, sulfuric acids, and a number of pesticides, are toxic. Long-term exposure to toxic particulate matter causes a variety of recurring health problems.

Certain types of heavy metal particulate matter, namely iron, copper, nickel, and lead, cause respiratory illnesses. Lead particles



Emissions have decreased since 1970.

accumulate in body tissues and can damage the central nervous system. At high enough concentrations, lead is fatal. Levels of lead in the air have been greatly reduced in recent years because of laws requiring the use of lead-free gasoline.

One of the most widespread gaseous air pollutants is carbon monoxide (CO). Carbon monoxide is produced by the combustion of carbon-containing fuels. It is emitted by car exhaust, home heating systems, and industrial smokestacks. Carbon monoxide is colorless, odorless, and poisonous. Due to recently adopted air-quality standards, CO levels in the United States have been reduced by about 40 percent since the early 1970s. When it collects in enclosed places, CO can cause unconsciousness, and even death.

A colorless, but not odorless, polluting gas is sulfur dioxide (SO_2). Sulfur dioxide is produced during the burning of coal and oil, primarily in power plants, petroleum refineries, ore smelting plants, and paper mills. The gas causes a host of respiratory problems in humans and has been shown to reduce the yield of certain crops, such as lettuce and spinach. After clean air standards were enacted, SO_2 concentrations in the United States declined by 48 percent between 1980 and 2005.

Methane is another gaseous air pollutant. It is also a greenhouse gas, which means it traps heat in the atmosphere and therefore contributes to the greenhouse effect, which warms Earth. Methane belongs to a class of organic compounds called hydrocarbons whose molecules are formed from chains of one or more carbon atoms with hydrogen atoms attached to the chain. Hydrocarbons that evaporate into the air easily are in a class called volatile organic compounds (VOCs). There are thousands of VOCs, which may be in solid, liquid, or gaseous states at room temperature. Some, such as methane, are naturally occurring and pose little danger to human health at low concentrations other than as a greenhouse gas. Other VOCs, such as formaldehyde and chlorofluorocarbons, are dangerous. Some VOCs, such as benzene and benzopyrene, are carcinogens (cancer-causing substances). The primary sources of VOCs that pose a threat to human health are emissions by motor vehicles and industrial processes.

Nitrogen oxides are also a major air pollutant. The oxides of nitrogen include nitrogen dioxide (NO_2) and nitrogen oxide (NO). These gases can be produced naturally, by the action of bacteria, but they are also produced during fuel combustion, through the combination of nitrogen and oxygen. Due to fuel combustion (which occurs in motor vehicles and industrial processes), nitrogen oxide levels are up to one hundred times greater in cities than they are outside of urban areas. While nitrogen oxides are usually colorless, at high enough concentrations (such as those that exist over Los Angeles), nitrogen dioxide takes on a reddish-brown color.

High levels of nitrogen oxides may cause a higher incidence of some types of cancer in humans and may make the body more susceptible to heart and lung disease. Nitrogen oxides also undergo reactions with other chemicals in the air that result in increased levels of photochemical smog.

Photochemical smog In the United States, photochemical smog is commonly referred to simply as "smog." It is different from the pea-soup smog of London, which is a combination of sulfurous smoke and fog. Photochemical smog is a layer of air pollution near Earth's surface. This is the type of smog familiar to residents of Los Angeles and other large cities. The main component of smog is ozone, an odorless, colorless gas composed of three atoms of oxygen. Near-surface ozone is formed when nitrogen oxides and hydrocarbons (chemicals emitted by car

Smog covers the Los Angeles basin, California. FMA, INC.

exhaust systems, coal-burning power plants, chemical plants, oil refineries, aircraft, and other sources) react with strong sunlight.

Surface ozone is characterized by the Environmental Protection Agency (EPA), the U.S. government agency that deals with air pollution, as "the most widespread and persistent urban pollution problem." Surface ozone differs from "good" ozone in Earth's upper atmosphere. Upper atmosphere ozone shields us from the Sun's harmful ultraviolet rays.

Photochemical smog is difficult to see at ground level. When looking down at it from above, however, it appears as a brown haze. Photochemical smog is irritating to the eyes and throat.

The continuing saga of smog Smog in the United States, while down from its peak in 1988, is a continuing problem. In the 1980s, the federal government imposed a series of laws mandating cleaner exhaust from cars, smokestacks, and other sources of pollution. Those measures are credited for keeping the smog problem in check. At the same time that emission systems have become cleaner, however, there has also been a rise in the consumption of fossil fuels, like coal, oil, and natural gas. The increasing number of motorists, using greater amounts of gasoline, as well as the burning of increasing quantities of coal by utility companies, at least partially offsets any gains made in air quality.

The persistence of pollution by near-surface ozone (a primary component of photochemical smog) is particularly puzzling because emissions of the two ozone precursors, oxides of nitrogen and volatile organic compounds, have been declining in the United States and are tightly regulated by federal and state governments. Levels of other air pollutants regulated by the EPA, such as particulates, lead, sulfur dioxide, nitrogen dioxide, and carbon monoxide, have fallen by half or more since 1970.

In 2005, the EPA completed phasing in new standards for ozone, the so-called "smog threshold." The old standard allowed 120 parts per billion (ppb) of ozone averaged over a one-hour period. The new standard sets a limit of 80 ppb, averaged over a longer eight-hour period. (The old standard remains in effect for a region until that region meets or exceeds the old standard for three years in a row.) The U.S. government imposes penalties, such as withholding highway funds, on states that frequently surpass the threshold. Days on which the threshold is surpassed are called "ozone days."

Ozone concentrations of 80 ppb or higher are considered unhealthy to children, people with respiratory problems (such as asthma or emphysema), and adults who exercise or work vigorously outdoors. The EPA considers those categories of people "sensitive groups." Days on which ozone levels reach 80 ppb are considered "unhealthy air days." Ozone concentrations of 105 ppb or higher pose a health risk to the general population.

When the ozone concentration reaches 105 ppb, the government issues health advisories, cautioning people to remain indoors as much as possible and to avoid exertion outdoors. Such days are known as "shut-in days." The year 1988 logged the greatest number of ozone days for many eastern cities since smog record-keeping began in 1974. New York City, for example, had forty-three ozone days in 1988. Since 1998, the number of ozone days has generally declined. This is probably due to a reduction of smokestack emissions and different weather conditions in smog-prone areas.

The Air Quality Index To simplify air quality reporting, the EPA has developed the Air Quality Index (AQI) for specific locations. The index is based on concentrations of each of four major air pollutants regulated by the Clean Air Act, passed by Congress in 1970 and updated several times since then: ground-level ozone, particle pollution (also known as particulate matter), carbon monoxide, and sulfur dioxide. Each is each averaged over

Brush fires send thick haze over Kuala Lumpur, Malaysia, disrupting traffic and triggering health warnings, 2006. AP IMAGES.

some period of time, such as eight hours for ozone. According to the EPA, the use of a standardized measure makes it easier for people decide when to take precautions. The AQI is a "yardstick" used to measure health risks. The AQI is set so that a value of 100 corresponds to the national air quality standard for that pollutant. An AQI below 50 represents good air quality. When the AQI is higher than 100, people in sensitive groups are encouraged to limit their time outdoors. An AQI higher than 151 is considered unhealthy for the general population, in which case everyone is advised to limit their outdoor activity.

Nitrogen dioxide is no longer reported separately because the concentrations of nitrogen dioxide have remained very low for several years. However, nitrogen dioxide remains an important contributor to the formation of ozone, which is reported.

Under the Clean Air Act, metropolitan areas with populations over 350,000 are required to publicize the AQI when pollution levels are high; AQI reports are typically included in weather pages of newspapers. Some state and local air quality agencies declare "ozone action days" when the AQI reaches unhealthy levels. On ozone action days, residents are encouraged to limit automobile use, fill gas tanks only after dusk, conserve electricity, and reduce the use of air conditioners.

Record levels of smog set in 2002 Despite advances in air pollution, record smog was recorded in 2002. According to a report released by the Public Interest Research Group (PIRG), a private research organization, smog monitors in forty-one states and the District of Columbia recorded unhealthy levels of air pollution on some 8,800 separate occasions in 2002. This was a 90 percent increase over 2001. The report found that every region of the country exceeded the national health standard for ozone more often in 2002 than 2001, with the largest increases in midwestern, southeastern, and central states. California, Texas, and Tennessee led the nation in 2002 with the most smog days, which PIRG defines as days on which at least one ozone monitor in the state exceeds the national health standard. In addition, sixteen monitors at eleven national parks, including the Great Smokey Mountains and Yosemite, recorded levels of ozone in excess of the national health standard a total of 418 times during 2002.

