Biomes of the Earth

Deserts

Michael Allaby ILLUSTRATIONS BY **Richard Garratt**

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This book is printed on acid-free paper.

From Richard Garratt:
To Chantal, who has lightened my darkness

CONTENTS

CHAPTER 9
MANAGING THE DESERT 187

CONCLUSION 222

PREFACE

Earth is a remarkable planet. There is nowhere else in our solar system where life can survive in such a great diversity of forms. As far as we can currently tell, our planet is unique. Isolated in the barren emptiness of space, here on Earth we are surrounded by a remarkable range of living things, from the bacteria that inhabit the soil to the great whales that migrate through the oceans, from the giant redwood trees of the Pacific forests to the mosses that grow on urban sidewalks. In a desolate universe, Earth teems with life in a bewildering variety of forms.

One of the most exciting things about the Earth is the rich pattern of plant and animal communities that exists over its surface. The hot, wet conditions of the equatorial regions support dense rain forests with tall canopies occupied by a wealth of animals, some of which may never touch the ground. The cold, bleak conditions of the polar regions, on the other hand, sustain a much lower variety of species of plants and animals, but those that do survive under such harsh conditions have remarkable adaptations to their testing environment. Between these two extremes lie many other types of complex communities, each well suited to the particular conditions of climate prevailing in its region. Scientists call these communities *biomes.*

The different biomes of the world have much in common with one another. Each has a plant component, which is responsible for trapping the energy of the Sun and making it available to the other members of the community. Each has grazing animals, both large and small, that take advantage of the store of energy found within the bodies of plants. Then come the predators, ranging from tiny spiders that feed upon even smaller insects to tigers, eagles, and polar bears that survive by preying upon large animals. All of these living things form a complicated network of feeding interactions, and, at the base of the system, microbes in the soil are ready to consume the energy-rich plant litter or dead animal flesh that remains. The biome, then, is an integrated unit within which each species plays its particular role.

This set of books aims to outline the main features of each of the Earth's major biomes. The biomes covered include the tundra habitats of polar regions and high mountains, the taiga (boreal forest) and temperate forests of somewhat warmer lands, the grasslands of the prairies and the tropical savanna, the deserts of the world's most arid locations, and the tropical forests of the equatorial regions. The wetlands of the world, together with river and lake habitats, do not lie neatly in climatic zones over the surface of the Earth but are scattered over the land. And the oceans are an exception to every rule. Massive in their extent, they form an interconnecting body of water extending down into unexplored depths, gently moved by global currents.

Humans have had an immense impact on the environment of the Earth over the past 10,000 years since the last Ice Age. There is no biome that remains unaffected by the presence of the human species. Indeed, we have created our own biome in the form of agricultural and urban lands, where people dwell in greatest densities. The farms and cities of the Earth have their own distinctive climates and natural history, so they can be regarded as a kind of artificial biome that people have created, and they are considered as a separate biome in this set.

Each biome is the subject of a separate volume. Each richly illustrated book describes the global distribution, the climate, the rocks and soils, the plants and animals, the history, and the environmental problems found within each biome. Together, the set provides students with a sound basis for understanding the wealth of the Earth's biodiversity, the factors that influence it, and the future dangers that face the planet and our species.

Is there any practical value in studying the biomes of the Earth? Perhaps the most compelling reason to understand the way in which biomes function is to enable us to conserve their rich biological resources. The world's productivity is the basis of the human food supply. The world's biodiversity holds a wealth of unknown treasures, sources of drugs and medicines that will help to improve the quality of life. Above all, the world's biomes are a constant source of wonder, excitement, recreation, and inspiration that feed not only our bodies but also our minds and spirits. These books aim to provide the information about biomes that readers need in order to understand their function, draw upon their resources, and, most of all, enjoy their diversity.

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INTRODUCTION

What is a desert?

Sand dunes as high as hills stretch into the distance for as far as the eye can see. Above them, the clear sky is pale blue, the Sun small and blazing intensely. A wind drives grains of sand that sting the face, but it is a hot wind that brings no relief from the Sun's scorching rays. Nothing lives in this barren place and nothing could. There is no water. This is a desert.

At least, it is one kind of desert, the kind they show in movies, and the description contains one important mistake. Deserts usually look empty—deserted, in fact—but this does not mean they are uninhabited. During the middle part of the day, when the Sun is high in the sky, animals shelter from the heat. You may see signs of them around dusk and dawn. That is when they seek food. Even during the heat of the day, however, there are traps awaiting any unwary insect or small mammal that should venture abroad. Spiders, scorpions, snakes, and other hunters lie hidden, still, silent, and invisible, but ready to leap or launch a lethal strike at any victim that comes within range.

There are plants too. Plants cannot grow on the sand dunes, because the surface is too unstable for their roots to gain a secure hold, but there are a few shrubs scattered sparsely on the firmer ground. Many more plants lie below ground, waiting as seeds for the occasional rain that will supply enough moisture for them to sprout, grow, flower, and produce seed, all in the brief interval before the ground dries out again.

There are even people living not far away. Groups of them pass this way from time to time. Some ride in trucks, or occasionally on camels, carrying goods to be sold in a market in some distant town. Others walk beside their herds of sheep, goats, cattle, or camels. Their animals have exhausted the pasture in one area and they are on their way to another. The desert is not so deserted as it seems.

Sandy deserts certainly exist, but most deserts are not vast oceans of sand. They are rocky, with a hard surface covered with stones and gravel and outcrops of bare rock. Deserts are windy places and over thousands of years the wind blows away all the dust and sand, exposing the underlying rock and leaving the stones that are too heavy for the wind to lift. In some deserts there are rocks carved by the wind into fantastic shapes. The sand must go somewhere, of course. It piles up to form dunes, but the dunes are constantly shifting as the restless wind ceaselessly rearranges the landscape.

Nor are all deserts hot. Even those that are hot by day are often very cold at night, but some deserts are cold for most of the time. They comprise vast expanses of dry, windswept plains dotted with patches of coarse grasses and tough, thorny shrubs. Deserts of this type are found in the centers of continents, thousands of miles from the ocean. There are also deserts lying beside coasts, where fog is common but rain is extremely rare.

A coastal desert is not far from water, but the ocean might as well be a million miles away, because its waters hardly ever fall on the land. Other deserts are even closer to water that no plant root can absorb.

Most of Antarctica and Greenland are covered by ice that is an average 6,900 feet (2.1 km) thick in Antarctica and up to 10,000 feet (3 km) thick in Greenland. This is a vast amount of water, but it is useless to plants because it is frozen. The polar ice sheets have accumulated slowly over millions of years, from snow that fell but failed to melt. Only a very small amount of snow falls each year, but it is enough to replace the ice that slides into the ocean, drifts away as icebergs, melts, and is lost. Antarctica and Greenland are deserts.

They are all very different: The vast, blistering sand seas, the rocky desert, the cold continental plain, the coastal desert, and the polar ice caps. Yet, different as they are, there is one characteristic they share. All of them have a dry climate.

It is the dry climate that produces a desert, rather than the temperature. Deserts can be hot or they can be cold, but they cannot be wet. All of them are arid wildernesses.

Aridity—dryness—does not result simply from a low average rainfall. Temperature also plays a part. What matters is not the amount of water that falls from the sky, but the amount that is available to plant roots below ground.

As soon as raindrops fall from the base of the cloud that produced them, they enter relatively dry air and begin to evaporate. Some of the water evaporates before even reaching the ground. This is common everywhere in the world. Evaporation continues when the water does reach the ground, so that only a portion of the rain soaks into the ground to the region where plant roots can reach it.

Snow will vaporize in dry air without melting first. This is called *sublimation,* and it removes some of the snow as it falls and also some of the snow lying on the ground. If snow melts after it has fallen, some of the water will evaporate.

Water evaporates when the air is dry. The amount of water vapor that air can hold increases as the temperature rises, so water evaporates faster into warm air than into cold air. As water evaporates, the layer of air next to the water surface becomes very moist. Wind sweeps away this moist air and replaces it with drier air into which more water can evaporate. That is how the wind exerts the drying effect we make use of when we hang laundry outdoors to dry.

Warm temperatures and wind accelerate evaporation. This means that the rate of evaporation varies from place to place. Evaporation removes water before plants can derive benefit from it. A desert will form wherever the amount of water reaching the ground in the course of the year is insufficient to replace the amount that could evaporate over the same period, so that the ground remains dry for most of the time. Plants benefit from occasional heavy rain, but the moisture soon evaporates and, despite being briefly carpeted in flowering plants, the desert remains desert.

CHAPTER 1

GEOGRAPHY OF DESERTS

Where deserts are found today

Cameras mounted on orbiting satellites photograph every part of the Earth at frequent intervals and broadcast the pictures to receiving stations on the ground. Many of the photographs are taken in light at infrared wavelengths. Our eyes cannot detect infrared light, but plants reflect it strongly and it makes them appear red in photographs. Scientists use these false color satellite photographs to measure the areas of the Earth that are covered with vegetation and also those that are not—the deserts and semiarid regions that are almost deserts.

The result is startling. They show that deserts like the Sahara, Arabian, and Gobi Deserts cover approximately one-fifth of the land surface of our planet. When the polar deserts are added the total is close to 30 percent. In addition to these extremely dry deserts, there are also areas that support a little vegetation and receive some rain in most years. They are not quite deserts, but they are dry for most of the year. These areas occupy about 28 percent of the Earth's land surface. When all of these desert and desertlike areas are added together, the total amounts to about 58 percent of the land area of our planet—approximately 33 million square miles (86 million km^2).

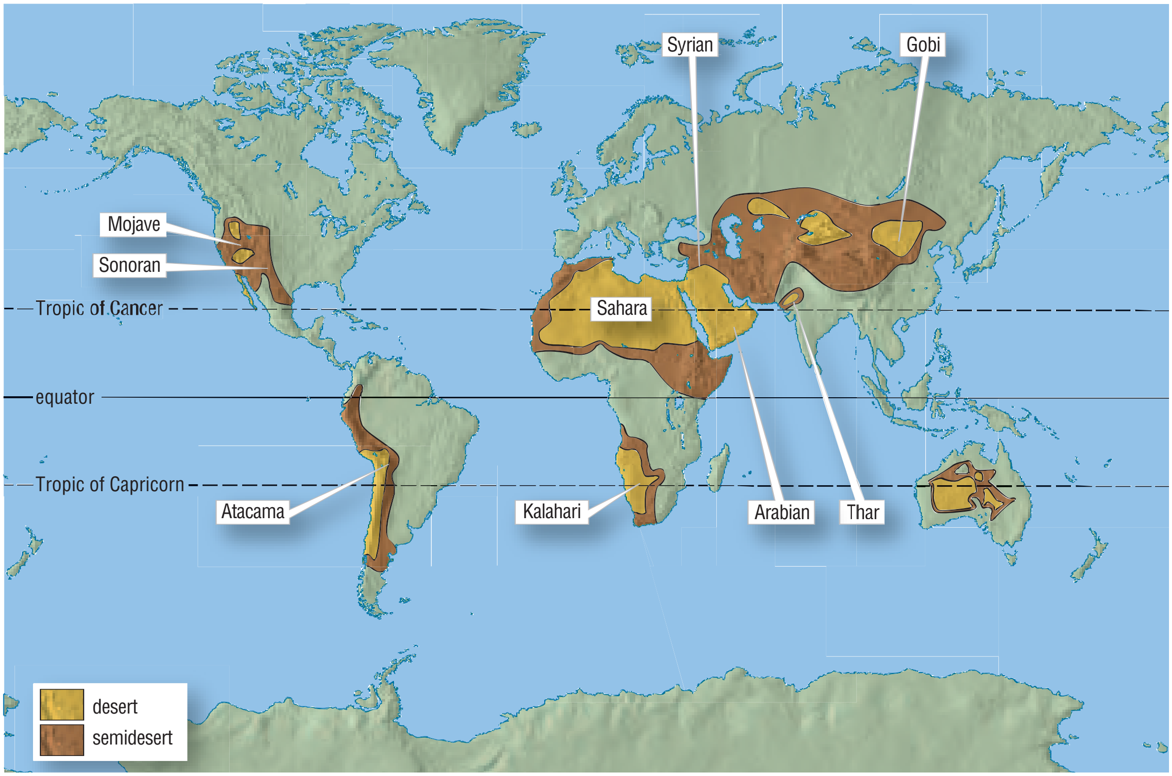
As the map on page 2 illustrates, there are deserts in every continent. The Mojave and Sonoran are the principal North American deserts. There is also a large area of semidesert to the west of the Great Salt Lake, Utah, centered on latitude 40°N. The Mojave Desert, in California, lies approximately between latitudes 34°N and 37°N, to the southeast of the Sierra Nevada. The Sonoran Desert, also known as the Yuma Desert and in the north as the Colorado Desert, is the largest North American desert, lying partly in Arizona and California, and partly in Sonora Province, Mexico.

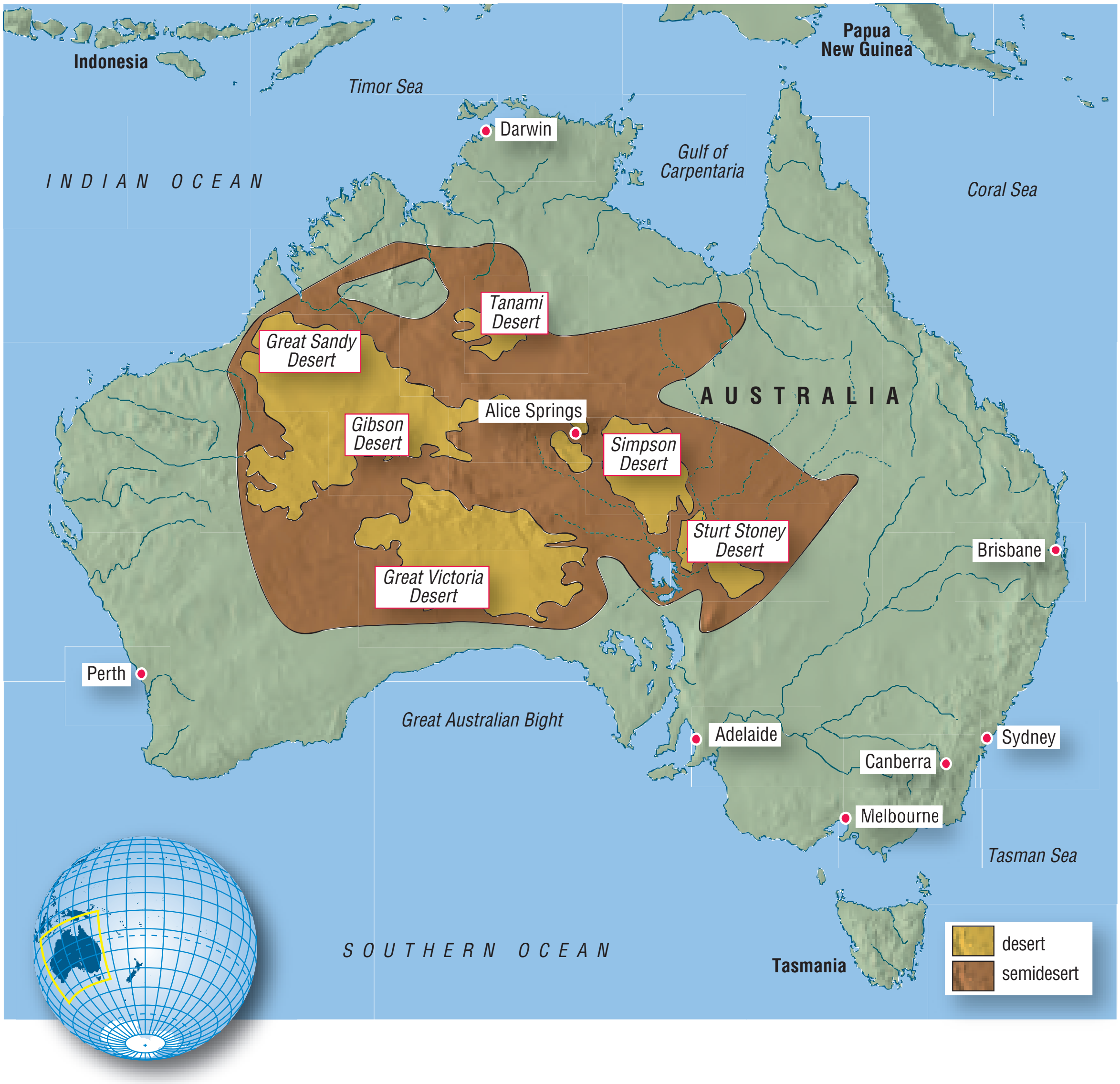
In South America the Atacama Desert, running parallel to the coast of Chile between latitudes 5°S and 30°S, is the world's driest desert. The Patagonian Desert covers all of Argentina to the east of the Andes and south of the Colorado River, at latitude 39°S.

The Sahara is the world's biggest desert. It covers most of Africa north of latitude 15°N. Desert conditions continue eastward through Ethiopia and Sudan, and across the Red Sea, where the Arabian Desert covers the whole of the Arabian Peninsula, and to its north the Syrian Desert covers much of the Middle East. South of the equator, the Kalahari Desert extends from the tropic of Capricorn to about 27°S. To its west, the Kalahari merges into the Namib Desert—almost as dry as the Atacama—that runs along the coast of Namibia.

There are several deserts in central Asia. The largest and most famous is the Gobi, centered on latitude 40°N. To its west there lies the Taklimakan, or Takla Makan, Desert, con-

Location of the world's deserts. Regions of semidesert occupy a much bigger area.





The five Australian deserts: the Great Sandy, Gibson, Great Victoria, and Simpson Deserts, and the Nullarbor Plain

sisting mainly of drifting sand dunes. These deserts are located to the north of the Himalayas. To the south, in India, there is the Thar, or Great Indian, Desert.

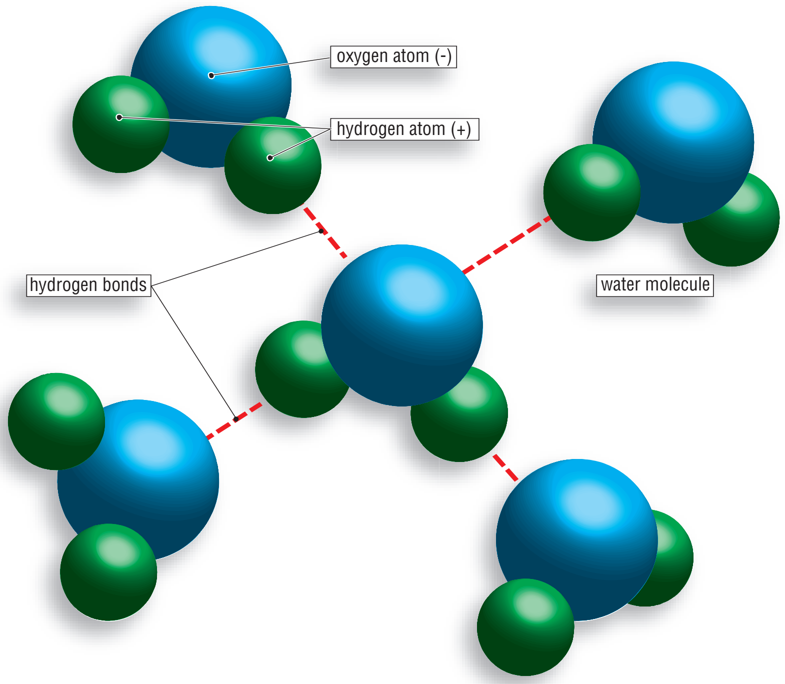
Deserts cover a large part of the western side of the Australian interior. The tropic of Capricorn passes through the center of the Australian deserts. There is not one Australian desert, but five. The map shows their locations. The Great Victoria Desert is the largest, stretching across much of Western Australia and South Australia. To its south, the Nullarbor Plain is also desert, and the Gibson Desert lies to its north. The Simpson Desert is farther to the east, lying to the north of Lake Eyre, a large salt lake and, at about 60 feet (18 m) below sea level, the lowest point in Australia.

How deserts form

Deserts form when the climate becomes warmer or drier. The two are not always the same, because if the temperature rises more water will evaporate from the oceans. There will be more cloud and more rain. So a warmer climate is usually a wetter climate. A fall in temperature will reduce the rate of evaporation. There will be less cloud and less rain. The climates of the world were very much drier during the last Ice Age than they are today.

It sounds, then, as though warmer weather should make deserts shrink, but this is not necessarily the case. Warmer weather increases the rate of evaporation, but if the evaporation rate increases more than the rainfall, then the ground will become drier despite the rainfall having increased. Higher temperatures also reduce the rate at which water vapor condenses. As it grows warmer, the air is able to hold more moisture as water vapor, so although the amount of moisture in the air increases, less cloud forms and rainfall decreases. Deserts are more likely to form if the climate becomes cooler, but they may form if average temperatures increase.

Liquid water (H_2O) consists of groups of water molecules that are held together by *hydrogen bonds* between the hydrogen (H) atoms of one molecule and the oxygen (O) atoms of two adjacent molecules. The illustration on page 5 shows how hydrogen bonds link molecules. The groups of molecules move around and slide past one another, and the individual molecules vibrate. If the temperature rises the molecules have more energy. They vibrate more vigorously and the groups move faster. As the temperature continues to rise, more and more molecules absorb sufficient energy to break free from the hydrogen bonds and escape into the air as separate molecules of water vapor.



Hydrogen bonds. Hydrogen bonds form between the positive charge at the hydrogen end of the water molecule and the negative charge at the oxygen end of adjacent molecules.

While this is happening, molecules of water vapor are also striking the surface of the liquid water and merging into it, so water molecules are both leaving and entering the liquid. If more molecules leave the liquid than enter it, the water evaporates, and the higher the temperature the faster is the rate of evaporation, because the molecules have more energy.