Los Angeles: The bad news and the good news Due to its large population and high number of sunny, warm days, Los Angeles, California, has the worst smog problem in the United States. Between 1980 and 2006 the population of the city of Los Angeles grew 38 percent, to over four million. During the 1980s, the number of miles being logged by motorists increased 75 percent; however, between 1990 and 2000 the increase was only 13 percent. Los Angeles leads the nation in the number of motor vehicles with an average 1.8 registered automobiles per licensed driver. But the main problem in Los Angeles is not the number of cars, miles driven, or number of drivers. The problem is widely considered to be congestion. Los Angeles drivers do not travel an excessive amount, but due to congestion, the number of hours spent idling in traffic is much greater. As a consequence, the skyline of downtown Los Angeles is blanketed in the summer by a nearly permanent reddish-brown haze.

There were sixty-two days in 1998 in which smog levels were above the federal threshold of 120 ppb in Los Angeles. Conditions improved

What level is healthy?

The EPA uses a standard system for qualitatively reporting the health effects of each of the major pollutants, based on the AQI for that pollutant.

- Good air quality: No health impacts are expected when air quality is in this range.
- Moderate air quality: Unusually sensitive people should consider limiting prolonged outdoor exertion.
- Unhealthy air quality for sensitive groups: Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.
- Unhealthy air quality: Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion.
- Very unhealthy air quality: Active children and adults, and people with respiratory disease, such as asthma, should avoid all outdoor exertion; everyone else, especially children, should limit outdoor exertion.
- Hazardous air quality: Government will issue health warnings of emergency conditions. The entire population is likely to be affected.

slightly in 1999, and over the summer Los Angeles passed on the notorious distinction of having the worst summertime smog day to Texas City, Texas. The respite for Los Angeles was only temporary, however. Since 1999, Los Angeles and Southern California have regained the dubious status as the smoggiest place in the United States. In 2004, the American Lung Association listed the ten worst places to live. The Los Angeles area topped the list. Four of the worst five counties were in Southern California. The Texas Gulf Coast industrial complex was bumped back down to fifth place.

1. Los Angeles-Riverside-Orange County, CA
2. Fresno, CA
3. Bakersfield, CA
4. Visalia-Porterville, CA
5. Houston-Baytown-Huntsville, TX
6. Merced, CA
7. Sacramento-Arden-Arcade-Truckee, CA-NV
8. Hanford-Corcoran, CA
9. Knoxville-Sevierville, LA and Follette, TN
10. Dallas-Fort Worth, TX

In 1967, the U.S. Congress gave California the right to require tighter auto-emissions standards than the rest of the country. Los Angeles's cars and trucks, and its industry, are now among the cleanest in the nation; yet its pollution remains among the worst. Why is the smog in Los Angeles so bad?

Ozone, the main constituent of smog, is created when ultraviolet (UV)rays from the Sun stimulate chemical reactions between nitrogen oxides and volatile organic compounds (VOCs). These photochemical reactions increase as the concentrations of nitrogen oxides, VOCs, UV, and the air temperature all increase. The climate and topography (shape of the land surface) in Los Angeles combine to make it a near-perfect candidate for smog. For half the year, Los Angeles has hot and dry weather. Mountains to the north, east and south trap the air from generally light ocean breezes. The nitrogen oxides and VOCs from traffic and industry accumulate and smog forms under the action of the famous Southern California sun. It rarely rains in Southern California in the summer, so smog is not washed out of the air.

California continues to take steps to battle smog. The EPA recently granted California's request for a "preemption" of federal air standards

Even natural areas suffer from smog

A 1999 study by a coalition of environmental groups demonstrated that no place in the United States is immune from smog. The group found, in fact, that many summer vacation places are just as smoggy as the cities vacationers leave behind. For instance, in the Great Smoky Mountains (the half-million acre park on the Tennessee-North Carolina border), like other natural areas, receive pollution from upwind coal-burning power plants (some are hundreds of miles away) as well as from visitors' motor vehicles. Due to the effects of ozone and acid rain (rain that is made more acidic by sulfuric and/or nitric acid in the air), some thirty species of plants in the Great Smoky Mountains National Park have been damaged or wiped out. Other natural areas that suffer smog in similar concentrations as big cities include the northern tip of Cape Cod; Acadia National Park on the coast of Maine; the Indiana Dunes on Lake Michigan; and the Hamptons on New York's Long Island.

On Earth Day in April 1999, Vice President Al Gore announced the goal of restoring clear vistas to our national parks by 2064. To implement this goal, President Bill Clinton's administration proposed a set of new clean-air guidelines for 37 national parks and 119 wilderness areas. On June 15, 2005, the EPA issued final amendments to its July 1999 regional haze rule. These amendments apply to the provisions of the regional haze rule that require emission controls known as Best Available Retrofit Technology (BART) for industrial facilities emitting air pollutants that reduce visibility. These pollutants include fine particulate matter and compounds which contribute to particulate formation, such as oxides of nitrogen, sulfur dioxide, volatile organic compounds, and ammonia. The amendments include final guidelines, known as BART guidelines, for states to use in determining which facilities must install controls and the type of controls the facilities must use.

for small nonroad engines such as lawn mowers. In addition, in 2005 California adopted a more stringent standard for ozone of 70 ppb averaged over an eight-hour period (the federal standard is 80 ppb averaged over an eight-hour period). From 2007 on, small engines sold in California will have to meet much stricter emissions requirements.

Temperature inversions The effects of air pollution are most intense when an inversion exists in the atmosphere. An inversion occurs when a layer of warm air exists above a colder layer of surface air. The warm air acts like a lid, preventing the surface air from rising. An inversion may last for several days.

Normally, the concentration of pollutants in urban areas is moderated by the upward motion of air, as well as the horizontal motion of winds. When an inversion forms, however, it traps air pollutants close to the ground. After several days of an inversion, the concentration of smog

Ways You Can Reduce Smog

The following list includes steps you can take, and encourage your family to take, to reduce smog.

- Instead of driving, walk, ride bikes, or take public transportation whenever possible.
- When driving is necessary, arrange car pools.
- Use a manual lawn mower instead of one that is fueled by gasoline or electricity.
- Keep your car tuned up, so it uses gasoline as efficiently as possible.
- Conserve energy. Turn off unnecessary lights and appliances.
- When filling the tank of your car, snowmobile, or other equipment, do not allow gasoline to spill; after filling, close the gas cap tightly.
- Use nontoxic cleaning supplies and paints whenever possible.
- Tightly seal the lids of household cleaners, garden chemicals, paint thinners, and other chemical products in order to prevent evaporation of toxic chemicals.

may increase to the point that cars must drive with their lights on, even during the day, and people with asthma suffer a marked increase in attacks.

Smog and human health Photochemical smog takes the greatest toll on children, people with asthma or other respiratory disorders, and people who do strenuous work or exercise outdoors. About one-third of all Americans belong to these groups, considered "sensitive groups" by the EPA. People in the sensitive groups are urged to limit their time outdoors and not exert themselves when ozone levels are high.

Ozone irritates the respiratory system, causing symptoms such as coughing, sneezing, sore throat, and difficulty taking deep breaths. Some people respond to smog with chest pains, burning eyes, headaches, and dizziness. In the presence of high levels of ozone, people with asthma are more prone to asthma attacks. One reason for this is that the allergic response to elements that trigger asthma attacks, such as dust mites, pollens, fungus, pets, and cockroaches, is heightened when ozone is strong.

Ozone also has the potential to damage the lining of the lung. When cells in the lung die after a high ozone day, the lung repairs itself by manufacturing new cells. Repeated assault on the lungs by high levels of ozone, however, can cause permanent lung damage. Ozone also aggravates emphysema, bronchitis, and other lung diseases, and sometimes weakens the body's ability to fight off bacterial infection in the lungs. If children are repeatedly exposed to dangerous levels of ozone, scientists fear that they may experience reduced lung function as adults. A 1998 study in Los Angeles found that when ozone levels are high, there is a marked increase in the numbers of people hospitalized with lung and heart ailments.

Clean-air legislation In 1970, the U.S. Congress enacted the first Clean Air Act: a law regulating the air pollutants emitted by cars, factories, and other sources. The act required the Environmental Protection Agency (EPA) to set air quality standards, to enforce those standards in every state, and to update the standards as necessary to "protect public health with an adequate margin of safety."

In 1977, when it became apparent that most states were failing to meet the clean-air standards set in 1970, the Clean Air Act was amended with new target dates for compliance. The amended law also exempted older, coal-burning power plants from many of the act's requirements. EPA officials reasoned that the plants would soon be retired, and therefore that expensive smokestack renovations would not be worth the money. However, many of the older power plants, especially those in the Midwest were still running twenty years later.

In 1997, EPA administrator Carol Browning announced a tough new set of clean-air regulations that would be implemented in 2008. The allowable level for ozone was lowered. The 1997 rules also called for a sharp reduction of harmful emissions (specifically nitrogen oxides, the main cause of smog) coming from twenty-two states east of the Mississippi River, beginning in 2003. The new rules took aim at power plants in the Midwest and East, especially those exempted by the 1977 rule.

Lawyers for utility companies sought relief from the new air-quality rules in the District of Columbia Circuit Court of Appeals. On May 14, 1999, the court ruled in favor of the utility companies and set aside the EPA's stricter emissions restrictions. The court also voided the new ozone limit of 80 ppb.

In response, EPA officials worked hard to restore the 1997 amendments, petitioning the courts to rehear parts of the case. After further legal

What do lawn mowers and airplanes have in common?

Both airplanes and lawn mowers emit a lot of air pollution. Lawn mowers, chain saws, weed trimmers, and leaf blowers emit large amounts of carbon monoxide and several smog-forming, particulate-matter pollutants. Since a lawn mower has none of the emission control systems of a car, its pollution goes directly into the air.

Using a gasoline-powered lawn mower produces the equivalent pollution of driving a car for several hundred miles. It has been estimated that backyard power tools produce 5 to 10 percent of all the nation's smog-forming pollutants. One way to cut down on this pollution is to retire old lawn mowers in favor of one of the cleaner models introduced to the market in 1996, or to use a manual push-mower.

An airplane burns fossil fuel and releases pollutants into the air from each of its several engines. In addition to emitting about 3 percent of all carbon dioxide due to human activities worldwide, airplane engines also give off carbon particles (soot), sulfur dioxides, and nitrogen oxides.

At present there are about fifteen thousand commercial jet aircraft worldwide. Industry experts expect that number to double within twenty years. Scientists from the National Aeronautics and Space Administration (NASA) are currently conducting tests to more accurately determine what quantities of pollutants are produced by aircraft.

arguments, in March 2000, the D.C. Circuit Court issued a ruling that supported most portions of EPA's rules on limits of nitrogen oxides. However, the court required the EPA to reexamine several matters before moving ahead. By 2004, the EPA had finalized all the steps it had to take in response to the courts rulings, including separating the rules on nitrogen oxides into two phases.

In 2005, the EPA established other clean-air rules—the Clean Air Interstate Rule (CAIR), the Clean Air Mercury Rule (CAMR), and the Clean Air Visibility Rule (CAVR). The CAIR limits emissions of sulfur dioxide and nitrogen oxides in the eastern United States while the CAVR limits sulfur dioxide and nitrogen oxides emissions in the western United States. The CAMR limits nationwide mercury emissions.

However, legal battles and legislative debates continue. Of particular concern to many is the EPA's handling of New Source Review (NSR). On December 31, 2002, exactly thirty-two years after President Richard Nixon signed the Clean Air Act into law, the George W. Bush administration announced provisions that many considered significant rollbacks to NSR pollution control provisions. According to critics, the new rules would allow virtually all pollution increases from old, high-polluting sources to go unregulated and communities would not have any way to know when a nearby power plant is increasing the amount of pollutants pumped into the air. The new regulations went into effect in March 2003.

The Clean Air Act remains a work in progress. Further legal and legislative actions are possible as different parties gain control of the political process and environmental laws and regulations continue to evolve.

Acid rain

A secondary effect of air pollution is the acidification of rain. Acid rain (or more accurately acid precipitation) is rain, sleet, snow, fog, or hail that is made more acidic by pollutants in the air (rain is naturally slightly acidic). This occurs as a result of acid deposition, which is the deposit of acid particles by either wet (rain or snow) or dry (dust or gas) means. The primary pollutants responsible for acid deposition, sulfur dioxide and nitrogen oxides, are both by-products of the burning of fossil fuels. These pollutants are emitted by car exhaust systems, coal-burning power plants, chemical plants, oil refineries, aircraft, and other sources. They react with moisture in the air to produce sulfuric acid and nitric acid.

Acid rain raises the acidity of lakes and rivers in sensitive areas, making them inhospitable to many species of animals. It also kills trees and has been shown to harm human health. Sensitive areas include portions of the northeastern United States, eastern Canada, and northern Europe, where the bedrock is primarily granite. In areas where the bedrock is limestone, acid rain is not much of a problem because the acid combines with the limestone to produce harmless carbon dioxide.

Acid rain corrodes the surfaces of rocks, dissolving minerals, such as aluminum, that are harmful to living organisms. Aluminum is one of the most harmful substances dissolved by acid rain. When it washes into lake and rivers, it hampers the ability of fish to absorb oxygen through their gills. Dissolved aluminum has caused the deaths of entire fish populations in hundreds of highly acidic lakes and rivers in North America (especially in the northeastern United States and Canada) and in northern Europe.

Aluminum that is washed into the soil prevents the roots of trees from absorbing essential nutrients, ultimately killing the trees. Acid rain also makes plants more susceptible to frost, insects, and disease. In some areas where acid rain is a serious problem, entire forests have been wiped out. In Europe, so many trees have been stunted or killed that a new word, *Waldsterben* (forest death), has become part of the vocabulary.

Acid rain has also been shown to harm human health. In children, exposure to acid rain (and other forms of acid in the air or water such as acid fog, acid mist, acid snow, and acid dust) aggravates asthma. Even in healthy people, acid air pollutants can cause lung damage.

Acid rain damages property, too. It gradually dissolves marble—the stone from which many statues are made. Around the world, outdoor art classics are losing fingers, toes, and noses to acid rain. In Washington, D.C., in the mid-1990s, for instance, a marble sculpture of the Shakespearean character Puck lost an entire hand.

The acid rain express The parts of the world most affected by acid rain at present are the northeastern United States, southeastern Canada, central Europe, and Scandinavia. These locations, however, are not necessarily home to the greatest producers of acid rain-forming pollution.

Trees in the Great Smoky Mountains killed by acid rain. Aluminum washed into the soil prevents the roots of trees from absorbing essential nutrients. JLM VISUALS.

Airborne pollutants can travel for great distances before returning to Earth. For this reason, acid rain can affect ecosystems in even remote parts of the world, far from industrial centers. It is believed that

Sweden's acid rain problem, for instance, originates in England's smokestacks.

In the United States, the primary generators of sulfur dioxide and nitrogen oxides are large electrical power plants in the Midwest. The coal used in those plants, mined from midwestern and Appalachian coalfields, is particularly high in sulfur. The pollution from the midwestern power plants rises high in the air and is carried eastward and northeastward by the wind. When the pollution descends, it may mix with precipitation to form acid rain or acid snow. In dry regions the pollution falls to the ground as acid gas or acid dust.

The acidification of lakes, rivers, and forests is a serious problem throughout the eastern portion of the United States. Some of the areas most affected by acid rain are Maine, Vermont, New York, the upper peninsula of Michigan, Virginia, West Virginia, Maryland, Tennessee, and North Carolina.

Clean Air Act takes aim at acid rain

The 1990 amendments to the Clean Air Act contained provisions for controlling emissions, especially sulfur dioxide, that cause acid rain. The amendments required a reduction of sulfur dioxide emissions by power plants to 40 percent of 1980 levels. The law specifically targeted 110 big coal-burning power plants in 21 midwestern, Appalachian, northeastern, and southeastern states.

The emissions reduction was to be achieved by issuing each plant a certain number of emission allowances, beginning in 1995. Each allowance permits a plant to emit 1 ton (0.91 metric tons) of sulfur dioxide. Plants were barred from emitting more sulfur dioxide than their allowances stated. The number of allowances for each plant was set below that plant's 1990 level of sulfur dioxide releases.

Lakes remain acidic even as sulfur emissions drop Since the 1970s, when acid precipitation was identified as the cause of dying trees and the term "acid rain" was popularized, nations in North America and northern Europe have required factories to reduce their sulfur dioxide emissions. A study released in October 1999 showed that levels of sulfur compounds (the primary components of acid rain) in lakes and rivers at two hundred sites on both continents have decreased. The study's bad news, however, was that the acidity of many of the bodies of water tested has not declined and that bodies of water damaged by acid rain show no signs of recovery.

The study, undertaken by an international team of twenty-three scientists, found reduced acidity (on the order of 25 percent) in some lakes and rivers in Vermont, Quebec, and northern Europe. The remaining portions of North American included in the study, stretching from Maine to the Midwest, had unchanged levels of acidity in bodies of water.