When water evaporates, the air pressure rises because of the water molecules that have entered it, and it increases as more and more water molecules escape into the air. The increase is called the *vapor pressure,* because it is the proportion of the total air pressure that is due to water vapor. Increasing the vapor pressure also means that more molecules are pushed back into the liquid, however. Eventually a point is reached when the number of water molecules entering the liquid is equal to the number leaving. In other words, evaporation and condensation balance. The vapor pressure has then reached the *saturation vapor pressure* and the mixture of air and water vapor is *saturated.*

If the temperature of the air and water rises, the rate of evaporation increases. More water enters the air and the saturation vapor pressure increases. This means that the vapor pressure must reach a higher value before condensation catches up with evaporation, and it is why warm air is able to hold more water vapor than cold air can. The difference is startling. At sea-level pressure and freezing temperature, 32°F (0°C), one pound of dry air can hold 0.27 ounces of water vapor (3.5 g/km). At 86°F (30°C) one pound of air can hold two ounces of water vapor (26.5 g/km), and at 104°F (40°C) it can hold 31.5 ounces (47 g/km). At a temperature of –40°F (–40°C), in contrast, one pound of dry air can hold only 0.008 ounce of water vapor (0.1 g/km).

The amount of water vapor present in the air is known as the *humidity*. This can be measured in several ways, described in the sidebar, but the most widely used measure is *relative humidity* (RH). This is the amount of water vapor expressed as a percentage of the amount needed to saturate the air. As the temperature rises, so does the saturation vapor pressure, and the RH falls. No moisture has been added to the air or removed from it, but the higher saturation vapor pressure means that the air is effectively drier. If the temperature is 32°F (0°C), for example, and the RH is 57 percent, warming the air to 86°F (30°C) will reduce the RH to 7.5 percent. The actual amount of moisture in the air remains the same, but the air has become very much drier.

As the ground dries, plants begin to wilt. At first they will recover if there is a heavy shower of rain, but after a time without water they are beyond hope of recovery. The plants wither and die. Their roots slowly decay, leaving the soil without the countless millions of root fibers that bound soil particles together. The soil loses its structure. Clay soils dry out and crack until the ground is hard as concrete, with deep, narrow fissures. Silt soils turn to dust, sandy soils into fine grains. Dust and grains blow in the wind. They fall on land nearby, coating plants or even burying them, killing those plants and allowing more soil to bake or crumble to dust. This is how the desert spreads.

Humidity

The amount of water vapor air can hold varies according to the temperature. Warm air can hold more than cold air. The amount of water vapor present in the air is called the *humidity* of the air. This is measured in several ways.

The *absolute humidity* is the mass of water vapor present in a unit of volume of air, measured in grams per cubic meter (one gram per cubic meter = 0.046 ounces per cubic yard). Changes in the temperature and pressure alter the volume of air, however, and this changes the amount of water vapor in a unit volume without actually adding or removing any moisture. The concept of absolute humidity takes no account of this, so it is not very useful and is seldom used.

Mixing ratio is more useful. This is a measure of the amount of water vapor in a unit mass of dry air—air with all the water vapor removed. *Specific humidity* is similar to mixing ratio but measures the amount of water vapor in a unit mass of air including the moisture. Both are reported in grams per kilogram. Since the amount of water vapor is always very small, seldom accounting for more than 4 percent of the mass of the air, specific humidity and mixing ratio are almost the same thing.

The most familiar term is *relative humidity.* This is the measurement you read from hygrometers, either directly or after referring to tables—and it is the one you hear in weather forecasts. Relative humidity (RH) is the amount of water vapor in the air expressed as a percentage of the amount needed to saturate the air at that temperature. When the air is saturated the RH is 100 percent (the "percent" is often omitted).

Climate changes of the past

Libya is a vast country. Coastal cities such as Benghazi and Tripoli receive a little rain in winter, but the interior of the country lies inside the Sahara, where it hardly ever rains. The climate was not always so dry, however. In the Tibesti Mountains, on the border between southeastern Libya and Chad (see the map on page 10), there are caves containing wall paintings that were made between 7,000 and 8,000 years ago. The artists were hunters, and their pictures portray the elephants, hippopotamuses, antelope, deer, giraffes, buffalo, and crocodiles that they pursued. Some of the pictures depict people traveling in a type of canoe.

Elephants survived in North Africa until much later. Hannibal (247–183 or 182 B.C.E.), the Carthaginian general who fought against the Romans, used about 38 elephants in one of his campaigns and in 218 B.C.E. they crossed the Alps to invade Italy from the north—though few of them survived the journey. In Hannibal's day, elephants still lived wild in the forests and grasslands of Carthage (modern Algeria), isolated from the main elephant population in the south.

Lake Chad is in the southern Sahara. The map below shows its location. After rain has fallen the lake covers an area of about 10,000 square miles (25,900 km^2). But nowhere is it more than 20 feet (6 m) deep, and between rains its area shrinks, sometimes to as little as 4,000 square miles (10,360 km^2). About 5,000 years ago, however, Lake Chad was an inland sea, in places more than 150 feet (45 m) deep. The shores of that ancient sea can still be identified and the desert

Lake Chad. Situated in the west of Chad, this was once an inland sea.

sands still contain the bones of fish that swam in it. Obviously, the climate was much wetter then.

Changes in climate make deserts appear and vanish, and the Sahara is not the only desert to be affected. A prolonged period of warm, wet weather affecting a large area is known as a *climatic optimum*. The hunters of the Tibesti Mountains lived during what was probably the warmest and longest climatic optimum since the end of the most recent Ice Age. It lasted from about 10,000 to 4,000 years ago and its effects were felt throughout the world. Between 6,000 and 4,400 years ago the rainfall was heavy enough to cause flooding in several ancient cities of the Middle East, including Ur and Nineveh, in modern Iraq. Australia had a much wetter climate than it does today, and about 4,000 years ago farmers were growing melons, dates, wheat, and barley in what is now the Thar Desert, on the border between India and Pakistan, where the annual rainfall was 16–32 inches (400–800 mm). Today the Thar Desert receives five to 10 inches (127–254 mm) a year.

Between about 4,500 and 3,700 years ago, as that optimum was nearing its end, a civilization was flourishing to the west of what is now the Thar Desert, in the Indus Valley, centered on the cities of Mohenjo Daro and Harappa (see the map on page 11). The annual rainfall then was 16–30 inches (400–760 mm). Today it is about 3.5 inches (89 mm).

There was another climatic optimum in Roman times, when North Africa was called the "granary of Rome." Outlines of the fields can still be seen from the air in what is now sandy desert. Rain fell at Alexandria, Egypt, in every month of the year except August. Today no rain falls at Alexandria from the end of April until early in October, and the annual rainfall averages only seven inches (178 mm).

During the Middle Ages, from the 10th to 14th centuries, there was another warm period. That is when the biggest Native American city north of Mexico was built and flourished. Its remains can be seen at the Cahokia Mounds State Park, to the east of St. Louis, Missouri.

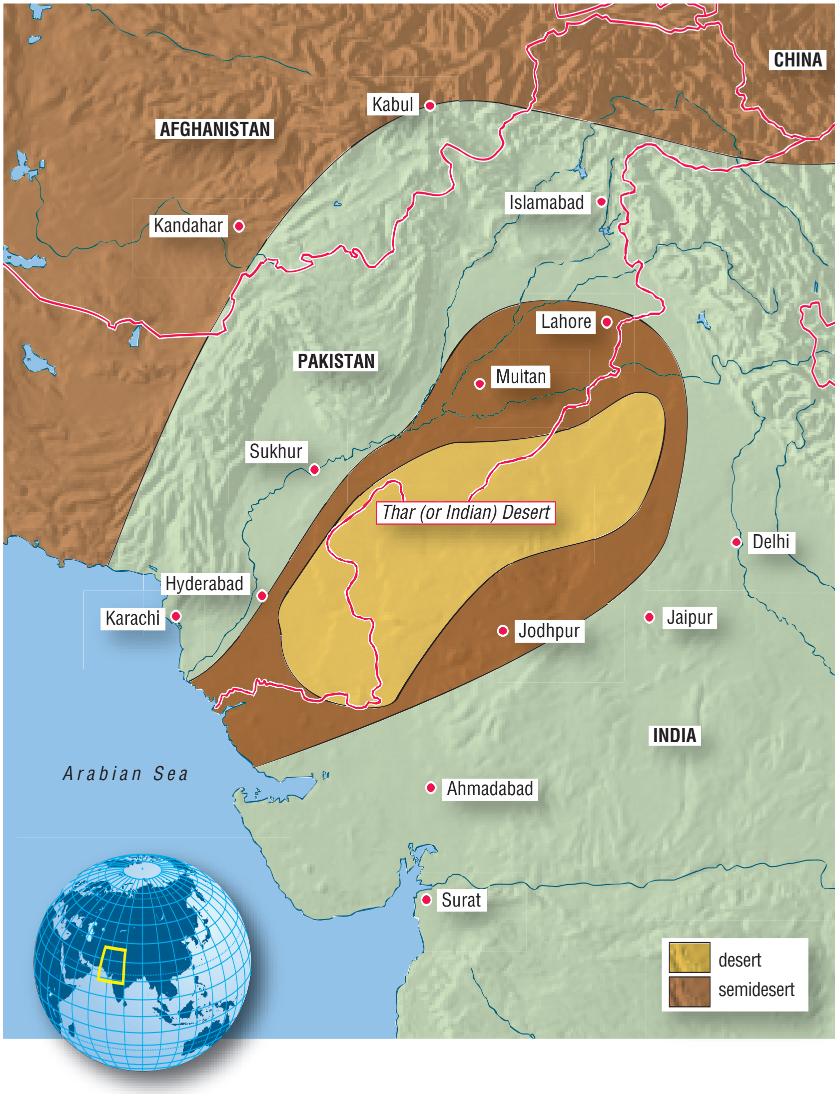
Climates are changing constantly. As they change, deserts advance and retreat and, in response, civilizations have risen, flourished, and fallen.

Subtropical deserts

Sahrá is an Arabic word meaning "wilderness" and it gives its name to the Sahara, a wilderness that covers more than 3.5 million square miles (9.1 million km^2), making it the biggest of the subtropical deserts. As the map below shows, parts of the Sahara are mountainous. Mount Tousidé in the Tibesti Mountains is an extinct volcano rising to 10,712 feet (3,265 m). Elsewhere there are low-lying basins, but much of the desert is on a plateau 1,300–1,600 feet (395–490 m) above sea level. The desert is conventionally divided into Atlantic, northern, central, southern, and eastern areas. The large Eastern Sahara is further divided into the Libyan and Nubian Deserts. The desert to the east of the Nile River in Egypt is considered part of the Arabian Desert. The Sahara continues to the east as the Arabian Desert, occupying virtually the whole of the Arabian Peninsula and the Syrian Desert, covering much of the Middle East.

As the name suggests, the subtropical deserts are centered on the tropic of Cancer in the Northern Hemisphere and the tropic of Capricorn in the Southern Hemisphere. Due to the way the continents are arranged over the surface of the Earth, there is less land in the Southern Hemisphere than in the Northern, and consequently the southern subtropical deserts occupy a smaller area than do those of the north.

The Sahara



Thar, or Great Indian, Desert, in northwestern India

A range of mountains, rising in some places to more than 9,000 feet (2,745 m) above sea level, runs down the western side of Arabia, parallel to the Red Sea coast. The central part of Arabia, to the east of the mountains, is called the *Najd* ("highland"). To the south of the Najd lies the largest sandy desert in the world, called the *Rub' al-Khali,* "the empty quarter," and covering about 230,000 square miles (595,700 km^2). The desert to the north of the Najd is called *An Nafud*. The name simply means "desert," but An Nafud is also called the Great Sand Desert. It has fewer watering places than the Rub' al-Khali and is more difficult to cross. *Ad Dahna',* a line of high sand dunes about 50 miles (80 km) wide—sometimes called a sand stream—stretches for about 800 miles (1,290 km) from An Nafud to the Rub' al-Khali, separating the Najd from eastern Arabia.

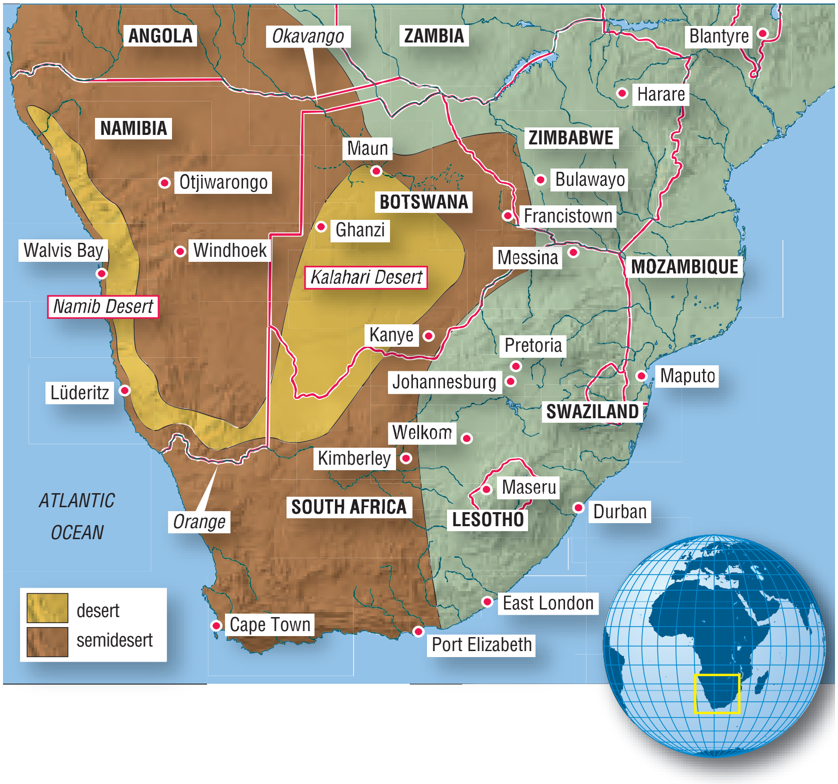
Extending northward from An Nafud, the Syrian Desert covers western Iraq, eastern Jordan, and southeastern Syria. Its Arabic name is *Badiyat Ash Sham,* which means "arid wasteland." It is a mixture of true desert and poor grassland.

Farther to the east, across the Arabian Sea, the Thar, or Great Indian, Desert covers about half of the Indian state of Rajasthan and part of eastern Pakistan. The map shows its location. The Thar is a sandy desert—*thar* means "sandy waste"—covering about 77,000 square miles (199,430 km^2).

The Kalahari Desert, in southern Africa, and the Australian deserts are the subtropical deserts of the Southern Hemisphere. The Kalahari covers about 275,000 square miles (712,250 km^2) and the Australian deserts about 1.3 million square miles (3.4 million km^2).

The map shows the location of the Kalahari, a desert that is not quite so dry as most subtropical deserts. Its annual rainfall ranges from 10 inches (254 mm) in the south to 25 inches (635 mm) in the north, although the eastern part of the desert receives only about five inches (127 mm) of rain a year. The Australian deserts receive less than 10 inches (254 mm) of rain a year. In both the Kalahari and Australian deserts the rate of evaporation is high enough to ensure that the ground is dry most of the time.

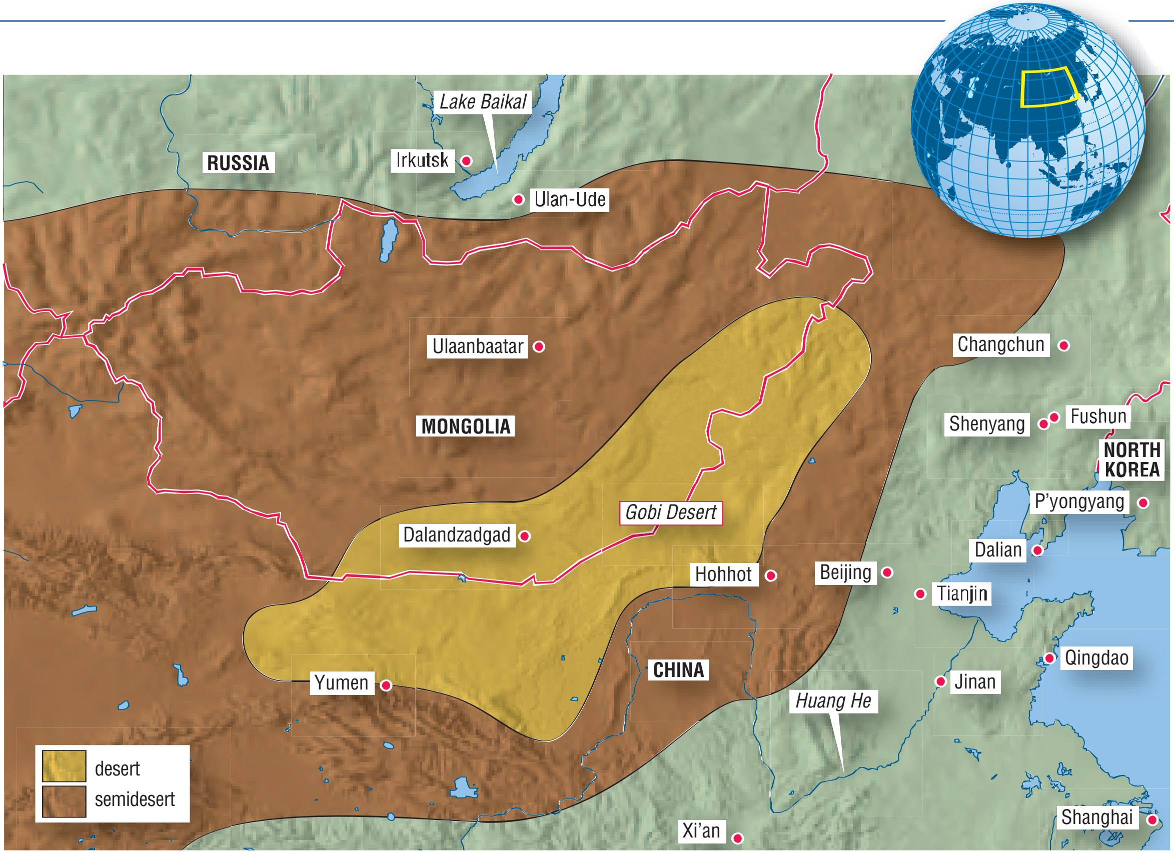
All of the subtropical deserts experience very high temperatures by day, but they can be very cold at night. At Timbuktu, Mali, for example, in the southern Sahara, average summer temperatures reach 110°F (43°C), but temperatures have been known to fall close to freezing on winter nights. In Salah, Algeria, it is even hotter, with July temperatures averaging 113°F (45°C) and sometimes rising to 122°F (50°C), but in winter the temperature at night sometimes falls below freezing. Frost is quite common in winter in many parts of Syria. The hottest place on Earth is El Azizia, Libya, where on September 13, 1922, the temperature rose to 136°F (57.8°C).



Kalahari Desert, in southern Africa

Deserts of continental interiors

At Ulan Bator (Ulaanbaatar), the capital of Mongolia, the temperature has been known to fall below freezing even in the middle of summer. Ulan Bator is situated on the central Asian steppe grasslands, but it is not far from the northern boundary of the Gobi Desert. There are no published weather records from the mining town of Dalandzadgad in the eastern Gobi, but Jiayuguan, on the southern border of the desert, has a dry climate. Almost no rain falls between October and February, and the average rainfall between March and September is 2.7–3.4 inches (69–86 mm). Winters are cool, with January average daytime temperatures of 27–30°F (from –3°C to –1°C); temperatures at nightfall to about 3–7°F (–16 to –14°C). Summers are warm, but not intensely hot. July is the warmest month in Jiayuguan, with daytime temperatures of 83–86°F (28–30°C). Hohhot, a town close to the eastern boundary of the Gobi, has an average temperature of 9.1°F (–12.7°C) in January and 72.7°F



Gobi Desert, in southern Mongolia and the Chinese autonomous region of Inner Mongolia

(22.6°C) in July. The Gobi occupies a plateau, about 3,000 feet (914 m) above sea level in the east and 5,000 feet (1,524 m) in the west, surrounded by mountains. Its surface is mostly bare rock and gravel but with sand dunes in some places.

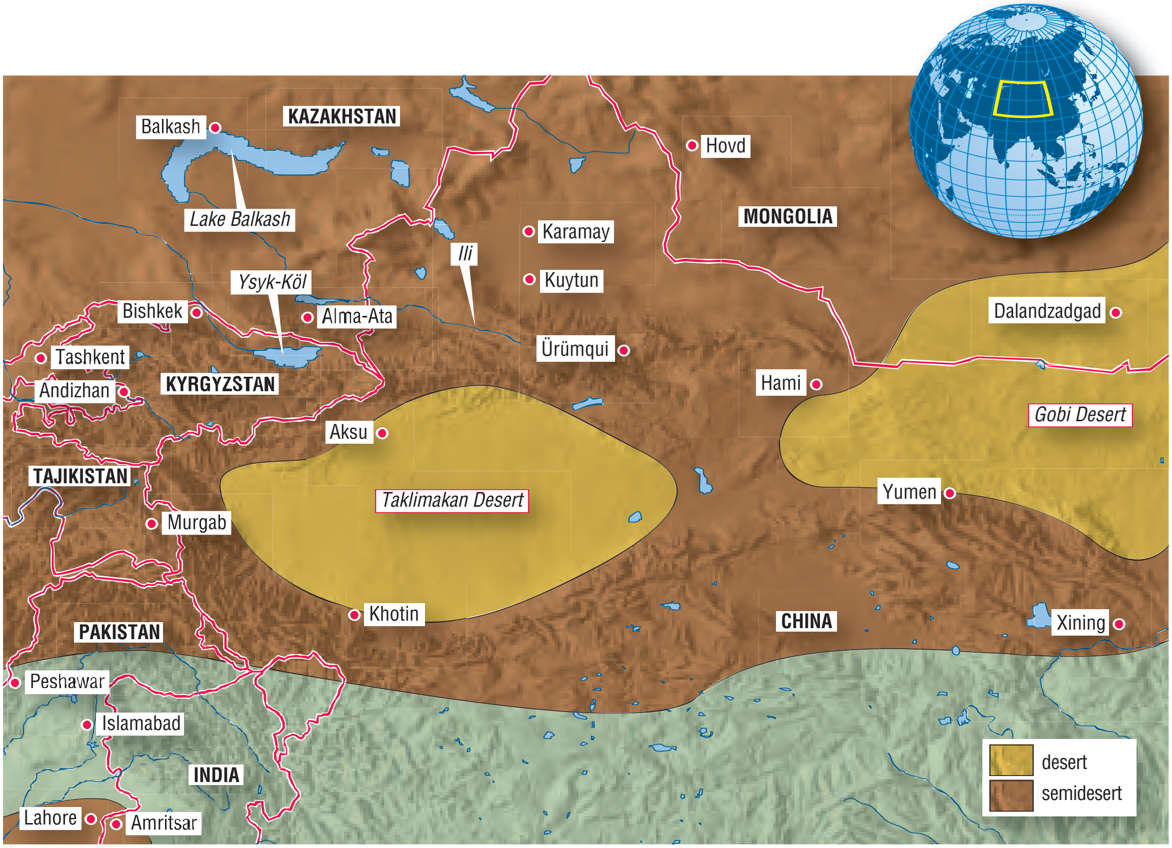
The total area amounts to about 500,000 square miles (1.3 million km^2). Part lies in southern Mongolia and part in the Inner Mongolia Autonomous Region of China. The map above shows its location. Although the center of the Gobi receives only one to two inches (25–50 mm) of rain a year, about three-quarters of the total area supports grass, thornbushes, and other shrubs. Hohhot receives almost 16 inches (406 mm) of rain a year (some falling as snow).

The Gobi is desert and semidesert because of its great distance from the ocean. It is a desert of the type found in the deep interior of large continents outside the Tropics.

West of the Gobi there is another, much drier desert, the Taklimakan, or Takla Makan, covering most of the Tarim Basin, a low-lying area adjoining the Tarim River, in the Xinjiang Uygur Autonomous Region of China. The map below shows its location. It is a sandy desert with large dunes, some as much as 300 feet (91 m) high, covering an area of about 105,000 square miles (272,000 km^2).

The climate is very dry. The western part of the desert receives an average of 1.5 inches (38 mm) of rain a year, but in the east the average is only 0.4 inch (10 mm). Sandstorms are common and often last for several days. It is also cool. Although the temperature sometimes rises to 100°F (38°C) the average July temperature is 77°F (25°C). In winter the temperature averages 14–16°F (–10°C) and it sometimes falls to –4°F (–20°C). There is some vegetation around the edges of the Taklimakan, but nothing lives in the inhospitable interior.

Taklimakan Desert, in western China, lies to the west of the Gobi Desert and to the north of Tibet.



Patagonia is the Southern Hemisphere counterpart of the Gobi and Taklimakan. A desert occupying the interior of a continent, it covers all of Argentina to the east of the Andes and south of the Colorado River, at 39°S. Its total area is about 300,000 square miles (777,000 km^2).

Although its climate is wetter than that of the Gobi and Taklimakan, nowhere in Patagonia receives as much as 10 inches (254 mm) of rain a year and little more than five inches (127 mm) a year falls in the central region. Average temperatures in central Patagonia range from 45°F (7°C) in July to 78°F (26°C) in January, but they have been known to rise to 99°F (37°C) in summer and to fall to 3°F (–16°C) in winter.

Patagonia is dry because weather systems arriving from the west lose their moisture as they cross the Andes. The desert lies in the *rain shadow* of the mountains. The Mojave Desert, in North America, is produced in the same way. It covers an area of 15,000 square miles (38,850 km^2) to the south and east of the Sierra Nevada (see the map on page 18). The average rainfall is less than five inches (127 mm) a year, but there are woodlands in the mountains and cattle graze in parts of the desert. Summer temperatures often rise above 100°F (38°C). Winter temperatures average about 55°F (13°C) by day, but at night they fall to well below freezing.

West coast deserts

Patagonia is unusual in lying on the eastern side of the continent. Its climate is dry because weather systems approach it from the west. Mild, moist air from the ocean rises to cross the Andes and loses its moisture on the western side of the mountains. By the time the air reaches Patagonia it is able to deliver only a very small amount of rain.

Deserts in the subtropics more often form on the western sides of continents. This is because there the prevailing winds blow toward the equator, bringing cool, dense air that remains close to the ocean surface and prevents moist air from rising and forming clouds. During the day, the land warms up rapidly, but the sea remains cool. Warm air rises over land and cooler air blows in from the sea to replace it. This is a sea breeze, and sea breezes blow on most afternoons

North American deserts

in many parts of the subtropics, but the approaching air has to cross cool ocean currents that flow parallel to the western coasts of continents (see "Ocean gyres and boundary currents" on pages 56–58). Contact with the cold water lowers its temperature, so the air tends to subside rather than rising. These climatic conditions produce *west coast deserts*.

The North American deserts, shown on the map above, are produced in this way, by air that has crossed the cool California Current. The Colorado Desert is part of the Sonoran Desert, also called the Yuma Desert and the Desierto de Altar. The Sonoran Desert covers 120,000 square miles (310,800 km^2). Most of the area is low-lying. The bed of the Salton Sea, a brackish lake in the Colorado Desert, is 235 feet (72 m) below sea level, but the average elevation in the Sonoran Desert is 1,000 feet (305 m). The annual rainfall ranges from about four inches (102 mm) to more than 10 inches (254 mm) in a few places. Summers are hot, with temperatures that average 90°F (32°C) and can reach 125°F (52°C). Winter days are mild and the nights are cool.

The Atacama, the driest of all west coast deserts, extends for about 600 miles (965 km) parallel to the coast of Chile

Atacama Desert, in Chile. This is the world's driest desert.

and has an area of about 140,000 square miles (363,000 km^2). The map above shows its position. Air arriving from the ocean loses some of its moisture when contact with the Peru Current lowers its temperature, and it loses the remainder as it crosses the coastal mountains. Most of the Atacama lies in a depression behind the mountains. Along the coast, the average annual precipitation amounts to about 0.4 inch (10 mm), although it arrives as fog, not rain. Iquique, in the north, received an average of 0.06 inch (1.5 mm) of rain a year over a period of 21 years, including four years when no rain fell at all. Arica received less than 0.03 inch (0.75 mm) a year over 19 years. Despite being so dry, however, the air is very humid (see the sidebar "Humidity" on page 7). Iron corrodes rapidly.

The Atlantic Desert, on the western side of the Sahara, is a west coast desert associated with the cool Canary Current, and there is another west coast desert in southern Africa, associated with the Benguela Current. This is the Namib Desert (shown on the map of the Kalahari Desert on page 13), separated from the Kalahari by hills, except in the south where the two deserts meet, and covering about 19,300 square miles (50,000 km^2).

Walvis Bay, on the coast about halfway along the approximately 932-mile (1,500-km) length of the Namib and about 50 miles (80 km) north of the tropic of Capricorn, receives an average of 0.8 inch (20 mm) of rain a year. The average for the desert as a whole is about two inches (51 mm) a year. Low clouds often drift in from the sea at night, bringing fog or light drizzle that clears quickly in the morning. The Namib is a very dry desert but not an especially warm one, despite its latitude. The average temperature at Walvis Bay is 66–75°F (19–24°C) throughout the year. Gravel covers the surface in the northern part of the Namib, but in the south there is a sand sea (see "Sand seas and sand dunes" on pages 37–41) with the highest dunes in the world. Some rise to almost 1,000 feet (305 m).

Polar deserts

As the air temperature falls, more and more water vapor condenses. Eventually the air is so cold that it contains almost no water vapor—it has been "squeezed dry." Greenland (Kalaallit Nunaat) and Antarctica are the coldest places on Earth. Because they are so cold they are also among the driest. They are polar deserts.

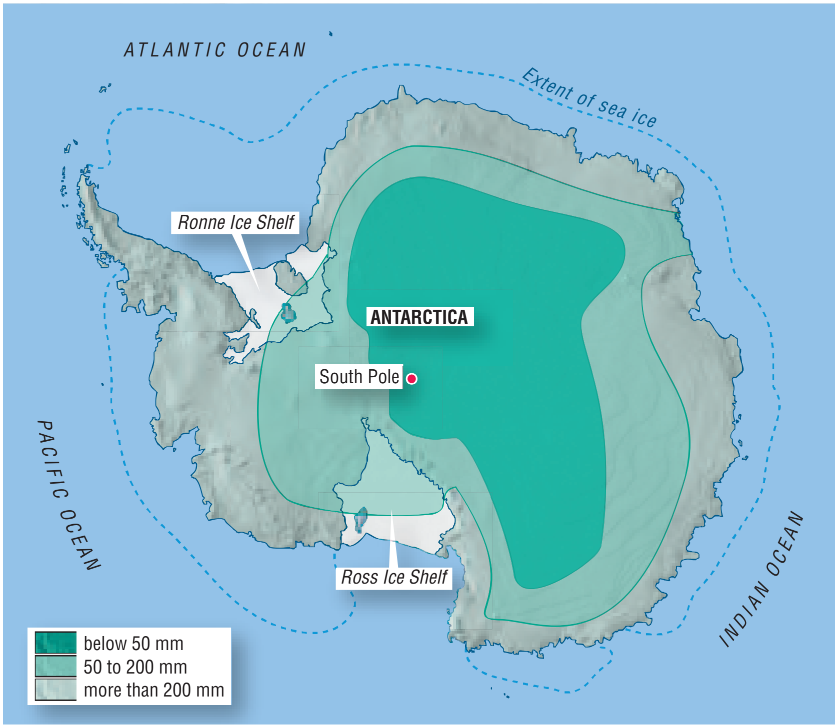
A team of German scientists spent the winter of 1930–31 on top of the Greenland ice cap studying weather conditions. They were the first people ever to overwinter on the ice and they recorded an average temperature of –52.9°F (–47.2°C) in February. In July the temperature never rose above 12.8°F (–3°C). Scientific expeditions have returned to the ice cap several times since then and have confirmed these temperatures.

Central Greenland is covered by ice that on average is about 5,000 feet (1,525 m) thick and more than 8,000 feet

(2,440 m) thick at its deepest point. Ice is frozen water, but this abundance of water is misleading. The climate is extremely dry, even for a desert. About three inches (76 mm) of snow falls each year. Snow takes up more space than liquid water because of the pockets of air between ice crystals, and after melting, this amount of snow is equivalent to about 0.3 inch (7.6 mm) of rain. The temperature never rises above freezing, so the snow never melts. Some is lost by sublimation—vaporizing directly into the dry air—but most remains where it lies. Its weight compresses the lower layers into ice and the ice sheet grows slowly thicker. At present it is growing thicker by about 0.8 inch (203 mm) a year. The ice sheet—the "Greenland desert"—covers an area of 708,069 square miles (1,833,898 km^2). That is almost the size of Texas, New Mexico, Arizona, California, and Mississippi combined.

Antarctica is much bigger. Its total area is about 4.8 million square miles (12.4 million km^2), which is more than half the area of North America. The Antarctic Peninsula and coastal

A typical landscape in Antarctica (Courtesy of Frans Lanting/Minden Pictures)



Precipitation in Antarctica. Most of the interior of the continent receives less than two inches (50 mm) of precipitation a year, measured by melting snow to give the rainfall equivalent.

areas receive the equivalent of more than about eight inches (200 mm) of rain a year. McMurdo station on the coast receives annually an average amount of snow equivalent to eight inches (200 mm) of rainfall. McMurdo has a desert climate, but it is a desert climate with frequent blizzards of snow blown up from the surface by fierce gales. As the map above shows, however, most of the continent receives the equivalent of less than eight inches (200 mm) of rain a year and a substantial area receives less than two inches (50 mm). At the South Pole, the average is little more than one inch (25 mm) a year.

Antarctica has a dry climate for the same reason that Greenland does: its low temperatures. Antarctica is much colder than Greenland, however, and so its air is even drier (see the sidebar "Why Antarctica is colder than the North Pole" on pages 69–70). Although the temperature near the coast reaches 32°F (0°C) for a short time in summer, it is never so warm as this inland. December—midsummer in the Southern Hemisphere—is the warmest month at the

Amundsen-Scott station at the South Pole, when the average temperature rises to –17.5°F (–27.5°C). Winters are much colder. In August, the coldest month, the average temperature is –75.9°F (–60.0°C). The average temperature over the whole year is 56.8°F (–49.3°C).

GEOLOGY OF DESERTS

How continents move

Britain has a cool, wet climate. Its weather systems arrive mainly from the west, so they have crossed the Atlantic Ocean and they bring moist air that produces clouds and rain as it rises to cross the hills. If you explore Britain, however, you may discover some features that do not square with the kind of weather you see and feel around you.

In the first place, there are large coalfields. Most of the mines are closed now, because there is less demand for coal than there used to be, but the mining villages still exist and some mines are now museums. Coal is made from partly decayed plant material. It forms in tropical swamps—but you will find no tropical swamps in Britain.

Visit the south coast of Devon—a popular vacation destination in southwestern England—and you will find distinctive cliffs. Like all coastal cliffs, they are the result of the sea cutting into what were once low hills. They are distinctive because of their brick red color. They are made from a rock called new red sandstone. New red sandstone consists of desert sand that has been cemented together. The Devon hills were once sand dunes. The weather can be very pleasant in Devon, but the climate is not in the least like that of a desert, and inland from the coast you will see fields of crops and gently rolling pastures.

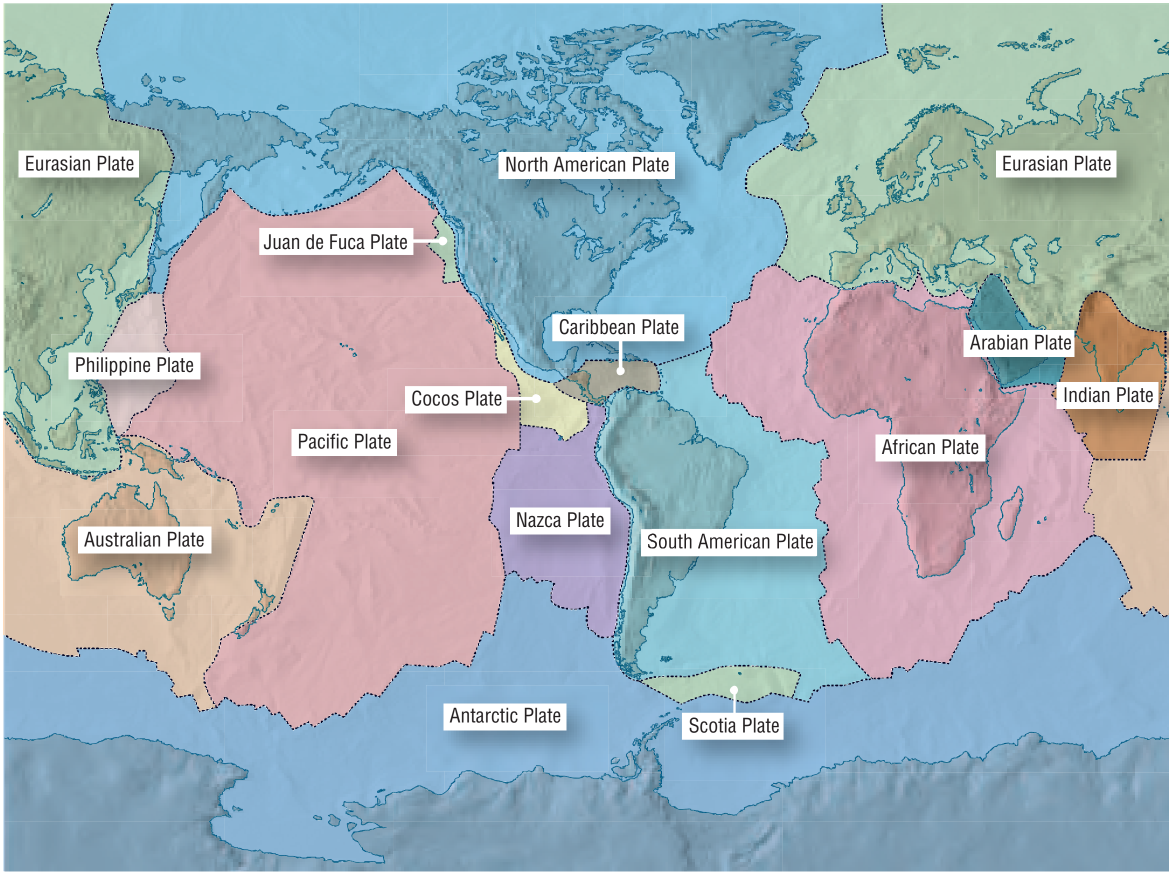
Nevertheless, there is no denying the evidence. British coalfields—and those of North America—were once tropical swamps. South Devon was once a hot desert, like the Sahara.

Climates change, but not to the extent of producing tropical swamps and hot deserts in Britain—an island in the latitude of Labrador. There must be another explanation, and there is. Britain once lay in the Tropics, and at another time it lay deep inside a vast continent, so far from the nearest coast that rain seldom reached it and it was desert. The continents have not always occupied the positions in which we see them today. They move around.

The suspicion that this might be so began as soon as there were reasonably accurate maps of the known world. People noticed that North and South America looked as though they might fit against Greenland, Europe, and Africa if only there were some way to push them all together—or perhaps they were once joined and have since been pushed apart.

More curious facts emerged as scientists gathered information from many parts of the world. There are several plant families that grow naturally in only a few places, but these are places separated by thousands of miles of open ocean. Marsupial mammals, the group that includes kangaroos and opossums, occur in Australia and New Guinea, and also in South and North America, on the opposite side of the Pacific Ocean. There were even more of these strange coincidences among fossil species. Animals move about, so perhaps there was some way they might have crossed oceans, but rocks stay put. Yet there are rock formations in West Africa that continue on the other side of the Atlantic, and rocks in the Highlands of Scotland that match rocks in Canada.

In the early years of the 20th century Alfred Lothar Wegener (1880–1930), a German meteorologist, drew together all of these strands of evidence, and more. He described the conclusions he reached in a short book called *Die Entstehung der Kontinente und Ozeane* (The Origin of the Continents and Oceans), published in 1912, and expanded them in a larger edition of the book published in 1915. Wegener proposed that the continents were once joined together into a single supercontinent that he called Pangaea—the name means "all Earth." Pangaea later broke apart and its fragments slowly moved to their present positions. Wegener thought that the mountains running down the western side of North and South America were due to crumpling of the continent as it was pushed westward, and that the Himalayas also formed by crumpling, due to a collision between India and Asia. He called this process *continental displacement* and maintained that it continues to the pres-



The major plates that form the Earth's crust

ent day. The name of the process was later changed. We know it as *continental drift.*

His idea found little support, despite the mountain of evidence he found to back it up. The problem was that geologists could think of no way for continents to move. They believed that the rocks forming the continents rested on a solid base and that consequently it was impossible for them to move. It was not until the 1960s, long after Wegener's death, that geologists discovered that the Earth's crust is divided into a number of sections, called *plates,* resting upon a layer of very dense hot rock that is able to flow. The plates are able to move and change their shape, or deform. Deformation is also called *tectonism* and the overall description, including continental drift, is now known as the theory of plate tectonics.

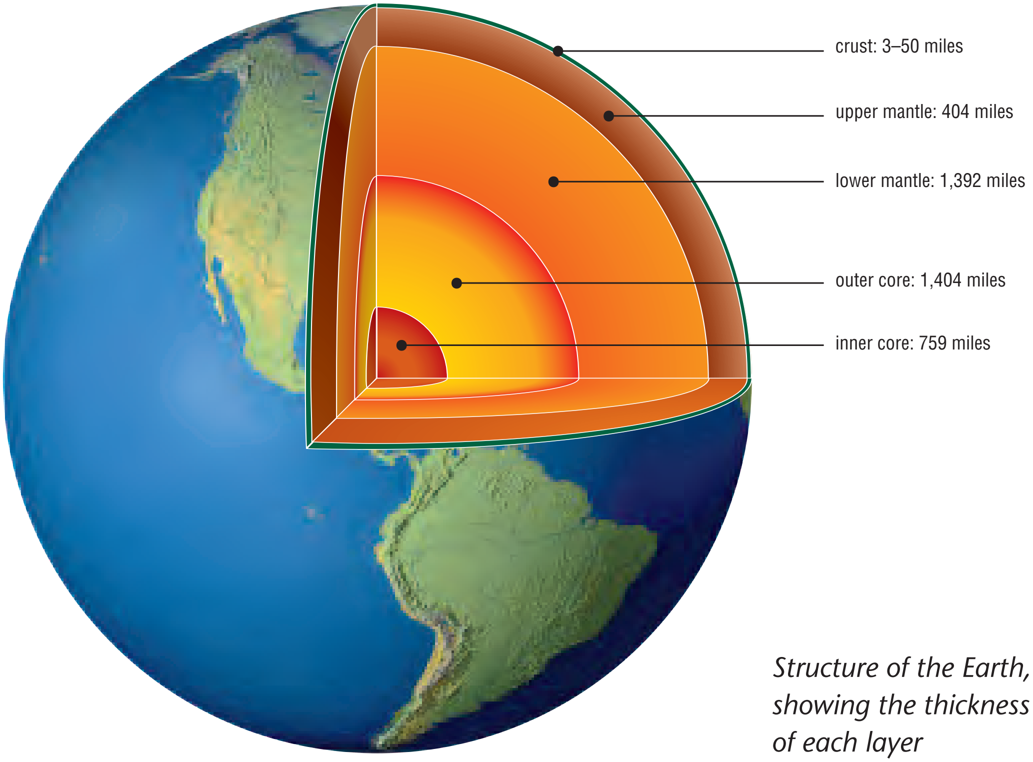
Continental drift and plate tectonics

The Earth is made up of layers, so it comprises a series of spheres, one inside another, as shown in the illustration on page 27. At the center is the solid *inner core,* with a radius of 759 miles (1,221 km) and made from iron, with some nickel and other metals. Surrounding the inner core is the *outer core,* 1,404 miles (2,260 km) thick. It is made from the same metals but is liquid. The outer core is surrounded by the *mantle,* made from rock. The lower mantle is about 1,392 miles (2,240 km) thick and solid. Its upper boundary is about 404 miles (650 km) below the Earth's surface. The upper mantle extends to the base of the *crust,* three to nine miles (5–15 km) below the floor of the oceans and 19–50 miles (30–80 km) below the surface of the continents.