Trout streams suffering in Virginia

If the state of Virginia's rivers are any indication, the acid rain problem in the eastern United States remains serious. A study by University of Virginia researchers in 1998 found that 50 percent of Virginia's rivers suffer from acid rain. The trout that were formerly plentiful in those rivers have seriously declined in number. Another finding of the study was that 6 percent of the state's streams are "chronically acidic," meaning they cannot support plant or animal life.

Researchers concluded that a 70 percent reduction (from 1980 levels) of sulfur dioxide emissions would be required to prevent greater acidification of rivers and lakes, not only in Virginia but throughout the northeastern United States (the 1990 Clean Air Act law aims for a 40 percent reduction from 1980 levels). The study's authors also pointed out the need for greater restrictions on emissions of nitrogen oxides, the second-greatest contributors to acid rain.

The results of that study illustrate the difficulty of de-acidifying lakes and rivers. Researchers concluded that tackling the acid rain problem would likely require further cuts in sulfur dioxide emissions. "We've been creating acid rain for a long time," stated Dr. Gary Lovett of the Institute of Ecosystem Studies in *The New York Times* on October 7, 1999. "It may take a long time to recover from its effects."

Decline of bases adds to problem One reason that acidity levels remain steady in lakes and rivers even as sulfur compounds decrease is that levels of calcium and magnesium are also on the decline. Magnesium and calcium are bases, that is, substances that react with acids to form salts. They neutralize acid rain, much as antacid medication neutralizes stomach acid. Calcium is also used by trees to build cell walls and magnesium is a component of chlorophyll, the substance that gives green plants the ability to photosynthesize (produce food from carbon dioxide, water, and sunlight).

The loss of calcium and magnesium has been attributed to acid rain. Acid rain removes those elements from the soil more quickly than they can be replaced by leaching from rocks. Throughout the northeastern United States, Ontario, and Quebec, magnesium and calcium levels in the soil have declined by around 50 percent since the 1960s.

Ozone depletion

While ozone in the lower atmosphere is bad, ozone in the upper atmosphere is good. Ozone in the upper atmosphere shields Earth from the Sun's harmful ultraviolet rays. The destruction of ozone by certain chemicals over the last few decades is a matter of great concern. Ozone is a colorless gas composed of three atoms of oxygen bonded together. Although ozone is commonly described as odorless, it does have a subtle and hard-to-describe odor. The "fresh" odor sometimes detected right after a summer thunderstorm may be from lingering ozone in the air.

Unlike surface ozone, which is a major air pollutant, upper-atmospheric ozone is not formed by an interaction of pollution and sunlight. The ozone layer high above Earth is formed by a reaction between molecular ozone (O_2) and atomic ozone (O), in the presence of sunlight. Ozone has three atoms of oxygen per molecule. Its chemical formula is O_3.

Earth's protective ozone layer lies between 10 and 25 miles (16 and 40 kilometers) above ground. It is in the upper part of Earth's stratosphere, a region of the atmosphere that is about 6 to 40 miles (14 to 62 kilometers) above ground. The concentration of ozone in the layer is a few parts per million. While low, this is thousands of times more concentrated than ozone near the surface. The ozone layer is important to humans and other living organisms because of its ability to absorb harmful ultraviolet radiation.

In recent years, the presence of certain chemical pollutants in the upper atmosphere has caused a reduction in concentration of ozone molecules in the ozone layer. This loss of stratospheric ozone has severe repercussions for human health, the most serious being a rise in cases of skin cancer. The term "skin cancer" refers to one of three diseases of the skin that are caused primarily by exposure to the ultraviolet in sunlight It is estimated that every 1 percent reduction in the ozone layer results in a 2 to 5 percent rise in the incidence of skin cancer. Other human consequences of the loss of protective ozone may include an increase in sun burns and eye cataracts, as well as the suppression of the immune system.

The most likely culprit behind ozone depletion is the class of human-made chemicals called chlorofluorocarbons (CFCs). CFCs can be liquids or gases, and appeared in all kinds of everyday products such as propellants in aerosol

How acidic is acid rain?

Acidity and alkalinity are measured on a scale called the pH (potential for hydrogen) scale. It runs from 0 to 14. Since it is a logarithmic scale, a change in one unit equals a tenfold increase or decrease of acidity or alkalinity. Therefore a solution of pH 2.0 is ten times more acidic than a solution of pH 3.0 and one hundred times more acidic than a solution of pH 4.0. A pH value of 0.0 is extremely acidic, 7.0 is neutral, and 14.0 is extremely alkaline (basic).

Any rain below pH 5.0 is considered acid rain. (Some scientists set the limit at 5.6.) Clean, unpolluted rainwater is normally slightly acidic, because the rain dissolves carbon dioxide as it falls through the air. In solution, carbon dioxide forms a weak acid. Normal rain and snow containing dissolved carbon dioxide has a pH of 5.6.

The acidity of rain varies according to geographical area. Eastern Europe and parts of Scandinavia have rain with a of pH 4.3 to 4.5; in the rest of Europe the rain is pH 4.5 to 5.1; in eastern United States and Canada, rain pH ranges from 4.0 to 4.6; and in the Mississippi Valley, it is 4.6 to 4.8. The rain around Lake Erie and Lake Ontario has a pH of about 4.2. The optimal pH range for most freshwater organisms is between 6.5 and 7.5.

Here are some common substances and their typical pH values:

- Battery acid: 1.0
- Lemon juice: 2.0
- Vinegar: 2.2
- Normal rain: 5.0 to 5.6
- Distilled water: 7.0
- Human blood: 7.4
- Baking Soda: 8.3
- Ammonia: 11.0

spray cans and foam-blowing canisters; in refrigerators and air conditioners; and in some cleaning solvents. When CFCs rise into the stratosphere, they form chlorine compounds that break down ozone molecules.

Levels of stratospheric ozone are kept in balance naturally. Ozone is produced in the stratosphere by the combination of molecular oxygen (O_2) and atomic oxygen (O). Ozone molecules are broken by the absorption of ultraviolet rays and by collisions with other oxygen atoms. The dust and gases emitted by volcanic eruptions also break down ozone molecules. By introducing CFCs into the equation, however, the balance becomes tilted in favor of ozone destruction.

The consequences of ozone depletion are not limited to humans. A decrease in ozone has also been linked to a reduction of crop yields, health problems in animals, and a loss of ocean phytoplankton. Phytoplankton are microscopic ocean plants that are a crucial link in the food chain of marine animals.

The Antarctic ozone hole Tests conducted above Antarctica in the late 1970s, at the end of the long, cold winters (in September and October), first revealed the problem of ozone depletion. In 1985, the concentration of ozone in the stratosphere above Antarctica decreased to the point where scientists began to refer to the area as the "ozone hole."

The ozone layer above Antarctica continued to thin at alarming rates throughout the 1980s, and by 1994 had been almost totally eliminated for a brief part of the year. At its worst, the ozone hole is double the size of the Antarctic continent. In many aspects the Antarctic ozone hole remains the most visible and striking example of how human-created pollution can damage the atmosphere.

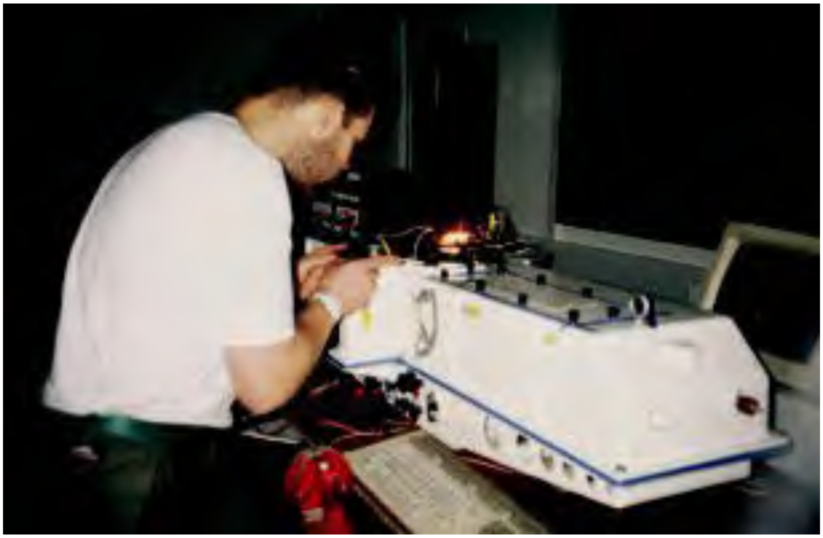
Experiment: Testing for Acid Rain

You can make your own indicator to test the acidity of rain using the following materials: three large leaves of red cabbage, white vinegar, baking soda (sodium bicarbonate), a pitcher, some rain water, and three clear glass jars.