The upper mantle is also made from rock, but it is much less dense than the rock of the lower mantle. Together, the crust and the uppermost part of the upper mantle compose the *lithosphere.* The lithosphere is rigid and brittle, but the part of the upper mantle beneath it, called the *asthenosphere,* is so densely compressed that its material is able to flow—extremely slowly, like a very thick liquid. The lithosphere floats on top of the asthenosphere.

Heat moves through the rigid lithosphere by conduction, but it moves by convection through the asthenosphere. Conduction is the transfer of heat by direct contact between objects at different temperatures, such as when you warm yourself by hugging a hot-water bottle. Convection is the transfer of heat by movement within a fluid—a liquid or gas. In the asthenosphere, material that is heated by contact with the hotter material below rises slowly, cools below the base of the lithosphere, and then sinks back into the mantle. The lithosphere consists of a number of sections, or *plates.* Convection causes movements in the asthenosphere that carry the plates with them, so that the plates move in relation to one another. The movement is slow, averaging about two inches (50 mm) a year. Some plates are diverging, some converging, and some are moving past one another. Continents rest

There are approximately 12 major plates and a number of minor ones. The map shows most of the largest plates. Plates move apart at ridges, where new material rises from beneath the crust and solidifies to make new crust. Where plates of different density converge, the denser plate will sink—be subducted—beneath the less dense. This may scrape sedimentary rock from the lighter plate to form new mountains. Oceanic crust is denser than continental crust, so subduction

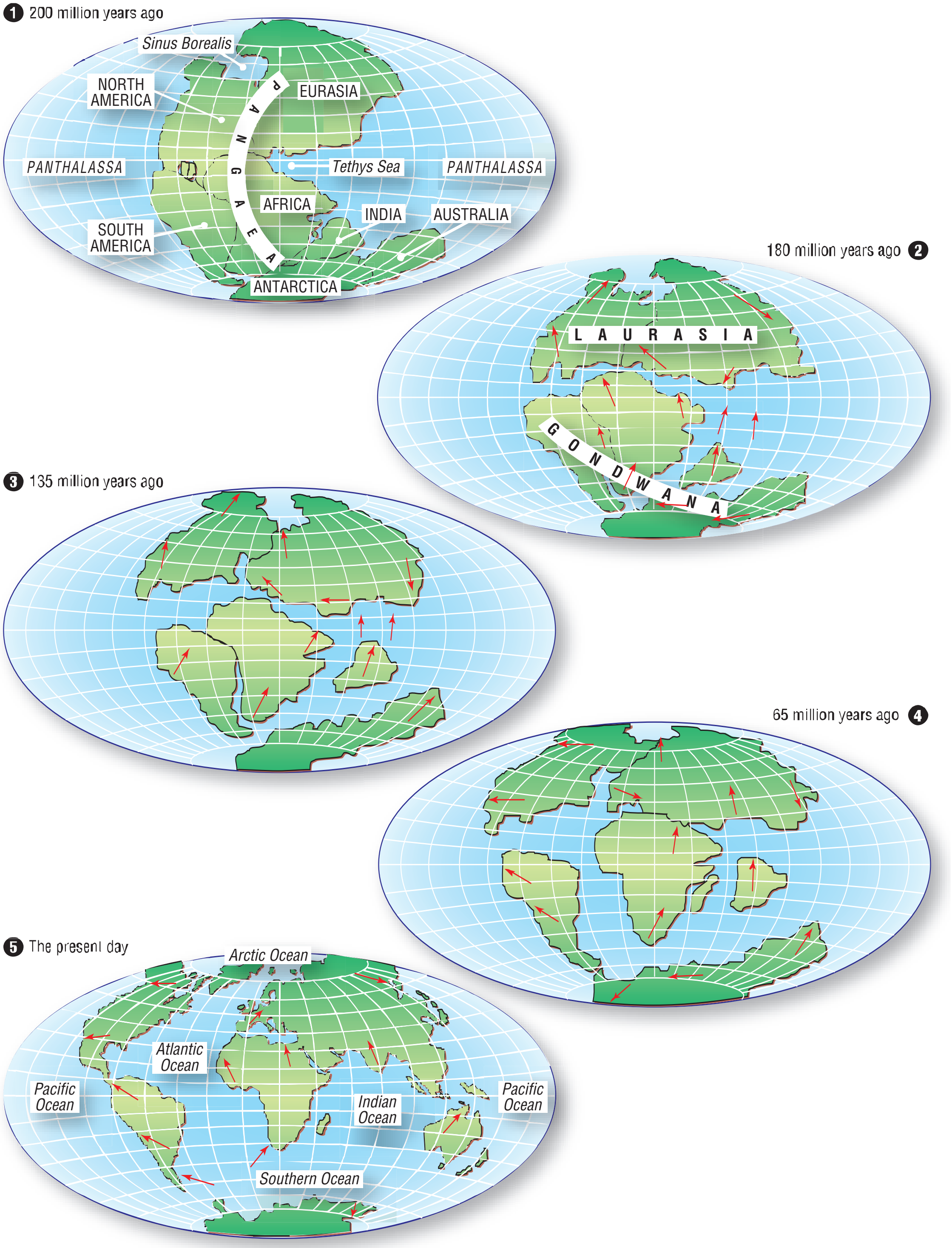


Structure of the Earth, showing the thickness of each layer

on plates, so as the plates move, so do the continents. At the same time, oceans open, expand, and then close until the continents on either side meet. The rate of movement is slow, but over many millions of years it drastically alters the map of the world. The maps on page 28 show how the continents and oceans are arranged today and where they were located 65, 135, 180, and 200 million years ago (Ma).

occurs at the margins of continents. Where two continental plates collide, neither plate is subducted; instead the rocks crumple to form high mountains, such as the Himalayas. Plates also move past one another along *transform faults*. All active plate margins are associated with earthquakes and volcanoes.

Scientists now understand the way continents move (see the sidebar on page 26). The theory of plate tectonics explains



❶ 200 million years ago

❷ 180 million years ago

❸ 135 million years ago

❹ 65 million years ago

❺ The present day

how it is that about 350 million years ago parts of Britain, Pennsylvania, and many other places were tropical swamps and how, some 250 million years ago, Devon was part of a vast desert.

How mountains rise and wear away

There are fossil seashells high in the Himalayas. It was by studying fossils of fish found in the rocks of the Alps, thousands of feet above sea level and hundreds of miles from the nearest coast, that scientists learned much of what we know about the kinds of fish that lived hundreds of millions of years ago. These mountains and others that formed in the same way are made partly from seafloor sediments that were compressed into sedimentary rock. Mountains such as these are produced when tectonic plates collide.

About 50 million years ago, during the period of the Earth's history known as the Eocene epoch, India, traveling northward on the Indian Plate, crashed into the southern edge of the Eurasian Plate. Continents are made from rocks that are less dense than the rocks forming the ocean floor. Consequently, when two continents collide it is impossible for one plate to sink beneath the other, because both plates are equally buoyant. Instead, the two sections of continental crust crumple upward, usually with one plate riding over the other. This produces very high mountain ranges. The collision between India and Eurasia raised the Himalayas—and the collision is not ended. India is still moving northward at a rate of 1.5–2 inches (4–5 cm) a year and crumpling has shortened the Indian Plate by about 600 miles (1,000 km). As a result, the Himalayas are still rising, though they are probably not growing higher because of rapid erosion.

The Rocky and Andes Mountains, running down the western side of North and South America respectively, grew over a

(opposite page) *Continental drift. The maps show the arrangement of the continents at different times in the past and their arrangement today. The arrows indicate the direction in which the continents have moved and are still moving.*

much longer period, starting about 230 million years ago in the Jurassic period and ending about 100 million years ago, during the Cretaceous (see the table below). These mountains are highly complex and formed in several distinct stages, but the process began when the North and South American Plates started traveling westward, separating from each other and riding over several ocean plates.

Geologic time scale

Eon/ Eonothem	**Era/ Erathem**	**Subera**	**Period System**	**Epoch/ Series**	**Began Ma***
		Quaternary	Pleistogene	Holocene	0.11
				Pleistocene	1.81
Phanerozic	Cenozoic	*Tertiary*	Neogene	Pliocene	5.3
				Miocene	23.03
			Paleogene	Oligocene	33.9
				Eocene	55.8
				Paleocene	65.5
	Mesozoic		Cretaceous	Upper	99.6
				Lower	145.5
			Jurassic	Upper	161.2
				Middle	175.6
				Lower	199.6
			Triassic	Upper	228
				Middle	245
				Lower	251
	Paleozoic	Upper	Permian	Lopingian	260.4
				Guadalupian	270.6
				Cisuralian	299
			Carboniferous	Pennsylvanian	318.1
				Mississippian	359.2
			Devonian	Upper	385.3
				Middle	397.5
				Lower	416
		Lower	Silurian	Pridoli	422.9
				Ludlow	443.7
				Wenlock	428.2
				Llandovery	443.7
			Ordovician	Upper	460.9
				Middle	471.8

Eon/ Eonothem	Era/ Erathem	Subera	Period System	Epoch/ Series	Began Ma*
				Lower	488.3
			Cambrian	Furongian	501
				Middle	513
				Lower	542
Proterozoic	Neoproterozoic		Ediacaran		600
			Cryogenian		850
			Tonian		1000
	Mesoproterozoic	Stenian			1200
			Ectasian		1400
			Calymmian		1600
	Paleoproterozoic	Statherian			1800
			Orosirian		2050
			Rhyacian		2300
			Siderian		2500
Archean	Neoarchean				2800
	Mesoarchean				3200
	Paleoarchean				3600
	Eoarchean				3800
Hadean	Swazian				3900
	Basin Groups				4000
	Cryptic				4567.17

Source: International Union of Geological Sciences, 2004.

Note: *Hadean* is an informal name. The Hadean, Archean, and Proterozoic eons cover the time formerly known as the Precambrian. *Quaternary* is now an informal name and *Tertiary* is likely to become informal in the future, although both continue to be widely used.

*Ma means millions of years ago.

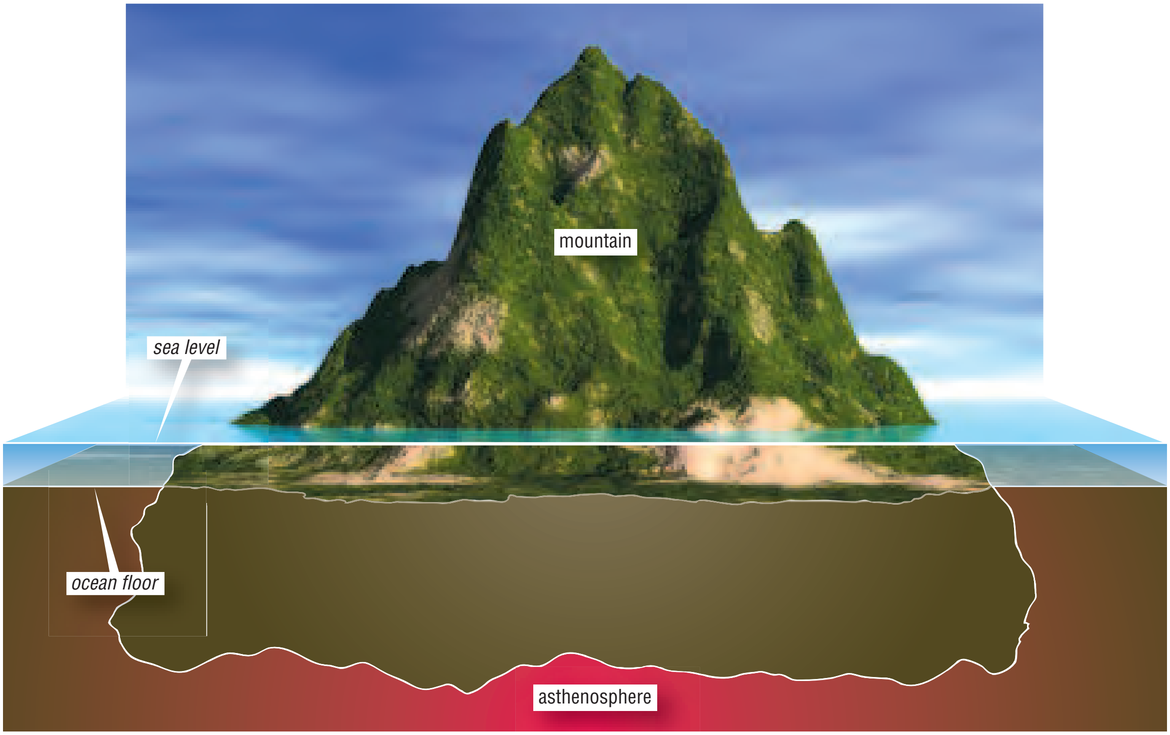
This is the way many mountains form. The process of mountain-building is called an *orogeny.* The Himalayas and Alps result from the *Alpine-Himalayan orogeny* and the mountains of western America from the *Cordilleran orogeny.*

No sooner does a mountain begin to rise than it begins to wear away by *weathering*—a relentless process of *erosion.* Although the Himalayas are still being pushed upward, this does not mean that mountaineers who climb Mount Everest today have to scale a higher peak than those who climbed the mountain several decades ago. Indeed, the opposite may be true, and due to weathering Everest may be a few inches shorter now than it was about 20 years ago.

Snow accumulates in depressions high in the young mountains and its weight compresses the lower layers into ice. Eventually the ice is so thick that it overflows and begins to move down the mountainside as a glacier. Glaciers scour away at the rock beneath them, pushing loose rocks and gravel ahead of them and to the sides. At the same time, water flows into small cracks between rocks and freezes in winter. It expands as it freezes, widening the cracks and breaking off small fragments of rock. Wind blows tiny rock grains against the rock, wearing away the surface. Lower down the mountain, where the temperature is above freezing, rivers carry some of this eroded material down onto the plains and eventually to the sea.

Little by little, the mountains wear away, but while they are being eroded another process is making them rise. Mountains are made from continental rocks, which are less dense than the material of the asthenosphere beneath them

Isostasy. Mountains have roots that extend into the asthenosphere, like the part of an iceberg that lies below the ocean surface. As the upper part of the mountain is worn away by erosion, the mass of the mountain decreases and it rises higher in the asthenosphere.



(see the sidebar “Continental drift and plate tectonics” on page 26). Mountains float in the asthenosphere, so that the part we see protruding above the surface is only part of the complete mountain. Below the level of the ocean floor the mountain extends downward, like the part of an iceberg that extends below the surface of the sea. The illustration shows how a mountain floating in the asthenosphere resembles an iceberg floating in the sea. As the exposed part of the mountain erodes, the total mass of the mountain decreases and therefore the mountain rises, to float higher in the underlying rock.

Erosion continues until eventually, after a very long time, the mountains are reduced to low rolling hills. The softer rocks disappear first, but finally even the hardest rock is worn away.

Although the mountains disappear, the rock from which they are made survives. Ground into tiny grains, the mountain rock is carried away by rivers and blown by the wind, until it reaches the sea. There it settles to the bottom as sediment that one day will sink back into the Earth’s mantle or be raised above the surface once more to form part of a new range of mountains.

Desert soils

Soil is a mixture of mineral particles and the decomposed remains of plant and animal material, called *humus*. The mineral particles are usually derived from the underlying rock by chemical reactions that dissolve certain compounds present in the rocks, thus weakening the rock and allowing fragments to be detached.

Plant roots absorb some of the compounds released in this way, but the compounds are soluble in water and gradually, as the soil grows older, they are washed to deeper levels. Nutrients that have drained in this way accumulate some distance from the surface until, in a mature soil, there are distinct layers, called *horizons,* extending from the surface all the way down to the bedrock.

Soil formation begins with bare rock and reaches maturity with deep, layered soils that support luxuriant plant life and the animals associated with it. The rate at which soil develops depends on the climate. It happens fastest where summers are warm and winters mild, and where there is abundant rainfall throughout the year. The physical and chemical characteristics of the resulting soil vary according to the composition of the underlying rock—known as the *parent material*—and the type of vegetation that grows in it. There are many possible variations and consequently there are many types of soil. Pedologists—scientists who study soils—classify them in much the same way that biologists classify plants and animals. The sidebar on page 35 outlines the way classification works.

Deserts have a dry climate, so desert soils develop very slowly. Lack of moisture greatly slows the release of mineral compounds from the rock, and the dry climate means that vegetation is sparse. There is less dead plant and animal matter to contribute organic matter and structure to the soil, and decomposition happens more slowly. Dead leaves, plants, animal wastes, and animal bodies tend to dry out rather than decompose.

When rain does fall, it is often torrential. Most of the water runs off across the surface (see “What happens when it rains” on pages 45–47). Rain that does soak into the ground seldom penetrates deeper than about 40 inches (1 m). Calcium carbonate and silicate compounds—oxides of silicon—are washed downward by the rain and tend to accumulate at this *wetting front,* where they may solidify into a hard layer. At about the same level some desert soils have accumulations of clay, salt, or gypsum (calcium sulfate).

Some areas that are deserts today were not always deserts. Much of the northern Sahara was farmed as recently as Roman times. In places like these the soil formed under different climatic conditions and the old soils are preserved. These soils may date from before the last Ice Age, making them more than 75,000 years old.

Lack of water means that there are few plants and the soil contains very little organic matter. Because the land is barren it is natural to assume that the soil is infertile. This is not the case, however. Desert soils are among the most fertile of all soils. This is because there is insufficient rain to wash away the soluble nutrients. Really ancient soils, such as those of

How soils are classified

Farmers have always known that soils vary. There are good soils and poor soils, heavy soils containing a large proportion of clay, sandy soils that dry out rapidly, and light, loamy soils that retain moisture and nutrients. Loam is a mixture of sand, silt, and clay—mineral particles of different sizes. In the latter part of the 19th century Russian scientists were the first to attempt to classify soils. They thought that the differences between soils were due to the nature of the parent material—the underlying rock—and the climate. They divided soils into three broad classes. *Zonal* soils were typical of the climate in which they occur, *intrazonal* soils were less dependent on climate for their characteristics, and *azonal* soils were not the result of climate. Azonal soils include windblown soils and those made from silt deposited by rivers on their floodplains. Individual soil types were placed in one or other of these broad groups. This system remained in use until the 1950s, and some of the Russian names for soils are still widely used, such as Chernozem, Rendzina, Solonchak, and Podzol.

American soil scientists were also working on the problem, and by the 1940s their work was more advanced than that of their Russian colleagues. By 1975 scientists at the United States Department of Agriculture had devised a classification they called "Soil Taxonomy." It divides soils into 10 main groups, called orders. The orders are divided into 47 suborders, and the suborders are divided into groups, subgroups, families, and soil series, with six "phases" in each series. The classification is based on the physical and chemical properties of the various levels, or *horizons,* that make up a vertical cross section, or *profile,* through a soil. These were called "diagnostic horizons."

National classifications are often very effective in describing the soils within their boundaries, but there was a need for an international classification. In 1961 representatives from the Food and Agriculture Organization (FAO) of the United Nations, the United Nations Educational, Scientific, and Cultural Organization (UNESCO), and the International Society of Soil Science (ISS) met to discuss preparing one. The project was completed in 1974 and is known as the FAO-UNESCO Classification. Like the Soil Taxonomy, it was based on diagnostic horizons. It divided soils into 26 major groups, subdivided into 106 soil units. The classification was updated in 1988 and has been amended several times since. It now comprises 30 reference soil groups and 170 possible subunits. The FAO has also produced the World Reference Base (WRB), which allows scientists to interpret the national classification schemes.

tropical rain forests, have lost almost all of their plant nutrients and when farmers clear the forest to grow crops they find that after a few years they have to apply large amounts of fertilizer. All the desert soil needs is moisture. Provide water, and crops will flourish in it.

What is sand?

Think of deserts and the first picture that springs to mind is likely to be one of a landscape covered with sand. Sand is one of the most abundant substances on Earth and an ingredient of most soils. Take a pinch of moist soil and rub it between your thumb and forefinger, and if it feels gritty—and probably it will—the soil contains sand.

Sand grains are tiny fragments of rock. Most sand is made from quartz, which is *silica*—the common name for silicon dioxide (SiO_2). Quartz is an important ingredient of many rocks, especially granite and rocks related to granite. Granite forms when molten rock cools and solidifies. As it cools, the minerals it contains form crystals. Silica forms quartz crystals, which are triangular in cross section. They are hard and it is their sharp edges that make sand grains gritty.

The size of the crystals depends on the rate at which the molten rock cooled. Large crystals grow in rock that cooled slowly. If the rock cooled rapidly the crystals are small, and if it cooled very fast they may be so small they are visible only under a microscope. Pure quartz is clear, like the best quality glass, but impurities transform it into colored versions, some of which are semiprecious stones. Amethyst (purple), cairngorm (dark brown), and citrine (yellow or orange) are varieties of quartz.

Beach sand is a mixture of quartz grains mixed with particles of other minerals and variable amounts of shell fragments. Desert sand is usually made almost entirely from quartz. Sand grains range in size from 0.002 to 0.079 inches (0.05–2 mm). Soils also contain silt and clay. Silt comprises grains that are smaller than 0.000002 inch (0.05 μm), and clay particles are smaller than 0.00000008 inch (0.002 μm). When they are moist, these particles cling to one another, but when they are completely dry, silt turns to fine dust and clay either turns to dust or packs together into a hard mass—bricks are made from clay. (One micrometer (μm) is one millionth of one meter.)

Deserts are often extremely hot by day but very cold at night. This wide range in temperature makes rocks expand and contract repeatedly, shattering them into fragments that are rolled about by the wind until repeated impacts have broken them into small grains. Occasional torrential downpours of rain wash the grains down hillsides and discharge them onto the plains below, where they quickly dry. The smallest and lightest particles travel farthest. Silt and clay tend to accumulate in hollows, as sediments on the beds of temporary lakes. The wind carries some silt particles beyond the desert. Windblown silt forms deposits of a type of soil called *loess*.

Gravel and larger stones are carried for much shorter distances, but each downpour carries them a little farther. After thousands of years they cover extensive areas.

Dry sand is blown away by the incessant wind (see "Dust storms and sandstorms" on pages 74–76). That is why deserts contain large areas of bare rock or boulders that have been worn smooth by the erosive action—sandblasting—of windblown sand.

Airborne sand eventually falls to the ground, and it does so in particular areas because of the direction and strength of the prevailing winds. Just as repeated rainstorms produce surfaces of gravel and stone, the wind deposits sand in areas that grow into vast seas of sand.

Sand seas and sand dunes

For much of the Carboniferous period, 362.5–290 million years ago, the land that now forms the Sahara and Arabian Peninsula lay beneath the sea. Sand covered the seabed. Over time the sediment was compressed and the sand grains cemented together, forming sandstone. The sea retreated but returned about 70 million years ago and deposited more sand. When the land finally arose from the sea much of its surface consisted of sandstone that immediately began to erode. Today sand is abundant.

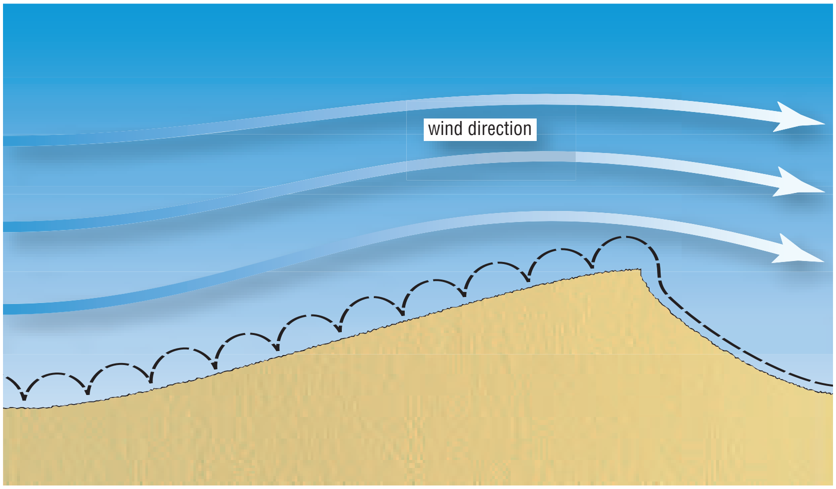
Sand is so abundant that in places it resembles the sea—a sea of sand, complete with waves. A sand sea in the Sahara is called an *erg* and there are several (see the map on page 10).

One of the largest, the Great Eastern Erg, in Algeria, covers about 74,000 square miles (192,000 km^2). The ergs lie in depressions, resembling ocean basins, where sand collects. The Great Eastern and Great Western Ergs are separated by about 60 miles (100 km) of higher ground where the surface is covered by gravel. The Rub' al-Khali (Empty Quarter) of Arabia is also a sand sea.

Level expanses of sand often have a rippled surface, like a beach at low tide. In the desert, of course, the ripples are produced by the wind and not by water. Gradually the wind carries loose sand into places where it piles up into dunes. The world's biggest dunes are found in the Namib Desert (see "West coast deserts" on pages 16–19), but some Saharan dunes are 100 feet (30 m) high.

Sand dunes are hills of windblown sand. Wind has the power to raise sand grains, but usually they fall to the surface again within a short distance. No one is quite sure how a dune begins, but once there is a small pile of sand, the wind blowing up the side of the pile will carry sand toward the top.

Wind accelerates as it blows over the heap. This is because the surface-level air has farther to travel than the air above it, well clear of the surface, but it must arrive on the far side at the same time. As it accelerates, the wind raises sand grains from the upwind side of the heap and carries them up the slope. When the wind reaches the top it slows sharply and no



How sand dunes form. The wind blows sand grains up the gentle slope on one side of the dune. At the crest the grains tumble down the steeper side.

Barchan dunes, with their "horns" pointing downwind, in the Skeleton Coast National Park, Namibia (Courtesy of Gerry Ellis/ Minden Pictures)

longer has enough energy to carry the sand, so sand falls onto the top of the heap.

There is a limit to how steep the sides of a sand heap can be. Although moist grains will stick together—that is what makes it possible to build sandcastles on the beach—dry sand will not hold together in this way. If you pour dry sand onto the center of a heap of sand, sand grains will run down the sides. The pile will grow higher and wider, but its sides will not grow any steeper. They will never slope at an angle of more than 35°. This is the *angle of repose* for dry sand. Sand is carried up the shallow slope on the upwind side of a dune, but when it is released at the top the grains roll down to give the downwind side a slope of about 35°. The illustration on

Types of sand dunes

Sand dunes are built by the wind and it is the wind that gives them their characteristic shapes. The commonest type is the *barchan* dune. It is crescent shaped with the horns of the crescent pointing downwind. Barchan dunes form where the supply of sand is limited and the wind blows mainly from one direction.

Crescent-shaped dunes sometimes develop the other way around, with the horns pointing into the wind. They are then *parabolic* dunes. It is easy to tell whether a crescent-shaped dune is a barchan or parabolic dune. One side of each ridge will slope gently and the other will be much steeper. If the steeper side lies between the horns it is a barchan dune, and if the steeper side lies on the opposite side to the horns it is a parabolic dune.

The more sand that is available, the closer the barchans are to their neighbors. If there is enough sand, barchans may join together to form long, wavy lines of dunes. These are *aklé* dunes.

Alternatively, a plentiful supply of sand may allow the horns of the barchans to grow much longer until the dunes are very long, narrow, wavy *barchanoid ridges.*

If there is abundant sand and the wind nearly always blows from the same direction, long dunes form at right angles to the wind direction. These are *transverse* dunes—and are the type of dune that most commonly forms behind sandy beaches.

Transverse dunes cannot form if the wind direction varies by a few degrees to either side of an average direction. Instead, the sand is heaped into wavy dunes that are aligned with the average wind direction. These are *longitudinal* or *linear* dunes. Sometimes they have very sharp crests. They are then known as *seif* dunes—*seif* is from the Arabic word *sayf,* which means “sword.” Some seif dunes are more than 100 miles (160 km) long.

There are places—the northern Sahara is one—where the wind pattern is very complex and no single wind direction predominates. Under these conditions dunes form with ridges aligned in several directions. This produces a *star* or *stellar* dune.

Dunes also develop on the downwind side of large boulders and other obstacles. The wind carries sand around or over the obstacle and drops it on the far side. This produces a *tail* dune, with the tail pointing downwind.

The biggest sand structure of all is called a *draa.* It is a transverse or longitudinal dune that is up to 1,000 feet (300 m) high, with wave crests up to 700 yards (650 m) apart. Draas are about 0.5–3 miles (0.8–5 km) apart and they extend for hundreds of miles. They often have smaller dunes superimposed on them.

Rhourds are a variety of very large star dunes that form where dunes of other types intersect. They are sometimes star-shaped draas.

page 38 shows how this process produces the typical ridge along the top of a sand dune.

Some sand dunes move. Despite their size, they are not landmarks that can guide the traveler. The biggest of them, called *draas,* move up to two inches (5 cm) a year. Dunes vary in shape according to the amount of sand available to build them and to the constancy of the wind direction. Each type of dune has a name (see the sidebar on page 40), but sand dunes are either approximately straight, lying parallel to one another, or crescent shaped.

Desert pavement and desert varnish

You would expect trucks and cars, even tough utility vehicles, to move across the desert slowly, bouncing and lumbering over the rocks and now and again being brought to a standstill with their wheels spinning in loose sand. This is what desert driving is often like, but not always. In some places the traffic moves almost as fast as if it were on a road, each vehicle pursued by a cloud of dust that can be seen for miles but that emphasizes the speed. Speed is possible because over large areas the desert surface is made from half-buried rounded stones that are securely embedded so they do not slide or roll. The surface is almost as good as a road. It is called *desert pavement.*

It takes many thousands of years for the desert to produce such a paved or cobbled surface. There are two ways it can happen. Both result in a stable, solid surface that will bear the weight of trucks.

Torrential streams that flow after rainstorms may transport sand, dust, gravel, and stones of all sizes down steep hillsides, depositing the mixture on a plain at the foot of the hills. Rainstorms do not occur very often and most of the time the streams carry no water at all, but occasional torrents repeated over many thousands of years may spread enough material to cover a substantial area. The deposit arrives on the plain as mud, but the mud quickly dries and then the wind begins to work on it. A light breeze will blow away fine dust, and a wind of more than 12 MPH (19 km/h) will blow sand grains.

Little by little, the wind blows away the dust and sand, leaving behind the stones that are too heavy to shift, until finally all the sand and dust are gone and only the stones remain.

Alternatively, the stones may have been there all the time, mixed with sand and dust to produce a surface with just a few stones scattered about randomly. When it rains, the water washes dust and sand downward. The particles fill small air pockets below ground and work their way around and beneath the stones. From time to time the wind deposits more dust over the surface and the rain then washes the dust below the surface. When the ground dries, the packed dust cracks, making more spaces for windblown dust to fill. Very slowly, the dust and sand are washed beneath the stones, and the stones work their way to the surface. Eventually the stones form a surface layer, like a road pavement, lying above a layer of compacted sand and dust that contains very few stones.

Desert pavement does not consist merely of bare stone, however. Usually the stones have a coating of *rock varnish*—more often known as *desert varnish*. It is found on rocks in many places, but it develops best and is most clearly seen in deserts, where more rocks are exposed and the dry conditions allow time for the varnish to grow, for it grows very slowly.

The thickness of the varnish varies, but it is usually less than about 0.001 inch (30 μm). The varnish is made from clay particles that are cemented firmly to the rock by hydroxides of manganese and iron. Geologists are uncertain about both where the manganese comes from and how the varnish accumulates on the stones. Some scientists think that small changes in acidity trigger chemical reactions that deposit the varnish onto the stones. Others think the process is biological and that bacteria are responsible.

Whatever the cause, desert varnish is found only in hot deserts. Rocks in cooler deserts have a different coating. It is called *silica glaze* and consists of silica (silicon dioxide, SiO_2) mixed with aluminum and iron. Silica glaze is usually up to 0.008 inch (200 μm) thick and makes the rocks shiny and white or orange in color, or sometimes darker. There are rocks covered with silica glaze in the dry valleys of Antarctica—the coldest of all deserts.

There are also rust-colored rocks, both in Antarctica and in hot, extremely dry deserts. The rocks from these diverse areas look similar and all of them are coated with a film containing iron, but the precise composition of the film varies, depending on the conditions.

Mesas, buttes, and other desert landforms

Sandstone and limestone are sedimentary rocks that cover the surface of many deserts. They are made from compressed and cemented material that once lay on the ocean floor where they accumulated as horizontal layers, and in some deserts the rocks retain this orientation. Later, hot, molten, *igneous* rock—from *ignis,* the Latin word for "fire"—rose from below and pushed into the sedimentary layers. When the igneous rock cooled it remained as an intrusion into the sedimentary rock.

Igneous rock, such as granite, is much harder than sedimentary rock, and the forces of erosion that are powerful enough to wear away the sedimentary rock leave the igneous rock exposed. Erosion is ceaseless in the desert. Every wind raises dust and sand particles and dashes them against solid surfaces. This relentless sandblasting wears away the sedimentary rock, at the same time releasing more mineral grains to contribute to further erosion.

Where the sedimentary layers are horizontal, erosion first levels the landscape by wearing away protruding rocks that are more exposed to the wind and its load of sand. This leaves a level plain. But erosion continues, wearing at the surface of the plain, eventually producing structures with names in the languages of the places where they were first seen or of the explorers who described them.

As the sedimentary rock is removed, the igneous intrusions are revealed. Some remain as fragments of the plain, standing like steep-sided, flat-topped hills. A hill of this shape is called a *mesa*—the Spanish word for "plateau."

Further erosion reduces the size of the mesa until all that remains of it is a tower of rock with a flat top. This is called a *butte*—a French word meaning "hill" or "knoll."

A larger igneous intrusion may be left as a steep-sided hill standing alone on the plain. This is an *inselberg*—a German word that means “island mountain.”

Sand and wind are the principal agents of erosion, but they are not the only ones. Salt can also sculpt rocks into curious shapes and can make *pedestal rocks*. A pedestal rock is a large rock that stands on top of another rock to which it is connected by only a narrow neck.

Mineral salts, including common salt (sodium chloride) form part of the crystalline structure of many rocks, and each time it rains some of the salt at the rock surface dissolves and the solution seeps into tiny cracks in the rock. The heat and wind quickly evaporate the water and the salts crystallize once more, expanding as they do so and splitting the rock. Salt crystals inside the rock also expand and contract with changes in temperature, but by a much larger amount than the other minerals around them. This also causes rock fractures.

Erosion often wears away one layer of rock more rapidly than the layers above and below it. Sometimes this makes a recess, called an *alcove,* around a section of rock. Rainwater collects in the alcove, salts from the rock dissolve into it, and when the water evaporates the salts crystallize. Grains of salt and sand grains detached by the expansion during crystallization then blow away in the wind. With each repetition of the process the alcove becomes deeper until the rock above it is left standing on a narrow neck. It has become a pedestal rock.

Salt solutions also collect in small depressions on the rock surface. As the salt and sand grains blow away, the depressions deepen to become pits, called *alveoles,* from *alveus,* the Latin word for “cavity.” The alveoles grow larger until the rock is honeycombed with holes. These larger holes are *tafoni* (singular *tafone*)—an Italian name that was first used to describe holes of this type in Corsican rocks.

Dissolved salt can also produce a vast, absolutely level salt flat, known variously as a *playa* (Spanish for “beach”), as a *salina* in South America (Spanish for “salt mine”), and as a *sabkha* (Arabic for “salt flat”) in Africa. Playas lie in basins surrounded by high ground. At one time, when the climate was moister, lakes or coastal lagoons filled the basins. The water was rich in salts dissolved out of the surrounding rocks and washed into the basins. When the climate became drier the water evaporated, leaving behind the salts. The Bonneville salt flats in Utah, used for attempts to break the world land-speed record, are a playa.

Gypsum (calcium sulfate) and calcite (calcium carbonate) are among the salts found in playas. As they crystallize, surrounded by sand grains, they can form the attractive, flower-like shape called a *desert rose.*

What happens when it rains

Here and there gullies break up the desert surface. Usually about seven feet (2 m) deep and 10 feet (3 m) wide, they are called *arroyos* in North America, *dongas* in Southern Africa,

A cumulonimbus cloud producing a rainstorm over Amboseli National Park, Kenya (Courtesy of Gerry Ellis/ Minden Pictures) and *wadis* or *ouadis* in the Sahara and Arabia. They are dry river courses, but the rivers that occasionally flow through them are not like the gentle, predictable rivers of temperate lands. Crossing an arroyo is not difficult, but lingering in one to camp or even to picnic can be dangerous. When the river flows it does not begin as you might expect, as a dampness on the bed that increases to a trickle before it is recognizably a river. The bed remains bone dry until, with no warning, a wall of muddy, rock-laden water as high as the banks of the arroyo advances along the stream channel so fast that there may be no time to escape.

It seldom rains in the desert. Clouds quite often cross the sky, but they are too small to deliver rain. Occasionally rain may fall from a larger cloud, but the drops are small. They fall slowly and evaporate in the dry air below the cloud before they can reach the ground. The rain hangs tantalizingly out of reach beneath the cloud like a gray veil, called *virga*.

Only really huge storm clouds are able to produce raindrops that are big enough to reach the ground. A big raindrop falls at about 20 MPH (9 m/s), which means it does not spend very long traveling from the cloud to the ground, so there is less time for it to evaporate. It also means that it falls with considerable force.

Storms are more likely in the mountains than over the plains. Moist air is forced to rise as it crosses mountains, and as it rises its temperature falls (see the sidebar “Adiabatic cooling and warming” on page 55) and its water vapor starts to condense. Under certain conditions this can trigger the formation of large *cumulonimbus* clouds—the clouds that bring violent thunderstorms, heavy rain, and cloudbursts as they begin to disappear (see the sidebar “Lapse rates and stability” on page 60).

Rainwater falling on the bare mountainsides flows away between the rocks along gaps that feed into the arroyos. Far away on the plain, the sky may be clear, with not a cloud in sight, and the storm may be too distant to be seen or heard. The torrent arrives without warning.

That is what makes arroyos dangerous places. Flash floods caused by violent desert storms can cause serious damage if they flow through a town. Floods struck northern Algeria during the period November 9–17, 2001, for example. They killed 750 people and left about 24,000 homeless.

Where the desert surface is sandy, rainwater soaks vertically downward. The combination of surface evaporation and the ease with which the water passes between the sand grains quickly dries the surface. Below ground, the water continues to move downward until it encounters an impermeable layer of clay or rock that checks its progress. Water then fills all the spaces between pebbles, gravel, and sand grains, saturating the material immediately above the impermeable layer. It is then called *groundwater.* The upper boundary of the saturated zone is known as the *water table.*

Groundwater flows, quite slowly, down the gently sloping surface of the impermeable layer. If the water is accessible in useful amounts, the saturated material through which it moves constitutes an *aquifer.*

There are natural depressions below ground in which groundwater accumulates, and water has been held in some of them for a very long time. Groundwater below the surface of the Sahara and under parts of the Australian deserts has been there since before the end of the last Ice Age—more than 10,000 years ago.

Wells and oases

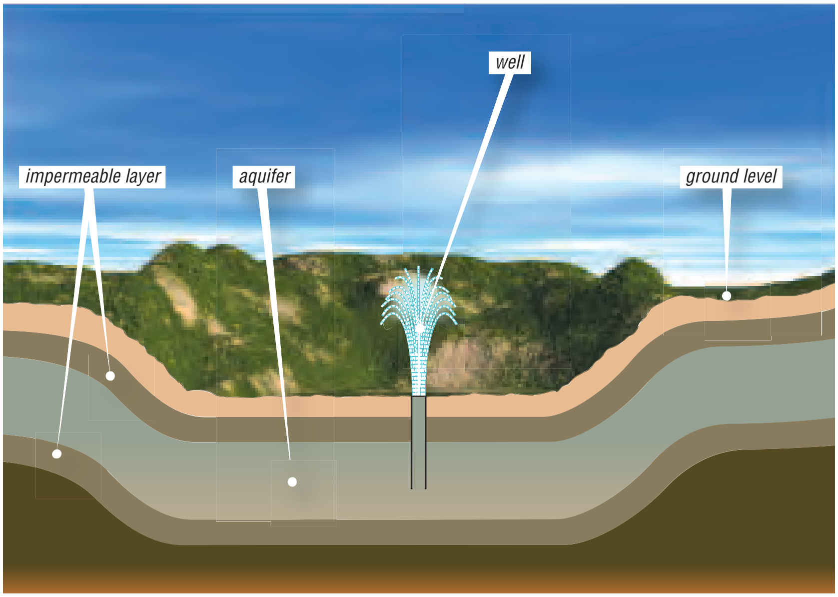
Dig a hole from the surface all the way down past the water table, and the bottom of the hole will fill with water. The hole is then a well, and people can take water from it by lowering a bucket on the end of a rope or, more commonly nowadays, by installing a pump that raises the water to a faucet.

Digging a well is hard work. The hole must be wide enough for at least one and usually more than one person to work. That means it will be up to eight feet (2.4 m) across, and all the excavated material has to be hauled to the surface. As they dig, the workers must secure the sides to prevent them from collapsing. Modern wells are not usually dug by hand, of course, but by drilling machines. Most wells are less than 100 feet (30 m) deep, but some are much deeper.

There are certain places where it is not necessary to use a pump or bucket to raise water from a well. The water rises to the surface without help and flows freely. The first well of this type was sunk in the year 1126 at the town of Lillers, to the west of Lille in northeastern France. In those days that part of France was called Artois. The Latin name for Artois was Artesium, and so the Liller well was called an *artesian* well. Artesian wells are sunk into *confined* aquifers.

Ordinarily, only sand or soil lies between an aquifer and the surface. Such an aquifer is said to be *unconfined*. In some cases, though, a second layer of impermeable material lies above the aquifer. The aquifer is then confined.