The first step is to chop up the cabbage and simmer it gently in a pot of water for ten minutes. Do not allow the mixture to boil vigorously. After ten minutes, the liquid should be a deep reddish-purple color. The liquid is neutral (not acidic or basic). Let the water cool, then pour it through a strainer or a coffee filter into a pitcher. This water serves as an indicator liquid with which you can test the acidity of other substances.

To see how the indicator liquid works, test it with two substances: one an acid and the other a base. Pour a small amount of indicator liquid into the bottoms of two drinking glasses. To one glass, add a few drops of vinegar and to the other, a pinch of baking soda. The vinegar, which is acidic, will turn the liquid pink. The baking soda, which is basic, will turn the liquid green.

Now you are ready to test some rainwater. To do this, pour a small amount of indicator liquid into the third jar. Now pour some rainwater into the jar. Note any color change. How does it compare to the indicator liquid with vinegar added? Normally, rainwater is slightly acidic and should create a faint pinkish hue in the indicator liquid. The more intense the pink color that is created, the higher the acidity of the rain.

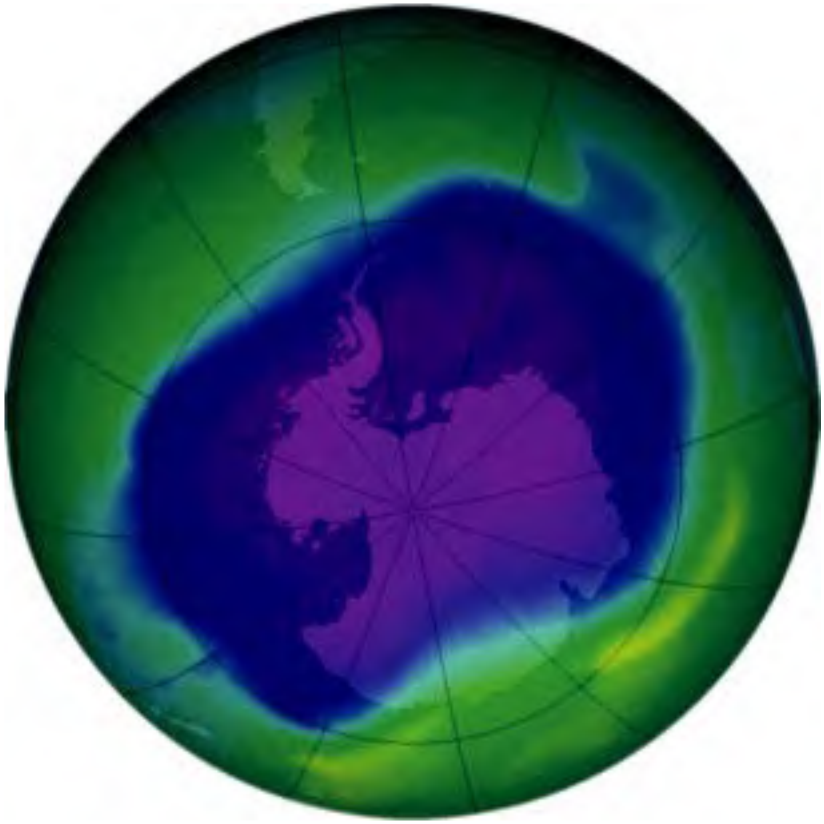


A scientist prepares to test the Dobson Spectrophotometer, a device used to measure ozone levels. ©GRAHAM NEDEN; ECOSCENE/CORBIS.

Measurements of the ozone layer over Antarctica began in 1978. In September 2006, the Antarctic ozone hole was measured at a record 10.6 million square miles (27.3 million square kilometers). At that time, the Antarctic ozone hole was also the deepest ever recorded. Near-total ozone loss was recorded at 13 miles (21 kilometers) above ground. Prior to 1997, ozone destruction did not extend higher than 9 miles (14 kilometers) in altitude. Ozone holes have also appeared in recent winters over the North Pole, northern Europe, Australia, and New Zealand.

Why does ozone depletion happen over the poles, where virtually no one lives and CFC use is practically nonexistent? It happens because both ozone and CFCs are carried around the planet by upper-level winds. The ozone layer is normally thickest above the tropics and from there it is distributed to the poles. During the cold Antarctic winter, however, a dome of extremely cold air forms, which blocks the distribution of ozone to the South Pole. At the same time, ice clouds form in the stratosphere. CFCs blown in from other parts of the world become trapped in these ice clouds. It is this combination of events that sets the stage for the depletion of the ozone layer.

Other parts of the world The stratosphere above other parts the world has also experienced a loss of ozone. Since 1979, the ozone layer over all parts of the world except the tropics has shown a marked depletion. The World Meteorological Organization has issued a series of research reports



A September 2006 satellite image shows a 11.4-million square mile hole in the ozone layer over the Antarctic. The blue and purple colors are where there is the least ozone; the greens, yellows, and reds are where there is more. AP IMAGES.

on ozone depletion. *Scientific Assessment of Ozone Depletion: 2002* confirmed that between 1979 and 1991, the ozone layer remained about 3 percent thinner over much of the Northern Hemisphere compared to pre-1980 levels. The Southern hemisphere mid-latitudes showed a 6 percent drop. The same study showed a 4 to 5 percent thinning of the ozone layer over the United States. New ozone holes also appear to be forming over the North Pole, Australia, and New Zealand. Even greater levels of ozone loss (up to 10 percent) have been found over Canada and northern Europe.

Chlorofluorocarbons destroy the ozone The main chemicals responsible for thinning the ozone layer are CFCs. CFCs are human-made hydrocarbons, such as freon, in which some or all of the hydrogen atoms have been replaced by fluorine atoms. CFCs were formerly used in refrigerators and air conditioners; as propellants in aerosol spray cans (such as deodorants, spray paints, and hair sprays) and foam-blowing canisters; and in some cleaning solvents.

When released into the air, CFCs slowly rise through Earth's lower atmosphere and up to the stratosphere. There they are converted by the Sun's ultraviolet rays into chlorine compounds. The chlorine compounds react with stratospheric ozone molecules (O_3), converting them into ordinary oxygen molecules (O_2). The release of CFCs into the atmosphere depletes the beneficial ozone layer faster than ozone can be recharged by natural processes. These are fueled by the reaction between molecular ozone and atomic ozone, in the presence of sunlight.

Other chemicals that contribute to the destruction of the ozone layer include halons (used in fire extinguishers), methyl bromide (used for fumigating crops), carbon tetrachloride (used in solvents and the manufacture of chemicals), methyl chloroform (used in auto repair and maintenance products), and hydro CFCs (HCFCs; similar uses as CFCs but considered slightly less damaging to ozone).

Attempts to curb ozone depletion Since the 1970s, when the world became aware the dangers of ozone depletion, there has been a flurry of national legislation and international treaties aimed at reducing the use of CFCs. In 1978, the United States government became one of the first nations to act, banning the use of CFCs in most aerosol cans.

The Montreal Protocol on Substances that Deplete the Ozone Layer, an international agreement drafted in 1987, called for the phasing-out of certain CFCs used in industrial processes by the year 2000. The protocol has been endorsed by ninety-three nations, including the major industrialized nations. In keeping with that accord, many countries have now greatly restricted the use of aerosol spray cans and other ozone-destroying chemicals. There is, however, a flourishing illegal trade in CFCs, especially in developing countries. In an effort to curb the trade, China Customs and the United Nations Environment Program launched Project Skyhole Patching in 2006. In the first six months of the program alone, nearly 72 tons (65 metric tones) of illegal ozone depleting substances were seized by authorities in China, India, and Thailand.

In the United States, the 1990 Amendments to the Clean Air Act set a timetable for the elimination of ozone-destroying chemicals. In 1993,

The global warming/ozone thinning connection

Some scientists are drawing a link between global warming and the continued reduction of the ozone layer. Increased concentrations of carbon dioxide (the main cause of global warming), which heat up the lower atmosphere, have a cooling effect on the stratosphere. This effect occurs because carbon dioxide traps heat in the lower atmosphere, preventing it from rising into the upper atmosphere.

In recent years, the stratosphere over both poles has been unusually cold. In 2006, a year of extreme cooling of the stratosphere over Antarctica, the ozone hole was wider and deeper than ever before recorded. The hole covered an area of 10.6 million square miles (27.3 million square kilometers). The ozone hole above Antarctica grows and shrinks with the seasons. Every September (the start of the Southern Hemisphere spring), increased sunlight energizes CFCs and other chemicals that destroy ozone molecules. The key stage of the chemical reaction takes place on the surface of frozen cloud droplets. Frozen droplets only form in extremely cold conditions. The lower the temperature in the stratosphere dips, the more plentiful frozen droplets become. When the concentration of frozen droplets increases, ozone breakdown accelerates.