Layers of rock and clay seldom lie horizontally. If the two layers confining an aquifer form a hollow, as shown in the illustration below, gravity will force water on the upstream side to sink into the hollow, putting the water in the hollow under pressure. Once the pressure is removed by cutting through the upper impermeable layer, the water held under pressure in the depression will rise to the level of the water to either side of the depression and the well will flow without pumping.



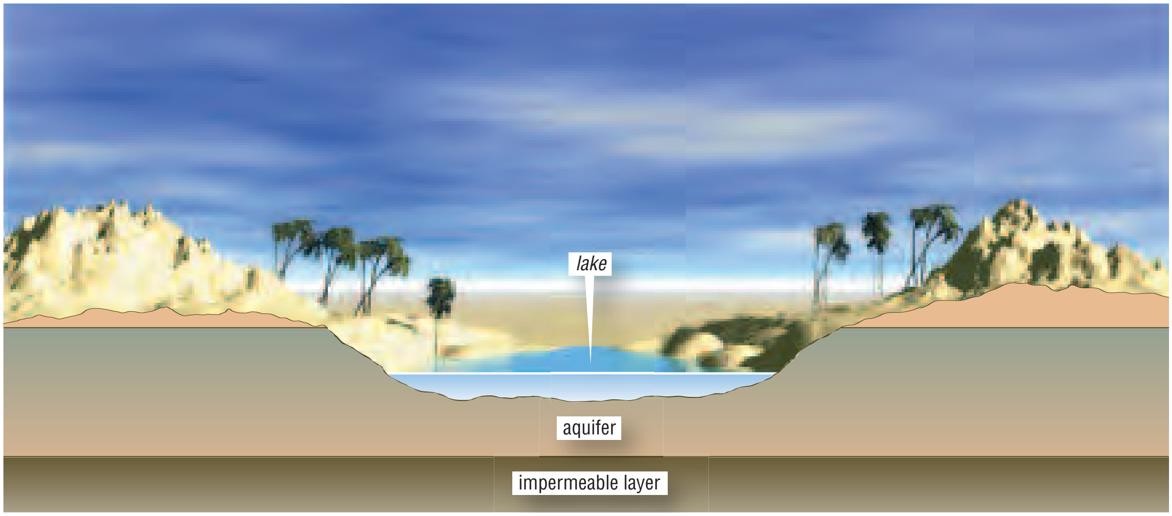
Artesian well. Where an aquifer is confined between two layers of impermeable rock or clay, and these layers form a depression, water will flow without pumping from a well sunk into the center of the depression.

Farms thrive in desert oases. These farms are in Oasis Dakhia, in the Sahara. (Courtesy of Gerry Ellis/Minden Pictures)

Nowadays Egyptians speak Arabic, but the native Egyptian language is Coptic, now used only in Coptic Christian church services. The Coptic word for "to dwell" is *oueh,* and "to drink" is *saa*. Run the two together and they produce *oasis*. An oasis is a place in the desert where people are able to live because there is water to drink and to sustain crop plants.

Many oases are supplied with water by rivers flowing down from mountains and into the desert. There are oases of this type in the Atacama Desert, fed by rivers from the Andes, and rivers flowing down from the Himalayas and the Karakorum Range feed oases in Asian deserts.

An oasis may also occur for no apparent reason. It is just a place where water lies at the surface or, more usually, just below the surface, within the reach of plant roots and easily accessible. The diagram on page 50 shows how an oasis of



Oasis. There is water below the ground in many parts of most deserts. If the bottom of a hollow in the ground surface is lower than the water table, a lake will form, and around the edges of the lake plant roots will be able to reach the moisture below ground.

this kind obtains its water. The water originates in rivers flowing from the mountains, just as it does with the more obvious oases. In this case, though, the water has sunk into the ground and become an aquifer. Erosion has hollowed out the ground, lowering the surface until it lies below the level of the water table. Water then lies on the surface or just below it, for the same reason that water fills the bottom of a well that penetrates the aquifer. In effect, the oasis is a well, but one from which all the overlying material has been removed.

Oases can be large. The Siwa oasis in western Egypt is six miles (10 km) long by four to five miles (6–8 km) wide and its water comes from about 200 springs. The ancient Egyptians knew it as Sekht-am, meaning “palm land.”

DESERT CLIMATES

Why there are belts of desert throughout the subtropics

Equatorial regions have a warm, wet climate. Except where they have been cleared, luxuriant forests cover the lowlands and extend up the mountainsides until they reach elevations where the air is too cold for them. Much of the land between the equator and the Tropics experiences this type of climate, but in the subtropics, to either side of the tropics of Cancer and Capricorn, the climate is different. That is where deserts encircle the Earth. In the Northern Hemisphere, the Sahara, Arabian, and Thar, or Great Indian, Deserts lie on or close to the tropic of Cancer, and the Kalahari and Australian Deserts lie on the tropic of Capricorn, in the Southern Hemisphere.

The warm, wet, equatorial climate and the hot, dry climate of the subtropical deserts complement one another. Both result from the fact that the Sun shines more intensely over the equator than it does over any other part of the world. Oddly enough, the deserts are also a consequence of the fact that more ocean than land lies along the equator.

Stand outdoors on a warm day and you will feel the warmth of the Sun shining on your body. You are feeling *radiant heat,* which is electromagnetic radiation similar to visible light, but at a wavelength our eyes cannot see. Air is almost completely transparent to radiation at this wavelength. Sunshine passes through it, barely affecting it. More solid objects, such as our bodies and the surface of land and water, are not transparent to it, however. They absorb the sunshine and it warms them. You cannot feel it, but when the sunshine warms your skin, some of that warmth is transferred to the layer of air touching your skin. As that air grows warmer, it expands and becomes less dense. It then rises away from you and denser, cooler air takes its place. The Sun is

General circulation of the atmosphere

The tropics of Cancer in the north and Capricorn in the south mark the boundaries of the belt around the Earth where the Sun is directly overhead on at least one day in the year. The Arctic and Antarctic Circles mark the boundaries of regions in which the Sun does not rise above the horizon on at least one day of the year and does not sink below the horizon on at least one day in the year.

A beam of sunlight illuminates a much smaller area if the Sun is directly overhead than it does if the Sun is at a low angle in the sky. The amount of energy is the same in both cases, but the energy is spread over a smaller area directly beneath the Sun than it is when the Sun is lower. This is why the Tropics are heated more strongly than any other part of the Earth and the amount of heat falling on the surface decreases with increasing distance from the equator (increasing latitude).

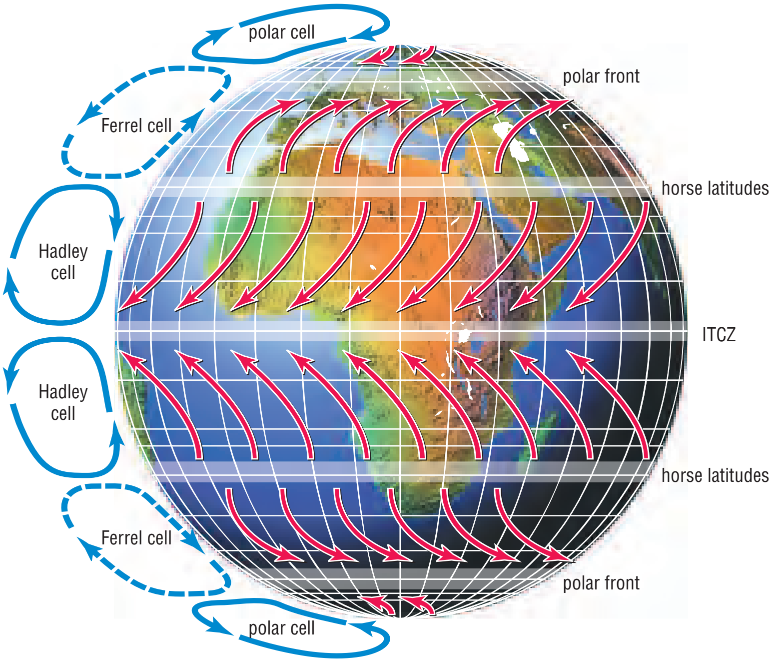
The Sun shines more intensely at the equator than it does anywhere else, but air movements transport some of the warmth away from the equator. Near the equator, the warm surface of the Earth heats the air in contact with it. The warm air rises until it is close to the tropopause, which is the boundary between the lowest layer of the atmosphere (the troposphere) in which air temperature decreases with height, and the layer above (the stratosphere), where the temperature remains constant with increasing height. The height of the tropopause is around 10 miles (16 km), and at this height the air moves away from the equator, some heading north and some south. As it rises, the air cools, so the high-level air moving away from the equator is very cold—about –85°F (–65°C).

This equatorial air subsides around latitude 30°N and S, and as it sinks it warms again. By the time it reaches the surface it is hot and dry, so it warms this region, producing subtropical deserts. At the surface, the air divides. Sometimes called the horse latitudes, this is a region of light, variable winds or no winds at all. Most of the air flows back toward the equator and some flows away from the equator. The air from north and south of the equator meets at the Intertropical Convergence Zone (ITCZ), and this circulation forms a number of vertical cells called *Hadley cells,* after George Hadley (1685–1768), the English meteorologist who first proposed them in 1735.

Over the poles, the air is very cold. It subsides, and when it reaches the surface it flows away from the poles. At about latitude 50–60°N and S, air moving away from the poles meets air moving away from the equator at the polar front. The converging air rises to the tropopause, in these latitudes about seven miles (11 km) above the surface. Some flows back to the poles, forming polar cells, and some flows toward the equator, completing Ferrel cells, discovered in 1856 by the American climatologist William Ferrel (1817–91).

Warm air rises at the equator, sinks to the surface in the subtropics, flows at low level to around latitude 55°, then rises to continue its journey toward the poles. At the same time, cold air subsiding at the poles flows back to the equator. The diagram below shows how this circulation produces three sets of vertical cells in each hemisphere. It is called the "three-cell model" of the atmospheric circulation.

If it were not for this redistribution of heat, weather at the equator would be very much hotter than it is, and weather at the poles would be a great deal colder.



General circulation of the atmosphere. Warm air rises over the equator, moves away from the equator at high altitude, and subsides over the Tropics; there it divides, some flowing back toward the equator and some flowing away from the equator. This forms a series of Hadley cells. Cold air subsides over the poles and flows away from the poles at low level. This forms a series of polar cells. Air rises where Hadley-cell air flowing away from the Tropics meets polar-cell air flowing toward the equator. The air flows toward the equator at high altitude, descending where it meets high-level Hadley-cell air. This forms a series of Ferrel cells.

warming you by radiation and you are warming the air by the process called *convection*. Your body is like a radiator, absorbing warmth and then warming the air with it.

The Earth behaves in exactly the same way—but on a much bigger scale. Its land and water surfaces absorb sunshine, their temperatures rise, and they warm the air in contact with them. The warm air then rises, distributing the Sun's warmth by convection.

It is moist air. Around the equator there is more sea than land for the sunshine to warm, and as the water grows warmer its molecules start to break free and enter the air. Water evaporates and the water vapor rises in the warm air. As it rises, the air grows cooler and the water vapor condenses to form huge clouds. These clouds produce the rain that gives the region its wet climate.

Very high in the sky, the rising air levels off and moves northward and southward, away from the equator. When it reaches the latitudes of the two Tropics, the air meets air moving in the opposite direction, toward the equator. *Convergence*—the meeting of air—makes the air subside all the way to the surface, where some of it flows back toward the equator and the remainder flows away from the equator. This movement of air—rising over the equator, traveling away from the equator, subsiding over the Tropics, and returning to the equator—forms a *convection cell*. It is one part of the overall movement of the atmosphere that transports warmth from the equator to the Poles. The process is called the *general circulation of the atmosphere* (see the sidebar on page 52).

The air moving away from the equator at high altitude is very cold and very dry. It is cold because when air rises its temperature falls. As the air grows colder, its capacity for holding water vapor decreases. That is why clouds form, and it is also why the high-altitude air is so dry: It lost its moisture during its rise.

As it subsides again, the air becomes warmer; this change of temperature is called *adiabatic* (see the sidebar on page 55). The air warms faster as it descends than it cooled when it rose over the equator. This is because rising moist air cools at the *saturated adiabatic lapse rate,* averaging 3°F per 1,000 feet

(6°C/km), but subsiding dry air warms at the *dry adiabatic lapse rate* of 5.4°F for every 1,000 feet (9.8°C/km). By the time the air reaches the surface it is very warm. It is still very

Adiabatic cooling and warming

Air is compressed by the weight of air above it. Imagine a balloon partly inflated with air and made from some weightless substance that totally insulates the air inside. No matter what the temperature outside the balloon, the temperature of the air inside remains the same.

Imagine the balloon is released into the atmosphere. The air inside is squeezed between the weight of air above it, all the way to the top of the atmosphere, and the denser air below it.

Suppose the air inside the balloon is less dense than the air above it. Denser air will push beneath it and the balloon will rise. As it rises, the distance to the top of the atmosphere becomes smaller, so there is less air above to weigh down on the air in the balloon. At the same time, as the balloon moves through air that is less dense, it experiences less pressure from below. This causes the air in the balloon to expand.

When air (or any other gas) expands, its molecules move farther apart. The amount of air remains the same, but it occupies a bigger volume. As they move apart, the molecules must "push" other molecules out of their way. This uses energy, so as the air expands its molecules lose energy. Because they have less energy they move more slowly.

When a moving molecule strikes something, some of its energy is transferred to whatever it strikes, and part of that energy is converted into heat. This raises the temperature of the struck object by an amount related to the number of molecules striking it and their speed.

In expanding air, the molecules are moving farther apart, so a smaller number of them strike an object each second. They are also traveling more slowly, so they strike with less force. This means the temperature of the air decreases. As it expands, air cools.

If the air in the balloon is denser than air below, it will sink. As it sinks, the pressure on the air will increase, its volume will decrease, and its molecules will acquire more energy. Its temperature will increase.

This warming and cooling has nothing to do with the temperature of the air surrounding the balloon. It is called *adiabatic* warming and cooling, from the Greek word *adiabatos,* meaning "impassable," suggesting that the air is enclosed by an imaginary boundary through which heat is unable to pass.

dry, and as its temperature increased, so did its capacity for holding water vapor. Thus the desert air can absorb a large amount of moisture without producing clouds.

Subsiding air produces high atmospheric pressure at the surface, and there are areas of permanent high pressure over the subtropics. Air flows outward from areas of high pressure, in this case as part of the general circulation of the atmosphere, and the outward movement blocks the entry of air from beyond the deserts. Incoming air might bring moisture, and so the high pressure is another factor keeping the subtropical deserts dry.

Ocean gyres and boundary currents

Many deserts lie on the western side of continents. The North American deserts, the Atacama of South America, and the Namib Desert of southern Africa are examples. These west coast deserts (see "West coast deserts" on pages 16–19) are dry because just offshore there is an ocean current carrying cold water. Contact with the cold water lowers the temperature of the layer of air near the surface, and the presence of a surface layer of cool, dense air makes the air highly stable (see the sidebar "Lapse rates and stability" on page 60). No air is rising and therefore no water vapor can condense to form clouds that might produce rain.

Ocean currents are driven by the prevailing winds and in every ocean they follow approximately circular paths, called *gyres*. Gyres turn clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Because they flow around the outer rims of ocean basins, the currents that flow close to and parallel to the coasts of continents are known as *boundary currents*. Western boundary currents in both hemispheres carry warm water toward the Poles. They are usually deep, narrow, and fast flowing. Eastern boundary currents carry cool water toward the equator. They are broad, shallow, and slow moving. Deserts occur along western coasts because their climates are influenced by nearby eastern boundary currents.

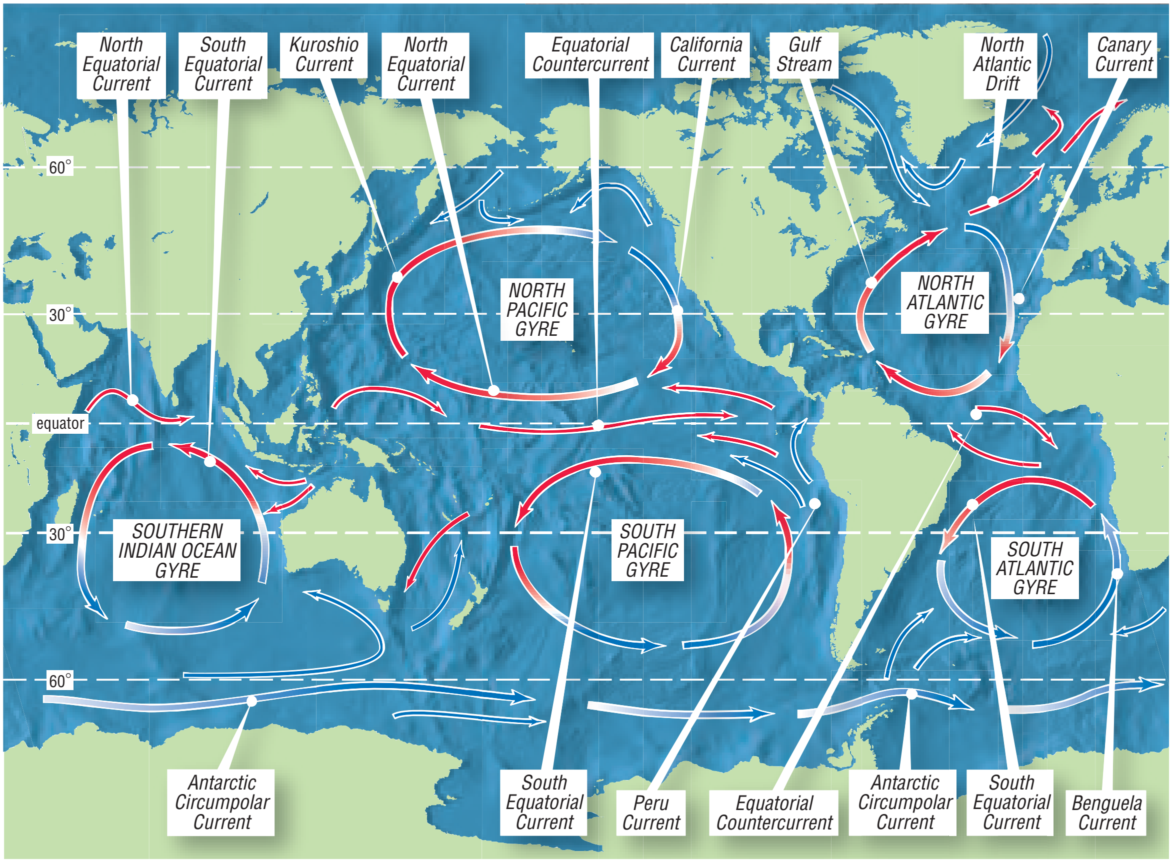
In the South Pacific, the South Equatorial Current moves from east to west, driven by the southeasterly trade winds. As it approaches Indonesia and Australia, it turns to flow southward, passing Australia as the warm East Australian Current. As it leaves the Tropics, the current enters the region where the prevailing winds are from the west and it joins the West Wind Drift, or Antarctic Circumpolar Current. This is the only ocean current that travels uninterrupted all the way around the world. It is able to do so because there is no continent in its path to deflect it.

Although the West Wind Drift travels all around the world, from west to east, at each of the southern continents a part of the current is diverted. In the South Pacific, this section of the current flows northward parallel to the South American coast, as the Peru Current, also called the Humboldt Current. The cold water of the Peru Current produces the stable air that gives the Atacama its extremely dry climate. The Peru Current then comes under the influence of the trade winds and turns to flow westward. It has become the South Equatorial Current once more.

The North Pacific gyre, which produces the North American deserts, begins as the North Equatorial Current, flowing westward. As it approaches Asia, it turns to flow northward, the western boundary current passing Japan as the warm Kuroshio Current. It continues to turn and crosses the ocean eastward as the North Pacific Current. It turns southward as it approaches North America, then flows parallel to the coast as the cool California Current, the eastern boundary current.

In the South Atlantic, the westward-flowing South Equatorial Current turns to flow southward past the South American coast as the warm Brazil Current. It joins the West Wind Drift, and as it approaches Africa part of this eastward-flowing water diverts northward, parallel to the coast, forming an eastern boundary current. This is the cool Benguela Current associated with the Namib Desert, and it rejoins the South Equatorial Current.

The North Atlantic gyre begins as the North Equatorial Current (flowing westward). As it approaches the Caribbean and Central America it becomes the Antilles Current and then the Florida Current, before turning to flow northward from the Gulf of Mexico as the Gulf Stream. The Gulf Stream divides, with one section continuing in a northwesterly



Gyres. The surface currents in all of the oceans follow approximately circular paths, called gyres, but the names of the currents change in different parts of each gyre. The map shows the gyres and some of the names of currents.

direction as the North Atlantic Current, also called the North Atlantic Drift, and the other flowing southward as the cool Canary Current—and bringing dry conditions to the Atlantic Sahara.

The Indian Ocean straddles the equator and it has two, rather more complicated gyres. The southern gyre includes the warm Agulhas Current, which flows along the African coast, and the cool West Australian Current. The map above shows the gyres, with the names of the principal currents.

Monsoons

Despite being in the same latitude as the Sahara, central and southern India and southern Asia are not deserts. They receive very little rain during the winter, but rainfall is heavy in the summer. Their climate is one of seasonal extremes. The Arabic word for "season" is *mausim* and it may have given us the name we use to describe these seasons. We call them the monsoons.

The winter monsoon is dry and the summer monsoon is wet. Between October and May, Bombay (now called Mumbai), India, receives an average 4.1 inches (104 mm) of rain. Between June and September the city receives an average 67.2 inches (1,707 mm). Parts of West Africa, northeastern Brazil, and the interior of the southern United States also experience monsoon seasons—in the United States it is the summer that is dry and the winter that is wet—but nowhere can compare with the extremes of the southern Asian climate.