Despite the record-setting ozone hold of 2006, there is some reason for hope. In 2005, the United Nations' Intergovernmental Panel on Climate Control released a report titled "Safeguarding the Ozone Layer and the Global Climate System," which stated: "Although considerable variability in ozone is expected from year to year, including in polar regions where depletion is largest, the ozone layer is expected to begin to recover in coming decades due to declining ODS [ozone-depleting substance] concentrations, assuming full compliance with the Montreal Protocol." However, the same report suggests that the projected increases of other greenhouse gases could possibly cool the stratosphere. This cooling of the stratosphere might have the effect of increasing ozone levels worldwide, but worsening the ozone depletion in other regions, like the Antarctic.

those phase-out dates were accelerated. According to the regulations, halons were eliminated in 1994; and CFCs, carbon tetrachloride, and methyl chloroform were eliminated in 1996. The most destructive form of HCFC, a substitute for CFC that also harms ozone, was scheduled to end production in 2003, but the manufacture of other forms of HCFC will be permitted until 2030 to give industrialists time to develop less harmful substitutes. After 2030, all forms of HCFC will be prohibited.

In September 1997, on the tenth anniversary of the Montreal Protocol gathering, representatives from more than one hundred nations met to reexamine the problem of ozone depletion. They agreed at that meeting to phase out methyl bromide, a chemical used in insecticides. Industrialized nations pledged to eliminate production of methyl bromide by

2005 and developing nations by 2015. As of 2007, methyl bromide production had decreased significantly, but the EPA still made some "critical use exemptions" to the phaseout.

The international efforts to protect the ozone appear to be working. Since 1988, there has been a substantial decline in the atmospheric buildup of CFCs. Experts suggest that concentrations of CFCs reached their peak before the turn of the twenty-first century, after which the ozone layer will begin the slow process of repairing itself. CFC molecules, however, survive in the atmosphere for fifty to one hundred years. As long as CFCs are present they will continue to damage the ozone.

Environmentally friendly sources of power

It is possible for even industrialized, automobile-dependent societies to meet basic needs and remain economically strong without harming the environment. What is needed to accomplish this are environmentally friendly sources of transportation, such as electric and hybrid cars, and cleaner sources of energy, such as solar power (electricity generated from the Sun) and wind power (electricity generated from wind).

Cars are responsible for one-third to one-half of all emissions that cause global warming, smog, and acid rain. Consequently, auto manufacturers face government regulations and public pressure to design and build cleaner cars. One result of this pressure has been the development of more efficient gasoline engines. Engines of recent-model cars put out just a small fraction of the pollutants that automobile engines emitted when the Clean Air Act was signed into law. They are also more powerful and more fuel-efficient. Auto manufacturers are also producing electric vehicles, hybrid gasoline-electric or diesel-electric vehicles, and vehicles powered by fuel cells (devices that generate electricity by combining hydrogen and oxygen).

Solar power and wind power are relatively clean, safe alternatives to burning fossil fuels. While solar and wind power are not completely harmless to the environment, they cause a fraction of the damage done by burning fossil fuels. There are numerous solar and wind power facilities operating throughout the world. In the United States in 1998, solar and wind power, together with hydroelectric power (power produced by moving water), accounted for approximately 8 percent of energy consumption. Fossil fuels and nuclear power made up the other 92 percent. The United States and many European nations have stated their intention to greatly increase the use of solar and wind power through the twenty-first century.

Electric cars Electric cars are automobiles that run on electric motors instead of gasoline-powered engines. The power that drives the electric current is stored in batteries. When the power runs low, an electric car's batteries must be recharged.

While electric vehicles are commonly thought of as a new technology, they have actually been around for a long time: They were first produced in the late 1880s. Electric cars, trucks, and buses, as well as electric trolleys and trains (with electricity supplied by overhead wires), were in widespread use at the beginning of the twentieth century. Electric vehicles were preferred over gasoline-powered vehicles because the latter class of vehicles were difficult to start, noisy, and required more maintenance.

The balance shifted in favor gasoline-powered vehicles in the 1910s, with the invention of the Kettering electrical self-starter. The starter eliminated the need for crank-starting gasoline-powered cars. By 1924, not a single electric vehicle was exhibited at the National Automobile Show.

While electric vehicles virtually disappeared in the United States, electric buses and trucks continued to be used in other parts of the world. For instance, in the latter part of the twentieth century there were thirty thousand electric vehicles in use in England and thirteen thousand in Japan.

The rise and fall of the modern all-electric vehicle Motivated by shrinking petroleum reserves and the polluting effects of gasoline emissions, auto manufacturers in the 1960s once again began looking toward electric automobiles. The motivation to produce all-electric automobiles also came from the Zero Emission Vehicle mandate (ZEV), a law passed by the state of California in 1990. This was a radical challenge to the auto industry to produce automobiles with zero tail pipe emissions. In 2003, the California Air Resources Board reduced the regulations outlined in the ZEV mandate, but while it was in effect this legislation jump-started the automakers' development of cleaner vehicles.

In 1996, General Motors began marketing a nearly silent, electric compact car called the General Motors EV1. The EV1 could accelerate from 0 to 60 miles per hour (0 to 97 kph) in 9 seconds, which is comparable to gasoline-powered cars. It was extremely fuel efficient, and could go 140 miles (218 kilometers) between charges. Honda also produced an electric car, the EV Plus. It was the first electric vehicle to be powered by nickel metal-hydride batteries (NiMH) instead of the traditional lead-acid batteries. However, these battery-powered cars did not perform well in cold weather. Ford produced an all-electric version of its Ranger pickup truck as well. All of these vehicles were produced in very limited quantities and production has ceased.

Most other major car makers have also ceased production of their all-electric vehicles. The motivation to produce zero-emission vehicles was reduced after the revision to California's ZEV mandate. Nearly all of the vehicles have been repossessed by the manufacturers and recycled.

At present, due to the high costs and limited capabilities of batteries, electric cars are only produced and sold in small numbers. However, the development of new technologies may bring the cost and performance of electric cars in line with gasoline-powered cars in the not-too-distant future.

The future of all-electric vehicles The primary obstacle to electric vehicle use has been the limitations of battery technology. Charging a battery can take several hours, and typical chargers can be expensive. Recent improvements to batteries and chargers, however, are making the process faster and easier. The widespread availability of NiMH batteries, which have a much better energy-to-weight ratio than lead-acid batteries, coupled with escalating oil prices in the early years of the twenty-first century, seems to have revitalized an interest in all electric vehicles. By late 2006, several companies had introduced new electrical vehicle prototypes and promised production would soon begin.

Hybrid cars Hybrid technology cars caught on with both consumers and manufacturers during the first years of the twenty-first century. A hybrid car contains a relatively small petroleum fueled engine, with a combined electric motor and generator. Electrical energy is stored in battery packs. The gasoline or diesel engine automatically recharges the battery packs as the car is being driven or while stopped. Hybrids (and all-electric vehicles) also use a technology called regenerative braking. When the brakes are applied, the energy of motion is converted by the motor/generator back to electrical energy and stored in the battery pack.

Hybrid cars smoothly switch back and forth between gas and electrical systems. Many hybrid vehicles use less petroleum fuel than traditional vehicles. They may get up to 70 miles (109 kilometers) per gallon,

Environmental concerns about electric and hybrid cars

While the use of electricity as fuel for automobiles solves some problems, it creates others. Greater use of electricity (for vehicles) translates to greater emissions from power plants. This is a concern especially in areas where older coal-fired generators are the source of electrical power. A purely electric vehicle will be responsible for more of some types of pollution, namely sulfates and particulates, and less of others, such as carbon monoxide and nitrogen oxide emissions, when compared to a hybrid vehicle. The environmental question may boil down to whether we prefer our pollution to be emitted from a single source, typically beyond city limits (the power plant), or from many sources, concentrated within city limits (automobiles).

Another problem is in the electric power grid, which is the system ofelectric power generation, transmission, and distribution used by the surrounding community. These grids are designed with capacity for maximum power demands, which occur at certain peak times (for example, on very hot summer days). Consumers may balk at being restricted from plugging in their cars during peak usage times.