Monsoons result from the fact that the land warms up and cools much more rapidly than does the ocean (see the sidebar "Specific heat capacity" on page 66). They occur only in tropical and subtropical regions, because they require intense warming of the surface. They also occur only over large continents, because they need a large land area adjacent to an ocean to generate the right atmospheric conditions.

In winter the land cools rapidly. As its temperature falls, the lower layers of air also cool. The air becomes dense, and as the cold air subsides the surface pressure increases. The subsiding air is dry and it flows out from the region of high pressure, producing very dry weather over land. The ocean cools much more slowly and so it remains warmer than the land until late in the winter. Air rises over the ocean, losing its moisture as it does so, and is then drawn over the land at high altitude, where it subsides. Winter is therefore a time of dry winds that blow from the land to the sea. They produce the dry winter monsoon.

In summer the situation reverses. The land warms faster than the ocean. Warm air rises over land, but over the ocean the air is still cold and it subsides. The flow of air reverses, with dry air moving at high altitude from land to sea, and moist air moving at low level from sea to land. The moist air rises as it crosses the coast and high ground inland. This makes it highly unstable (see the sidebar on page 60). Huge clouds form and produce violent storms and torrential rain.

Lapse rates and stability

Air temperature decreases (or lapses) with increasing height. The rate at which it does so is called the *lapse rate.* Although all air contains some water vapor, air that is not saturated with moisture—all of its moisture is present as vapor rather than liquid droplets or ice crystals—is said to be *dry.* When dry air cools adiabatically, it does so at 5.4°F for every 1,000 feet (9.8°C/km) that it rises. This is known as the *dry adiabatic lapse rate* (DALR).

When the temperature of the rising air has fallen sufficiently, its water vapor will start to condense into droplets. Condensation commences at the *dew-point temperature* and the height at which this temperature is reached is called the *lifting condensation level.* Condensation releases *latent heat,* which warms the air. Latent heat is the energy that allows water molecules to break free from each other when liquid water vaporizes or ice melts. It does not change the temperature of the water or ice, which is why it is called *latent,* meaning "hidden." The same amount of latent heat is released, warming the surroundings, when water vapor condenses and when liquid water freezes. Consequently, the rising air then cools at a slower rate, known as the *saturated adiabatic lapse rate* (SALR). The SALR varies, depending on the rate of condensation, but it averages 3°F per 1,000 feet (6°C/km).

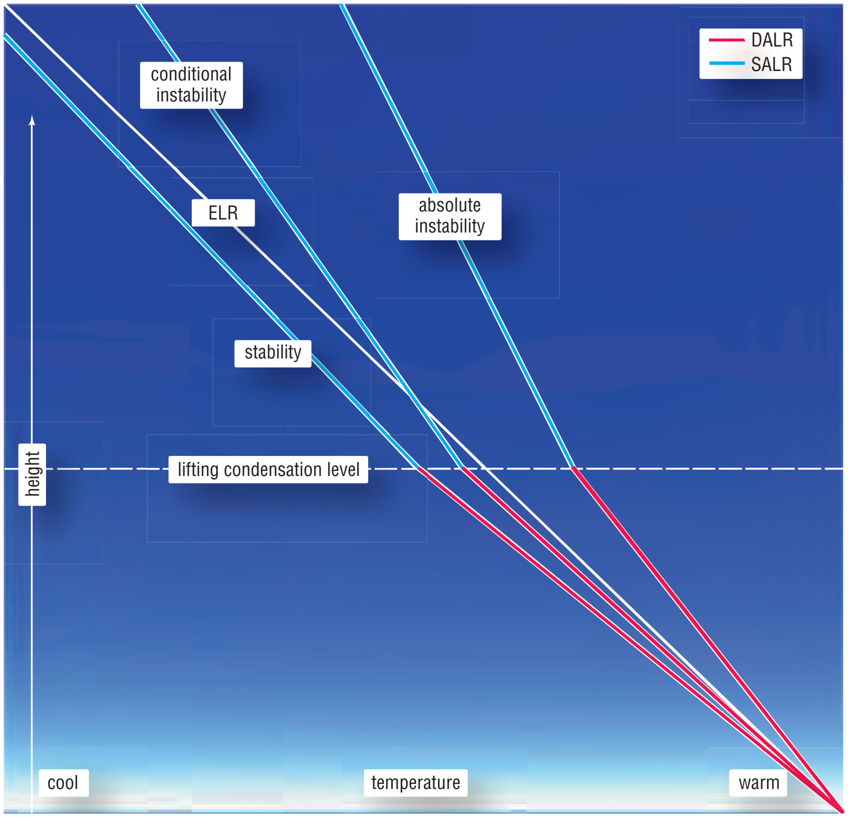
The actual rate at which the temperature decreases with height in air that is not rising is called the *environmental lapse rate* (ELR). It is calculated by comparing the surface temperature, the temperature at the tropopause (it is about –85°F; –65°C at the equator), and the height of the tropopause (about 10 miles; 16 km over the equator).

If the ELR is less than both the DALR and SALR, rising air will cool faster than the surrounding air, so it will always be cooler and will tend to subside to a lower height. Such air is said to be *absolutely stable.*

If the ELR is greater than the SALR, air that is rising and cooling at the DALR and later at the SALR will always be warmer than the surrounding air. Consequently, it will continue to rise. The air is then *absolutely unstable.*

If the ELR is less than the DALR but greater than the SALR, rising air will cool faster than the surrounding air while it remains dry but more slowly once it rises above the lifting condensation level. At first it is stable, but above the lifting condensation level it becomes unstable. This air is said to be *conditionally unstable.* It is stable unless a condition (rising above its lifting condensation level) is met, whereupon it becomes unstable. This is shown by the lines in the middle of the diagram on page 61.

Stable air brings settled weather. Unstable air produces heaped clouds of the *cumulus* type. The base of these clouds is at the lifting condensation level, and the cloud tops are at the altitude where the rising air has lost enough water vapor to make it dry once more, so it is cooling at the DALR. If the air is sufficiently unstable, however, the clouds can grow into towering *cumulonimbus* storm clouds. Equatorial air is usually unstable.



Stability of air. If the environmental lapse rate (ELR) is less than both the dry (DALR) and saturated (SALR) lapse rates, the air is stable. If the ELR is less than both the DALR and the SALR, the air is absolutely unstable. If the ELR is less than the DALR but greater than the SALR, the air is conditionally unstable.

The Indian monsoons are intensified by the influence of the Himalayas and the Tibetan Plateau. Winter temperatures fall very low over central Asia and Tibet. The high pressure this produces does not affect the air to a very great height, but it is fed by air subsiding from the jet stream to the north of the Himalayas (see "Air masses, fronts, and jet streams" below through page 65). Air flowing southward from the Asian high-pressure zone loses any moisture it may carry as it crosses the Himalayas. By the time it reaches India it is extremely dry. Its temperature rises as it descends from the mountains (see the sidebar "Adiabatic cooling and warming" on page 55). The prevailing winds over India are the trade winds, blowing from the northeast. These strengthen the flow of air descending from the mountains.

In spring, as the land heats up, air rises by convection and there are scattered storms. At this time the Intertropical Convergence Zone (ITCZ) is moving northward. The ITCZ is the belt where the northeasterly trade winds of the Northern Hemisphere and southeasterly trade winds of the Southern Hemisphere meet. The ITCZ finally halts along the southern edge of the Himalayas. The winds over India then blow from the southwest, bringing air from the Arabian Sea and the summer monsoon.

Spring is the hot season. Temperatures inland rise above 90°F (32°C). In Jacobabad, Pakistan, the average daytime temperature in May is 111°F (44°C) and it has been known to reach 123°F (51°C). As the ITCZ moves northward, the trade winds slacken and the air becomes still. When the rains arrive they do so suddenly. Clouds have been building for some time until there is a "burst of monsoon," when the skies open and there is a deluge. The monsoon begins in the southeast, reaching southern China early in May, and advances in a northwesterly direction, reaching Pakistan in July.

Air masses, fronts, and jet streams

Air lying over a continent or an ocean acquires fairly uniform characteristics. After a time the temperature, pressure, and humidity at any altitude are much the same everywhere.

This may sound obvious, but it was not until the early 20th century that the implications of this fact were discovered. In 1917 a Norwegian physicist and meteorologist named Vilhelm Bjerknes (1862–1951) left the University of Leipzig, Germany, where he had been a professor, and returned to Norway to establish and become director of the Bergen Geophysical Institute. He gathered together a team of talented scientists, who set up a network of weather stations throughout Norway. The weather stations reported their measurements and observations to Bergen, where Bjerknes and his team assembled them to produce pictures of atmospheric conditions over a large area. The scientists found that the characteristics of air over a large area were often similar everywhere, but that they differed radically from the characteristics of air somewhere else. They called a large, uniform volume of air an *air mass*.

Air masses are given names that describe them. The first division is between continental air (abbreviated as c), which is dry, and maritime air (m), which is moist. These divisions are qualified further according to the latitude in which the air mass formed, as arctic (A), polar (P), tropical (T), and equatorial (E). The names are then combined to give continental arctic (cA), continental polar (cP), continental tropical (cT), maritime arctic (mA), maritime polar (mP), maritime tropical (mT), and maritime equatorial (mE). There is no continental equatorial air, because oceans cover most of the equatorial region.

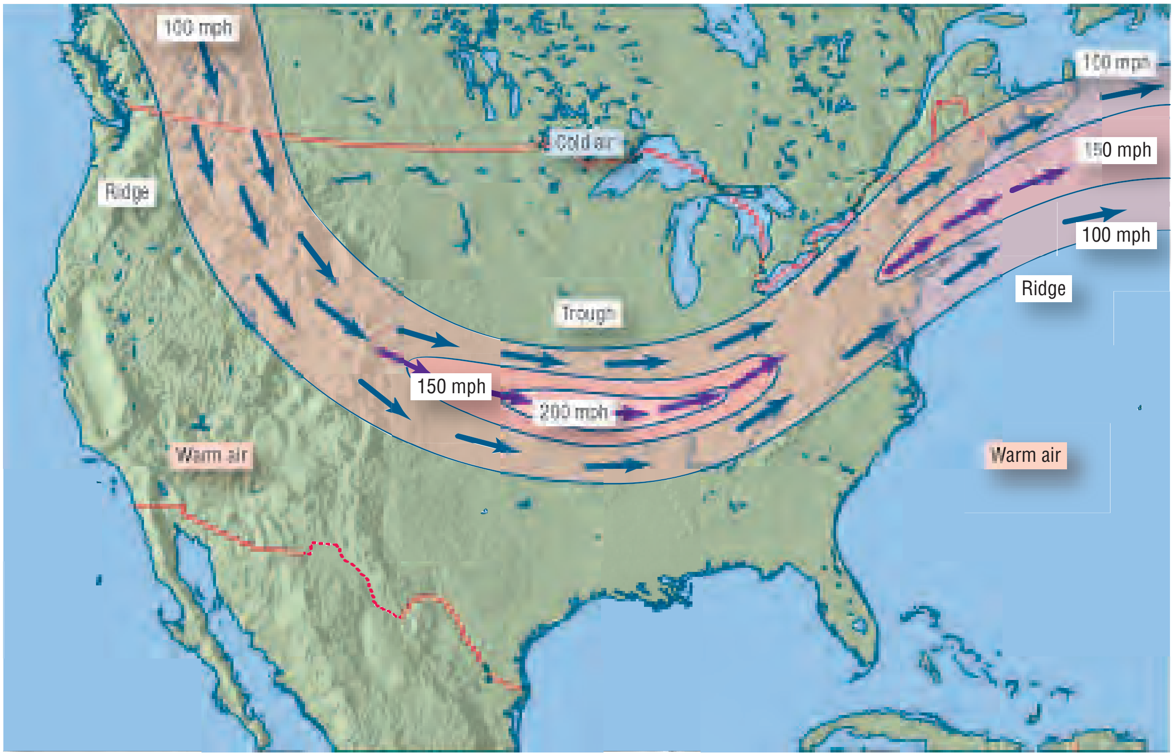
The Bergen scientists also found that although different air masses move about, they do not mix readily with one another. One air mass is cooler and denser than the air mass adjacent to it and rather than mixing, the warm air rides above the cool air. When Bjerknes and his colleagues made these discoveries it was wartime and the newspapers were full of stories of battles. It seemed to the Norwegian scientists that air masses were a little like opposing armies, and the boundaries where air masses meet and struggle against one another were like fronts, and so that is what they called them. It is the name we still use.

Air masses move, and as they do so their characteristics change. Continental air gathers moisture as it crosses the ocean, for example, and maritime air loses moisture as it crosses a continent. Carried by the prevailing winds, air masses move along tracks that are approximately parallel to the equator, so the changes in air mass characteristics affect the moisture the air carries much more than its temperature. Fronts are named for the air behind them. If the air is warmer after the front has passed it is a warm front. If the air is cooler after it has passed it is a cold front.

Weather maps on TV and in newspapers show the positions of fronts on the surface, using standard symbols to identify them—red semicircles for a warm front and blue triangles for a cold front. Cold fronts travel faster than warm fronts. Consequently, cold air tends to push beneath warm air, raising it from the ground. Once the warm air starts to rise the two fronts begin to merge. They are said to be *occluded* or to form an *occlusion,* symbolized by alternating semicircles and triangles. Eventually the cold air raises all of the warm air clear of the ground. The fronts then disappear, together with any weather associated with them.

In middle latitudes, frontal weather systems often follow one another, traveling from west to east. They are produced along the *polar front.* This is the front between tropical and polar air that forms where the polar and Ferrel cells meet (see the sidebar "General circulation of the atmosphere" on page 52).

Frontal systems move because they are following waves—north-south undulations—traveling along the polar front and the strong wind, or *polar jet stream,* that blows along the top of the front just below the tropopause. A jet stream is a ribbon of wind, 60–300 miles (100–500 km) wide, often blowing at more than 120 MPH (200 km/h) and occasionally at as much as 300 MPH (500 km/h). The jet stream results from the sharp difference in temperature across the polar front. It blows from west to east in both hemispheres. The Northern Hemisphere polar jet stream moves northward in summer and retreats to the south in winter. It is usually located at about 50°N in summer and 40°N in winter, but sometimes it moves farther. Its total range is from 30°N to 70°N. Because the jet stream results from the contrast in temperature between tropical and polar air, it is strongest in winter,



Ridges and troughs in the jet stream across North America. A trough is the region where the jet stream projects southward. A ridge is the region where the jet stream projects northward.

and that is also when the weather systems it produces are most pronounced.

The jet stream follows a wavy course and from time to time the waves grow bigger, extending toward the equator as *troughs* and toward the pole as *ridges,* as shown in the illustration. Troughs bring polar air and low pressure, with cold, wet weather, to regions as far south as Arizona and New Mexico. Ridges carry tropical air, with high pressure and fine warm weather, as far north as Alaska. Ridges and troughs sometimes remain stationary for several days or weeks, producing prolonged spells of fine or wet, hot or cold weather.

Why hot deserts are cold at night

Soon after sunrise the temperature begins to climb. At In Salah, Algeria, however, in the heart of the Sahara where the average rainfall is only 0.7 inch (17 mm) a year, the nights can be cold. In Salah is at latitude 27.2°N, almost in the Tropics, yet between December and February the temperature occasionally falls below freezing at night.

As the morning advances the temperature continues to rise. By mid afternoon it has reached its maximum, and that is hot. Even in the middle of winter—December and January—the temperature at In Salah has been known to reach 88°F (31°C). July is the hottest month, when the average afternoon temperature is 113°F (45°C) and it can rise to 122°F (50°C). At night the temperature drops to an average 83°F (28°C) and sometimes to 73°F (23°C).

Death Valley, at latitude 36.47°N in California's Mojave Desert, experiences even greater extremes of temperature.

Specific heat capacity

When a substance is heated, it absorbs heat energy and its temperature rises. The amount of heat it must absorb in order to raise its temperature by one degree varies from one substance to another, however. The ratio of the heat applied to a substance to the extent of the rise in its temperature is called the *specific heat capacity* for that substance. It is measured in calories per gram per degree Celsius (cal/g/°C) or in the scientific units of joules per gram per kelvin (J/g/K; 1K = 1°C = 1.8°F). Specific heat capacity varies slightly according to the temperature, so when quoting the specific heat capacity of a substance it is customary to specify the temperature or temperature range to which this refers.

Pure water has a specific heat capacity of 1 cal/g/°C (4,180 J/g/K) at 59°F (15°C). This means that at 59°F (15°C) one gram of water must absorb one calorie of heat in order for its temperature to rise by one degree Celsius (or 0.56 cal to raise its temperature by 1°F). Seawater at 17°C (62.6°F) has a specific heat capacity of 0.94 cal/g/°C (3,930 J/g/K).

The desert surface consists of granite rock and sand. At temperatures between 68°F (20°C) and 212°F (100°C), the specific heat capacity of granite is 0.19–0.20 cal/g/°C (800–840 J/g/K). Within the same temperature range, the specific heat capacity of sand is 0.20 cal/g/°C (800 J/g/K). These values are typical for most types of rock.

Water has a specific heat capacity about five times that of rock. This means that water must absorb five times more heat than rock to produce a similar rise in temperature. It is why water warms up so much more slowly than sand and rock. Visit the beach on a real-

The average maximum temperature in July is 117°F (47°C), but 134°F (57°C) has been recorded. In January the average minimum temperature is 38°F (3°C), but it has been known to drop to 15°F (–9°C).

It comes as no surprise to learn that the Sahara and other subtropical deserts are hot places, especially in summer. The surprise is that the temperature drops so far during the night. Over the course of 24 hours in every month of the year, the average temperature at both In Salah and Death Valley changes by 26–30°F (14–17°C).

Temperatures are always measured in the air well clear of the ground. Air is heated by contact with the ground and so the diurnal change in air temperature reflects a change in the

ly hot day in summer and by lunchtime the sand will be so hot you have to run across it to avoid hurting your bare feet, but when you splash into the water, it is refreshingly cool. The reason for this is the difference in the specific heat capacities of water and sand.

In the desert the rock and sand, with a low specific heat capacity, heat up rapidly. By the middle of the day the ground is extremely hot. Specific heat capacity works both ways, though: Substances that heat quickly also cool down again quickly. The molecular configuration that confers a rapid response to absorbed heat also ensures that the heat cannot be retained for long once the external supply shuts down.

The ground radiates its heat into the sky. If there were clouds, they would absorb much of this heat and reradiate it, effectively trapping heat and keeping the air warm. But the desert sky is cloudless and so the heat is lost into space.

During the day, the desert rock and sand absorb heat from the Sun. Their temperature rises and as it does so they reradiate their energy into the sky, but at the same time they continue to absorb solar radiation. The balance between the energy sand and rock absorb and the energy they radiate allows the surface temperature to rise to a peak in the early afternoon, after which it remains steady. Then, as the Sun sinks toward the horizon, the balance starts to shift. Radiation from the surface remains constant, but less solar energy is absorbed. The surface starts to cool, but slowly at first. Once the Sun sinks below the horizon and darkness falls, there is no more sunshine for the desert to absorb, but its radiation continues. The surface temperature then plummets. Desert nights are cold. Sometimes they are very cold indeed.

temperature of the ground surface. Even in the northern United States, a sandy beach on a summer afternoon can be hot enough to burn your feet. In the Sahara, by about 4 P.M. in summer the temperature of the sand can reach 170°F (77°C).

Desert surfaces are made from rock or sand—and sand is simply weathered rock (see "What is sand?" on pages 36–37). Rock and sand warm up quickly. To put this more technically, they need to absorb only a small quantity of heat before their temperature begins to rise. They are said to have a low *specific heat capacity* (see the sidebar on pages 66–67). Water has a much higher specific heat capacity, so it heats up much more slowly. That is why the sea or lake beside the beach is always a place to cool off, even in the hottest weather. At night the ground loses heat as readily as it absorbed it during the day. It cools rapidly, unlike water, which cools very slowly. That is why the desert is so hot by day and so much cooler, even cold, by about one hour before dawn, when the temperature is at its lowest.

The high specific heat capacity of water moderates the extremes of temperature near the coast. As the land warms up, air above it rises and is replaced by cooler air from over the water. This is a sea or lake breeze, and it blows most strongly in the afternoon, bringing cool air when the temperature over land reaches its maximum. At Algiers, on the coast of the Mediterranean Sea, the average temperature range is 10–15°F (5–8°C)—half that of In Salah. In summer the average temperature at Algiers reaches 84°F (29°C), and even on the coldest night in winter it never falls below freezing.

Why the climates that produce ice sheets are so dry

Both Greenland and Antarctica lie buried beneath ice that is more than one mile (1.6 km) thick, yet despite this abundance of water, both Greenland and the interior of Antarctica have a climate that is more arid than all but the driest deserts. In terms of the precipitation they receive, they are among the driest places in the world.

Why Antarctica is colder than the North Pole

Vostok is the name of a Russian research station in Antarctica, located at about 78.75°S. Qaanaaq is a small town in northern Greenland (Kalaallit Nunaat), at 76.55°N.

They are in comparable latitudes, but they have very different climates. At Vostok, January is the warmest month, when the average temperature is –26°F (–32°C). The coldest month is August, with an average temperature of –90°F (–68°C). At Qaanaaq, the average temperature ranges from a high of 46°F (8°C) in July, the warmest month, to a low of –21°F (–29°C) in February.

Both places are dry, despite all the snow and ice. Qaanaaq has an annual rainfall of 2.5 inches (64 mm). It falls as snow in winter, of course, but in order to standardize measurement it is converted to the equivalent amount of rainfall. Vostok has 0.2 inch (4.5 mm).