The best solutions for the environment are to drive less and use public transportation such as trains and buses. Another alternative is the use of clean energy, such as solar energy and wind energy, to produce the electricity used by electric vehicles. In the late 1990s, two demonstration projects were installed at Boston-area commuter train stations in which solar cells generated the electricity that was used for charging electric vehicles.

making refueling necessary only every 700–870 miles (1092–1357 kilometers). In 2007, most automobile and light truck manufacturers had at least one hybrid vehicle in their production line.

Fuel cell–powered cars Fuel cells are a promising, new source of power for vehicles. They run on liquid hydrogen or hydrogen-rich materials such as ethanol and methanol. Fuel cells work by combining hydrogen and oxygen (from the air) to produce electricity and water. The main drawback to fuel cells, at this point, is cost. In 2006, the price of constructing a fuel-cell vehicle was around $2 million. (The primary reason for the high cost is that two components of fuel cells, platinum and graphite, are very expensive.) Fuel cells are also very fragile and do not stand up well to the bumps of daily driving. Auto companies are researching ways to make a cheaper, more robust fuel cell. Fuel cells run on pure hydrogen are considered zero-emissions vehicles. The exhaust is pure water. Fuel cells that run on hydrocarbons or alcohols will still have some "tailpipe" emissions, including carbon dioxide.

Chicago, Illinois, and Vancouver, British Columbia, have prototype fuel-cell buses in their public transportation fleets. Other cities around the globe are following suit. In California, automakers, fuel companies, and government agencies are working in partnership to test fuel cell vehicle technology and are expected to produce more than sixty demonstration vehicles over the next few years. There are currently around five hundred fuel cell–powered cars in operation worldwide. They are all prototypes and are serving as test platforms for this emerging technology. A number of durability, performance, and cost issues must be overcome before fuel cell vehicles are ready for mass production.

Biodiesel

Biodiesel fuel is a renewable energy source that can be made from a number of biological substances, including corn oil and animal fat. It is most commonly made of vegetable oils, unlike conventional diesel fuel that is made primarily from petroleum. Biodiesel blends (part biodiesel and part conventional diesel fuel) can generally be used in unmodified diesel engines. With some modifications, most diesel engines can run on pure biodiesel. Pure biodiesel produces 75 percent less greenhouse gas emissions than conventional diesel fuel and is significantly less combustible (capable of catching fire and burning), which makes it safer.

Solar energy Solar radiation is the most plentiful, permanent source of energy in the world. Energy from the Sun is nonpolluting. It can be used directly for heating and lighting, or harnessed and used to generate electricity.

The sunlight that strikes Earth provides far more power than the world's inhabitants can use. The challenge of using solar power, however, is in concentrating and storing the energy. Storage is necessary for times when the Sun is not shining, such as at night and on cloudy days. In the absence of storage capabilities, solar energy alone cannot meet all of a community's energy needs—it must be supplemented by other sources of energy.

Great strides have been made in the development of solar power technologies since the early 1970s. France, Japan, Israel, the United States, and other countries are actively seeking ways to use solar energy as a major source of power. A handful of large-scale solar power stations are operational around the world. In addition, small-scale solar power systems provide electricity to more than 250,000 households worldwide, including a growing number of isolated areas and developing countries.

One of the biggest obstacles to widespread use of solar power has been cost. At the start of the 1980s, the cost of electricity from a photovoltaic panel (device that converts sunlight to electricity) was about one hundred times more expensive than electricity from conventional power

The solar furnace in Odellio, France. ©MORTON BEEBE/CORBIS.

plants. By the end of the 1990s, the price of solar energy–generated electricity in especially sunny locations was almost the same as the price of electricity from conventional power plants. In other areas, however, solar-generated electricity was around two to five times the cost of conventional electrical power. There is also a high cost to install the systems needed to provide solar-electric energy in homes and businesses.

Despite the relatively high cost of solar-generated electrical power, demand continues to increase. The solar power industry worldwide grew at an average annual rate of 16 percent between 1990 and 1997 (in the United States the industry tripled in size during that time period). According to the Worldwatch Institute, a nonprofit organization that monitors the environment and economic development, solar power is the world's fastest growing energy source.

Passive solar collectors There are the two types of systems that collect and store the Sun's heat: passive solar collectors and active solar collectors. Passive collectors have no moving parts, while active solar collectors use pumps and motors. Passive systems are usually used for home heating and active systems are generally used for producing hot water.

Passive solar collectors operate on the simple principle that when placed in the sunlight, an object will heat up. One passive home-heating system is called a Trombe Wall. It consists a black concrete wall with air vents at the top and bottom, set on the south side of a building. A double-glazed pane of glass is placed just outside of the wall. Heat passes through the glass and becomes trapped between the glass and the wall.

Cool air from inside the room is drawn into the bottom air vents and enters the space between the wall and the glass. The air is heated, rises, and returns to the room through the top vent.

Active solar collectors Active solar collectors use pumps and motors to heat water. A solar water heater (also called a solar thermal device) is a type of active solar heating system that used to supplement a traditional home water heater. The solar water heater consists of a network of copper tubes filled with antifreeze, placed on the roof of a house. The tubes are covered with insulated black panels that absorb the heat of the Sun.

A pump circulates the antifreeze through the tubes. The antifreeze is heated as it passes beneath the rooftop panels. It then flows through a heat exchanger (also called a heat pump), an instrument that extracts the heat from the antifreeze and transfers it to water in a storage tank. The cooled antifreeze is then pumped back to the rooftop tubes.

In some active systems a fluid is heated in order to produce steam, which is then used to spin a turbine (a machine with spinning blades) and generate electricity.

Photovoltaic cells Sunlight can also be directly converted into electricity. This is accomplished with photovoltaic cells (also called solar cells). Photovoltaic cells contain semiconductor crystals, such as crystalline silicon, that conduct an electric current under certain conditions. When sunlight strikes the semiconductor, its molecular structure is altered: Electrons move about and an electric current is created.

The electric current runs through a wire on the back of the cell and either travels into a device for immediate use, into a battery where it is stored for short-term use, or into the local power grid.

Photovoltaic arrays (panels containing large numbers of photovoltaic cells) supplement traditional means of electricity production in some regions where sunlight is plentiful. Outside of San Luis Obispo, California, for example, an electricity-generating array of photovoltaic cells generates enough power to supply 2,300 homes.

Photovoltaic arrays cannot be relied upon as a community's sole source of electricity because they do not function when the Sun is not shining. There is as yet no battery or other system that can store enough energy to get through long periods of lack of sunshine.

A solar panel consisting of a large array of connected solar cells. ©ADRIAN WILSON/BEATEWORKS/CORBIS.

Uses of photovoltaic cells In some isolated locations (such as research stations), rural areas, and less-developed countries that are not serviced by power lines, photovoltaic cells provide the only source of electrical power. Some 70 percent of the solar cells produced in the United States are shipped to developing nations.

Photovoltaic cells are also used in the desert to power machines such as water pumps, air conditioners, and telephones. Some motor vehicles have been outfitted with photovoltaic cells, which provide a portion of the vehicle's power. There are also computers, lights, televisions, heaters, air conditioners, and video games that are powered, in part, by photovoltaic cells.

Some buildings receive all or some of their electricity from photovoltaic cells. One example is the Four Times Square building, a modern skyscraper in New York City. Photovoltaic panels that line the exterior walls of the upper levels, satisfying a large portion of the building's energy needs.

Solar shingles, first offered for sale in 1996, are photovoltaic arrays that can be placed on rooftops. It takes 20 square feet (1.8 square meters) of shingles to power a 100-watt light bulb. In sunny locations, solar shingles covering a roof that is at least 400 square feet (37 square meters) are capable of producing enough energy for an average household.

Solar power plants There are numerous solar power plants in sunny locations around the world, supplying electricity to surrounding communities. Two experimental, large-scale solar power plants, called Solar One and Solar Two, operated in Southern California (in the Mojave Desert, east of Los Angeles) between 1983 and 1999. Both plants were capable of producing 10 megawatts of electricity. (A watt is a unit of electric power; 1 megawatt equals 1,000,000 watts.)

Solar One was in operation from 1983 to 1988. A series of mirrors (eighteen hundred in Solar One and nearly two thousand in Solar Two) tracked the movement of the Sun across the sky. The mirrors intensified the sunlight and directed it onto a "power tower," which was a tower

Jump on the solar power bandwagon!

How can you go about installing solar power equipment on your home? There are a number of catalogs from various suppliers listing the wide variety of products available. Many of these can be installed by the do-it-yourselfer. There are also books that describe the solar goods available, tell where you can find them, and explain how to turn your home into an independent producer of heat and electricity. A backyard photovoltaic panel, for instance, costs around a thousand dollars. It connects to a home's circuit breaker. If the panel generates more electricity than used by the household, the local utility company is obliged to purchase the excess.

You can also invest in solar-powered items like AM/FM radios, attic fans, flashlights, battery chargers, portable ovens, and watches, to name a few.

covered with pipes. The fluid running through the pipes became heated; that heat was transferred to a tank of water and turned the water into steam. The steam drove a turbine and the turbine's rotating blades powered an electrical generator. (In a generator, a magnet is turned through a coil of wire and produces electricity.) The electricity was fed into the local utility grid and transported to homes, factories, and businesses.

In 1995, Solar One was converted into Solar Two. It operated from 1996 until early 1999. Solar Two operated in essentially the same manner as Solar One except that it stored solar energy in a tank of molten salt. That system enabled Solar Two to generate electricity continuously, even during nonsunshine hours. "We're proud of Solar Two's success," stated U.S. Energy Secretary Bill Richardson in a news release after Solar Two was discontinued, "as it marks a significant milestone in the development of large-scale solar energy projects. It takes us a step closer to making renewable energy a significant contributor to the global energy mix, while helping to make our environment cleaner."

Nevada Solar One, another solar power plant, shares a similar name to Solar One, however it is quite different in structure. It uses solar receivers, (heating tubes filled with liquid) instead of a power tower. Nevada Solar One is being built in Boulder City, Nevada, by the U.S. Department of Energy, the National Renewable Energy Laboratory, and a private company, and when completed in 2007, will generate 64 megawatts of electricity. Solar Tres, located in Spain, uses technology developed for Solar One and Solar Two. However, Solar Tres is three times larger than Solar Two.

Wind power The use of wind as a source of energy goes back thousands of years. Since the Middle Ages, windmills have been used to pump water and perform other types of simple mechanical work. Even today, windmills are common fixtures on American farms. In the early half of this century there were around six million such windmills used for pumping water and generating electricity. However, windmills were quickly phased out as other forms of energy became available to farmers. By the end of the 1970s, there were only about 150,000 windmills still in use on farms across the United States.

In recent years, interest in wind energy has been rekindled. This is partially due to the polluting effect and growing scarcity of fossil fuels, combined with the apparent dangers of nuclear power. Wind energy, in contrast, is nonpolluting and inexhaustible (it can never be used up). Interest in wind energy has also been driven by continuous improvements in wind turbine and windmill efficiency since the 1970s. Today, a single modern wind turbine, placed in a location where winds are a fairly constant 10 to 12 miles per hour (16 to 20 kph), can meet all the electricity needs of one home. A "wind farm," consisting of hundreds or thousands of windmills in an area with strong winds, can provide enough electricity for an entire community.

The main challenge to the widespread use of wind power is its cost. New technologies, however, are continually being developed that promise to make wind power as cost-efficient as power from fossil fuels. The cost of electricity from utility-scale wind systems has dropped by more than 80 percent over the last twenty years. The price in the United States is now lower than the cost of fuel-generated electric power in some areas. The downward trend in cost is expected to continue as larger multi-megawatt turbines are mass-produced.

Use of wind power is growing quickly. As of 2003, wind power was the fastest-growing form of electricity generation on a percentage basis in the United States. Globally, wind power generation more than quadrupled between 1999 and 2005. The world leaders in wind power production in 2007 were Germany, Spain, the United States, India, and Denmark.

Wind turbines and wind farms Wind turbines have long blades, enabling them to extract large amounts of energy from the wind. An electrical generator captures the energy of the spinning blade and converts it to electricity. The electricity travels through wires to the bottom of the tower and to an electrical substation, after which it is fed into the local utility grid.

Twenty-eight percent of the United States' wind power is generated in Texas and California. According to a U. S. Department of Energy study, the windy states of Texas, North Dakota, and Kansas could generate enough electricity with wind energy to furnish the entire nation's electricity needs.

Most of the largest wind farms in Texas are situated on high mesas in far west Texas. In this region, there is a strong prevailing wind from the west. The wind speeds up as it rises to cross these mesas, and the placement of the wind turbines along the ridge tops takes advantage of this phenomenon. Also, Texas has planned two offshore wind farms along the Gulf Coast.

Wind turbines on a hillside. ©GEORGE LEPP/CORBIS.

One of California's largest wind farms (constructed in the early 1980s) sits at the edge of a mountain gap called Altamont Pass, about 30 miles (50 kilometers) east of San Francisco. Wind is naturally funneled through the gap at high speeds. Altamont Pass contains more than seven thousand 80-foot-tall (24-meter-tall) wind turbines. Each turbine produces between 40 and 750 kilowatts of power—enough electricity for 130,000 homes (1 kilowatt equals 1,000 watts). There are also two large wind farms in Southern California, at Tehachapi and Palm Springs.

Bigger and better wind turbines Wind power developers are designing larger, more powerful wind turbines, which are able to produce electricity more inexpensively than older models. The first generation of wind turbines, produced between 1978 and 1981, had blades that were 16 feet (5 meters) long, with rotor (rotating cylindrical device consisting of blades on a shaft) diameters of 33 to 36 feet (10 to 11 meters). They were capable of producing 22 to 30 kilowatts of power. The size and capability of wind turbines has steadily increased since that time.

By the late 1990s, rotor diameters were up to 217 feet (66 meters) and turbines were generating 1.65 to 2 megawatts of power. It is estimated that wind turbines will continue increasing in size and power to the practical limit of 5 megawatts and 490 feet (150 meters) in diameter. In 2005, the largest wind turbine in the world was a 6-megawatt giant installed in Germany. It has a rotor diameter of 410 feet (126 meters).

As turbines continue to get larger and more powerful, costs of wind technology are expected to continue falling.

The future of wind power The U.S. Department of Energy estimates that offshore wind farms alone could eventually supply all of the energy needs of the United States. That estimate is as high as 30 percent for other parts of the world. In 1999, the American Wind Energy Association, a group of wind-energy producers, predicted that by the year 2005 global use of wind turbines would have increased ten-fold and wind energy will be producing 18.5 gigawatts (one gigawatt equals one billion watts) of electricity worldwide. That estimate proved to be very low. In 2005, world wind energy production was over 65 gigawatts and growing rapidly.

In 2007, more than 46,221 megawatts of wind power were being produced throughout Europe and many new projects were in the works. Germany alone has 16,000 wind turbines, mostly in the north of the country—including three of the biggest in the world—with plans for even more expansion. Canada is also investing in wind power. By early 2007, wind power (primarily in Quebec) supplied 1,451 megawatts of electricity.

Small-scale wind power also looks promising. Wind turbines have been used for household electricity generation for many decades. Some early systems were built by hobbyists working with airplane propellers and automobile generators. Recently, small commercial systems have become widely available and are in use throughout the world. Household generator units of more than 1 kilowatt are now functioning in several countries. By using a combination of wind power, photovoltaics, and battery storage, a remote village, small island, offshore platform, or Australian ranch station can be independent of grid-supplied power.

Saving the planet

With the knowledge of the most serious environmental threats presently faced by Earth and its inhabitants comes the responsibility to find solutions. In an effort to reverse the trend of environmental degradation, scientists and environmental advocates are recommending that we, as a society, do the following:

- Decrease our consumption of coal and oil
- Develop alternative forms of energy, such as solar power and wind power

A matter of survival

There are a number of ways you can reduce your energy consumption, thereby helping to make the air cleaner and reducing your contribution to global warming. Here are a few suggestions:

- Purchase compact fluorescent light bulbs. They use 40 percent less energy than incandescent (regular) light bulbs.
- Turn off lights when you leave a room.
- Make sure your home is well-insulated. One easy way to reduce heat loss in winter is to install plastic sheeting over your windows.
- Keep your thermostat below 70°F (21°C) in the winter. Wear extra clothing to keep warm.
- Shut down your computer when it is not in use.
- Convince your family to walk, ride bikes, or take public transportation instead of driving whenever possible.
- When shopping for a new appliance, look for the Energy Star label. That label indicates that the appliance has a high energy efficiency.
- Use a manual lawn mower instead of one that is fueled by gasoline or electricity.
- Recycle paper, bottles, cans, and any other items accepted by recycling companies in your region, and purchase recycled paper goods.

- Increase the efficiency of automobiles, so they can travel for more miles on each gallon of gasoline
- Stop deforestation and replant trees on cleared lands

We can each make a difference by choosing to consume less and pollute less. That means, for instance, reusing and recycling items rather than disposing of them; minimizing our use of toxic chemicals, from lawn and garden fertilizers to household cleaning agents; and switching our means of transportation, whenever possible, from cars to bicycles or buses.

[*See Also* **Climate; Climate Change and Global Warming; Weather: An Introduction**]

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