The temperature range is similar for both: 64°F (36°C) at Vostok and 67°F (37°C) at Qaanaaq. The difference is that Vostok is much colder than Qaanaaq. This is because Qaanaaq is on the coast, albeit of an ocean that is frozen over for much of the year, and Vostok is in the interior of a large continent. The North Pole is located in the Arctic Ocean and the Arctic Basin is sea, surrounded by Eurasia, North America, and Greenland.

A large ice sheet covers East Antarctica, where Vostok is located. Air subsiding into the permanent Antarctic high-pressure region flows outward as a bitterly cold, extremely dry wind that blows almost incessantly. This combined with its elevation—Vostok is 11,401 feet (3,475 m) above sea level, on top of the thick ice—is what gives Vostok its cold, dry climate.

Antarctica also receives seven percent less solar radiation during its winter than the Arctic does in its winter. That is because the Earth's orbit around the Sun is not circular, but slightly elliptical, and the Sun is not at the center of the orbit. Earth is farthest from the Sun—*aphelion*—on about June 4, in the middle of the Southern Hemisphere winter. It is closest to the Sun—*perihelion*—on about January 4, in the middle of the Northern Hemisphere winter.

Qaanaaq is at sea level, but its altitude is not the principal reason for its warmer climate. It is warmer because of the sea. Ocean currents carry warm water into the Arctic Basin. The sea is frozen for most of the year, but there are gaps in the ice—called *leads*—that appear and disappear. Winds move the ice, piling it up in some places and leaving it thin in others. Heat escapes from the ocean where there are open water surfaces, but ice insulates the areas it covers. The sea temperature never falls below 29°F (–1.6°C); below

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this temperature the water approaches its greatest density and sinks below warmer water that flows in at the surface to replace it. When the air temperature over the water falls below the temperature of the sea surface, heat passes from the water to the air. This warmer air then moves across the ice. Consequently, air temperatures over the entire Arctic Basin are much higher than they would be if there were land rather than sea beneath the ice. The coldest temperature ever recorded over the ice in the Arctic is –58°F (–50°C) and over most of the Basin the average temperature ranges between about 4°F (–20°C) and –40°F (–40°C). On July 21, 1983, the temperature at Vostok fell to –128.6°F (–89.2°C).

The polar regions are dry principally because they are so cold. The amount of water vapor that air can hold depends on the temperature. The warmer the air, the more moisture it can carry. On a bitterly cold winter's day you sometimes hear people say, "It's too cold for snow." They are right. Air that is extremely cold is also extremely dry.

The polar regions are cold because of their high latitude. Even in summer, when the Sun remains above the horizon for 24 hours, producing the "land of the midnight Sun," the Sun remains low in the sky and its warmth is spread thinly over a large area, because of the low angle. In winter there are days when the Sun does not rise above the horizon at all.

The two polar regions are not equally cold, however. Both are in similar latitudes and both receive almost equal amounts of sunshine, but Antarctica is very much colder than Greenland or any other place inside the Arctic Circle. The sidebar on page 69 explains why this is so.

On a bright day in summer, in places sheltered from the wind, the sunshine can feel quite warm, yet it does not warm the ground. Up to 90 percent of the solar radiation is reflected by the snow. If you go outdoors on a sunny day following a fresh fall of snow you may need to protect your eyes from the glare, due to the light being reflected from the white surface. It is not only light that is reflected, however. Heat is also reflected, rather than being absorbed by the ground and warming it. Most surfaces reflect some of the sunlight falling on them. The proportion of the total sunshine a surface reflects is known as the *albedo* of that surface. The table below shows the albedo values for a variety of surfaces. They are percentages of the total sunlight falling on them and usually written as a decimal fraction. For example, fresh snow reflects 75–95 percent of the sunlight falling on it, so it has an albedo of 75–95 percent, which is written as 0.75–0.95. The permanently white surface helps ensure that ice-cold Greenland and Antarctica remain cold.

The air is just as cold and the cold, dense air sits heavily over the surface, producing permanently high atmospheric pressure. Air flows outward, away from centers of high pressure, called *anticyclones,* and, like the subtropical anticyclones that keep the hot deserts dry, air flowing out from the polar anticyclones prevents moister air from entering. The polar regions are dry partly because they lie beneath permanent anticyclones (see the sidebar "General circulation of the atmosphere" on page 52).

They are also dry simply because they are cold. Water molecules consist of two hydrogen atoms (H + H) joined to one

Albedo

Surface	Value
Fresh snow	0.75–0.95
Old snow	0.40–0.70
Cumuliform cloud	0.70–0.90
Stratiform cloud	0.59–0.84
Cirrostratus	0.44–0.50
Sea ice	0.30–0.40
Dry sand	0.35–0.45
Wet sand	0.20–0.30
Desert	0.25–0.30
Meadow	0.10–0.20
Field crops	0.15–0.25
Deciduous forest	0.10–0.20
Coniferous forest	0.05–0.15
Concrete	0.17–0.27
Black road	0.05–0.10

oxygen atom (O), producing H_2O, but the hydrogen atoms are both attached on the same side of the oxygen atom. In liquid water the molecules are linked together by *hydrogen bonds,* which are forces of attraction between the small positive electromagnetic charge on a hydrogen atom of one molecule and the negative charge on the oxygen atom of an adjacent molecule. Water molecules join together in small groups that are constantly breaking apart and forming again and that move freely past one another.

If the water is heated, its molecules absorb energy, making groups of molecules move faster and individual molecules vibrate more vigorously. When a molecule has absorbed enough energy it will vibrate so strongly that it breaks free from the hydrogen bond holding it to its neighbor. As more and more hydrogen bonds break, free molecules escape into the air and the liquid water evaporates.

Water vapor—an invisible gas that is not to be confused with steam, which is a cloud of liquid water droplets—is at the same temperature as the air in which it is dispersed. If the air temperature should fall, the water molecules will possess less energy and move more slowly. If the temperature falls far enough, when two molecules meet, a hydrogen bond may form between them. The water vapor will condense into liquid.

As the temperature continues to fall, more and more water molecules link to one another and clouds form. At temperatures below freezing molecules will form ice crystals. The water droplets and ice crystals then merge with one another to form raindrops or snowflakes, and fall from the cloud. Precipitation—rain and snow—removes water from the air, making the air drier.

Air is said to be *saturated* when it contains as much water vapor as it is capable of holding. Even in warm air this amount is quite small. When the air temperature is 86°F (30°C), one pound of air is able to hold 0.4 ounce (26.5 g/km) of water vapor. On a really hot day, when the temperature is 104°F (40°C), one pound of air can hold only 0.75 ounce (47 g/kg) of water vapor. It is never this warm in Greenland or Antarctica. The midsummer temperature in those places is more likely to be around freezing, and at that temperature one pound of air can hold 0.06 ounce (3.5 g/km) of moisture. At –22°F (–30°C), one pound of air can hold no more than 0.005 ounce (0.3 g/kg) of water vapor.

In fact, the air over Greenland and Antarctica is even drier than these figures suggest, because the surface is covered with ice, not liquid water. Ice will change directly into vapor, but it requires more energy to vaporize ice than it does to evaporate liquid water. Consequently, less water vapor enters the air above an ice surface than enters it from a liquid surface.

Why deserts are windy places

Desert air is seldom still. Trade winds blow across the subtropical deserts. These are the most dependable of all winds, blowing from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere, and they lose any moisture they might be carrying as they cross the hot desert surface. By the time they leave the desert they are very dry and very hot.

Trade winds leaving the Sahara are known as the *harmattan,* a hot, dusty, and often strong wind that blows only during the day. At night it dies down. It blows at all times of year, but in summer the monsoon winds (see "Monsoons" on pages 58–62) blowing in the opposite direction make it weaker and less frequent.

The harmattan is stronger than the trade winds because it is accelerated by the natural flow of air away from the anticyclone centered on the desert. When it arrives in tropical Africa the harmattan is so dry that it turns leaves yellow, hardens leather, and makes wood warp. Its extreme dryness comes as a relief to the inhabitants of the humid Tropics, however. They believe that it brings health benefits by driving away the extremely moist, oppressive air. They call it "The Doctor."

Khamsin is the Arabic word for "fifty." It is also the name of a hot, dry, southeasterly wind that in most years blows across Egypt and Sudan on 50 days in late winter and early spring. It results from the counterclockwise circulation of air around low-pressure systems over Sudan and the northern Sahara, which combine to draw in air from over Arabia. Fortunately, the 50 days are not consecutive and the wind seldom continues for more than three days. The khamsin brings temperatures of more than 100°F (38°C) and so much dust that cars must use their headlights in the middle of the day.

Air flowing away from the subtropical anticyclone produces some of the desert wind. The polar anticyclone also generates winds and, like the harmattan, they are accelerated, though for a different reason.

As well as being the coldest continent, Antarctica is also the highest. The average elevation is 8,200 feet (2,500 m) and the Amundsen-Scott Base, at the South Pole, is 9,301 feet (2,837 m) above sea level. The South Pole is approximately at the center of the continent and it is also near the center of the polar anticyclone. Consequently, air moving away from the anticyclone is also moving downhill as it approaches the coast and sea level. Winds that flow downhill are called *katabatic,* from the Greek word *katabatikos* meaning "going downward." As well as flowing down a pressure gradient, from high to low pressure, the air is also flowing under the force of gravity, which accelerates it. At the South Pole the average wind speed is 14 MPH (22.5 km/h) and there are many calm days. Near the coasts, on the other hand, calm days are rare and winds of more than 50 MPH (80 km/h), with still stronger gusts, are common.

Winds in the subtropical deserts are strongest in the afternoon and during the hottest months. These are when the sand and rock surfaces are hottest. Hot air expands and rises, and denser air replaces it at the surface. This makes the air very turbulent and generates strong, gusty winds.

Low-pressure weather systems also cross the desert from time to time. They bring no rain, of course, or even clouds, but they do bring winds that last for longer and are often stronger than the winds produced by daytime heating.

Dust storms and sandstorms

The Sahara is famed for its sand dunes and sand seas (see "Sand seas and sand dunes" on pages 37–41), but even in the Sahara there is almost no sand over more than two-thirds of the total area. Sand dunes cover no more than about two percent of the surface of the Sonoran Desert. Bare rock, stones, and gravel cover the ground. Sand cannot survive in these areas, because as fast as it gathers the wind sweeps it away. The removal of sand and dust by the wind is called *deflation*.

Even a light wind will raise fine dust from the ground, and a wind of 12 MPH (19 km/h)—a breeze strong enough to blow leaves and scraps of paper about—will raise medium-sized sand grains, provided the sand is dry. Deserts are windy places and this wind speed is often exceeded.

Once airborne, desert dust and fine sand can travel a long way. Saharan dust occasionally crosses the Atlantic and is washed to the ground over the United States, and when it is carried northward it has been known to fall over Finland. Desert dust is red and it colors the rain, which is then known as "blood rain." Dust from the Australian deserts sometimes falls as blood rain in New Zealand. The harmattan wind (see "Why deserts are windy places" on pages 73–74) brings relief to people in the hot, humid Tropics, but it also makes them close their doors and windows to keep out the dust.

A strong wind over a large sandy or dusty area will cause a dust storm or sandstorm. A storm of this kind has many local names. It is called a *simoom* in the Sahara, for instance, and *andhis* in the Thar Desert. It is a vast, swirling cloud of sand and dust, driven by the wind. It penetrates clothes and finds its way into houses through the smallest cracks around windows and doors. Driven into ears, mouths, noses, and eyes, the dust causes irritation and it can cause eye damage, even blindness. It also reduces visibility, sometimes almost to zero. In March 1998 poor visibility caused by a storm of this kind, driven by a khamsin wind, closed Cairo airport and the Suez Canal.

In July 2003 windblown sand and dust from the Syrian Desert produced the worst sandstorms in living memory in western Afghanistan. They filled wells and canals, destroyed crops, and contaminated the water supply to thousands of people. The storms began on June 5 and continued until the end of August, affecting about 12,000 people living in 57 villages. Up to 20 villages had to be abandoned because they had been completely buried in sand.

China and Mongolia also suffer. Winds from Siberia gather sand and dust in the Taklimakan and Gobi Deserts. In May 1993 one of these storms affected about 425,000 square miles (1.1 million km^2) of China, damaging 922,000 acres (373,000 ha) of cropland, killing 12,000 head of livestock, destroying 4,400 houses, and killing 85 people. In 2002 Asian dust storms and sandstorms reached the Korean Peninsula and Japan.

Desert storms on this scale are usually caused by cold fronts (see "Air masses, fronts, and jet streams" on pages 62–65). As it advances, a cold front pushes beneath the warmer air ahead of it. This produces strong turbulence and gusty winds that raise a cloud of dust and sand that advances with the front, like a wall of sand, which is often 3,000 feet (900 m) high. It is impossible to work during a sandstorm and even eating and drinking are difficult, because the sand and dust contaminate food and drink. At its approach, people take shelter and wait until it has passed.

Dust devils and whirlwinds

A sandstorm appears on the horizon as a dark wall towering to a great height. There is time to find shelter before it arrives. Dust devils are much smaller. They give little warning, but they are harmless and short-lived. Whirlwinds are terrifying. They leap from the ground unpredictably and have the power to demolish tents, wrench doors from their hinges, and hurl debris that may injure people nearby.

Dust devils and whirlwinds result from the fact that the desert surface warms unevenly through the day. Every surface reflects some of the Sun's heat. Pale-colored surfaces reflect more than dark surfaces, and dry sand reflects more than bare rock (see the table on page 71). This means that a surface covered with sand heats up more slowly than a bare rock surface, and it does not reach such a high temperature before starting to cool again. At about 6 A.M., as the day begins in the central Sahara, the temperature of the sand surface is about 80°F (27°C) and, depending on their composition, the rock surfaces are at 100–110°F (38–43°C). The sand reaches its maximum temperature of about 145°F (63°C) by noon, but

A dust devil approaches a flock of puna or James' flamingos (Phoenicoparrus jamesi) *in Chile* (Courtesy of Tui de Roy/ Minden Pictures)

the rock continues warming until about 2 P.M., when its temperature is about 175°F (79°C). By that time the sand has already started to cool, but the rock does not start cooling until about 5 P.M.

In a part of the desert where some of the surface is covered by sand and some by bare rock, by the middle of the afternoon the rock will be markedly warmer than the sand. That is the time of day when dust devils and whirlwinds are most likely.

If there is a wind—and there very often is—it will mix the air so that the difference in surface temperature produces no difference in air temperature. On a calm day, however, such differences do develop. Air over the rock is much warmer than air over the sand. The warm air expands and rises, and cooler air converges from all sides to replace it. Small local winds blow from the sand to the rock.

Converging air does not travel in a straight line. It turns, to the left in the Northern Hemisphere, until it is spiraling horizontally into the area it seeks to fill. Then it joins the rising air, still in a spiral. The rising air over the warm area is then spiraling upward.

If only a small area is heated, the spiraling air will raise a small amount of dust and lightweight material, such as dry leaves and scraps of paper. A larger area will produce a stronger spiral that raises more dust and sand, sometimes to a height of 300 feet (92 m).

The bigger the area of warm ground, the bigger the dust devil will be. That much seems obvious, but it may be less obvious why its winds are also stronger. The strengthening wind is due to a property possessed by all rotating bodies, and air spiraling into a central area is a rotating body. The property is *angular momentum* and it is *conserved.* This means that if one of the components of angular momentum changes, the other components will automatically adjust to ensure that the amount of angular momentum stays the same. The sidebar on page 79 explains this.

The wider the area from which air is drawn toward the center, the greater the outer radius of the spiral and therefore, because the angular momentum of the air is conserved, the stronger the winds will be at the center. On the largest scale, this produces whirlwinds.

A whirlwind develops in the same way as a dust devil, but it can rise to more than 6,500 feet (2 km) as a screaming, twisting funnel of sand and dust that looks very much like a tornado. It is not a tornado. It does not descend from a big, black storm cloud that would provide advance warning, but

Conservation of angular momentum

Imagine a body that is spinning about its own axis. You can measure the mass of the body, the radius of the circle it describes, and the speed of its rotation. Its speed of rotation is known as its *angular velocity* and is measured as the number of degrees through which it turns in a given time. The Earth, for example, completes one revolution in 24 hours. One full turn takes it through 360°, so the Earth's angular velocity is 15° per hour (360 ÷ 24 = 15). Angular velocity is usually expressed in radians per hour or per second. A radian is the angle between two radii of a circle that marks out on the circumference an arc that is equal in length to the radius. Therefore the circumference of a circle is 2π radians and 1 radian = 57.296°.

Multiply these three values together and the product, called *angular momentum,* is a constant. Call the mass *M,* the radius *R,* and the angular velocity *V,* and $M \times R \times V$ = a constant. *M, R,* and *V* are *variables.* They can be altered, but the constant must remain the same.

This is called the *conservation of angular momentum* and it means that if one of the variables changes, one or two of the others must also change in order that the constant remains the same. No one needs to do anything to make this happen; it is entirely automatic.

Dancers and ice skaters make use of the conservation of angular momentum when they perform pirouettes. The dancer starts spinning with her arms fully outstretched. The distance from the center of her body (the axis of her rotation) to her fingertips is the diameter of the circle her body describes; the radius is half of this. Then she slowly draws her arms inward to her body. This reduces her radius of spin. She has reduced one of the three variables and so one or both of the others must increase in order to compensate. Her mass cannot change (she cannot suddenly become heavier) and so the remaining variable, her angular velocity, has to change. It increases as her radius of spin decreases. In other words, she spins faster—but without making any additional effort beyond withdrawing her arms.

rises from the ground on a calm afternoon into a clear, blue sky—with no warning at all. It is weaker than a tornado, with winds that rarely exceed 60 MPH (96 km/h), but that is strong enough to be dangerous.

Whirlwinds are short-lived, but they often occur in "families." They rise suddenly and just as suddenly they die down, but as one dies another rises nearby. During their brief lives they move erratically over the ground. They are made of nothing more substantial than air, of course, made visible by the dust and sand they raise, but these pale, shrieking wraiths have been scaring desert dwellers for thousands of years.

CHAPTER 4

LIFE IN DESERTS

Photosynthesis, respiration, and desert plants

All animals depend on plants for their food, even in the desert. There is no such thing as a vegetarian snake, of course, but snakes eat animals that are vegetarians, and so the snakes depend on plants just as much as a small rodent that feeds on plant seeds. The reason there are few animals to be seen in the desert is not that the desert is too hot, too cold, or too dry for them; animals can adapt to these conditions. It is because plants find it much more difficult to adapt to the lack of water and consequently there are few plants. The lack of plants means there is not much for desert animals to eat.

Plants feed all animals. They occupy this important position because of their ability to manufacture carbohydrates, fats, proteins, and vitamins from raw materials they obtain from the air, the soil, and water. The process that provides the energy for the "plant factory" is called *photosynthesis,* a word derived from two Greek words—*phos,* meaning "light," and *syntithenai* meaning "to put together."

Photosynthesis depends on a pigment called *chlorophyll* contained in bodies called *chloroplasts* in cells just below the surface of leaves and other green parts of plants (such as unripe fruits). Chlorophyll is green and it is what gives plants their green color. Photosynthesis proceeds in two stages. The first stage depends on light, so it is called the *light-dependent* or *light* stage. The second stage does not use light energy and is called the *light-independent* or *dark* stage—although it also takes place in the light.

The light-dependent stage begins when a photon (particle) of light possessing precisely the right amount of energy strikes a chlorophyll molecule. The chlorophyll molecule absorbs the photon, causing an electron (a particle carrying negative charge) in the molecule to break free, leaving the chlorophyll molecule with a positive charge. The electron immediately attaches to a neighboring molecule. The addition of an electron releases an electron from that molecule, which attaches to another molecule, and electrons released in this way then pass from molecule to molecule along an *electron-transport chain* of molecules.

Some of the captured energy is used to convert adenosine diphosphate (ADP) to adenosine triphosphate (ATP) by the addition of phosphate (the reaction is called *phosphorylation*), the electron then returning to the chlorophyll. Converting ADP to ATP absorbs energy; converting ATP to ADP releases the energy. All living organisms use the ADP $\longleftrightarrow$ ATP reaction to transport energy and release it where it is needed.

The remaining energy is used to split a water molecule (H_2O, but it can also be written HOH) into hydrogen bearing a positive charge (H^+) and hydroxyl with a negative charge (OH^-). The H^+ attaches to a molecule of nicotinamide adenine dinucleotide phosphate (NADP), converting it to NADPH. The OH^- passes one electron to the chlorophyll molecule, restoring the neutrality of both chlorophyll and hydroxyl. Hydroxyls then combine to form water ($4OH \rightarrow 2H_2O + O_2\uparrow$). (The upward arrow indicates that the oxygen is released into the air.) This completes the light-dependent stage. Products from the light-dependent stage then trigger the start of the light-independent stage.

Using ATP from the light-dependent stage as a source of energy, the light-independent stage begins by attaching carbon dioxide (CO_2) obtained from the air to ribulose biphosphate (RuBP) in a reaction called *carboxylation* that is catalyzed by the enzyme RuBP carboxylase, or rubisco. In a cycle of reactions carbon is then combined with hydrogen obtained from NADPH; the NADP returns to the light-dependent stage. The cycle ends with the synthesis of molecules of glucose and of RuBP. The entire photosynthetic process is summarized as:

$$6CO_2 + 6H_2O + \textit{photon} \rightarrow C_6H_{12}O_6 + 6O_2\uparrow$$

$C_6H_{12}O_6$ is glucose, a simple sugar. Glucose is used as a source of energy, which is released by the process of *respiration,* and for the synthesis of starch and cellulose in plants and glycogen in animals. Glycogen can be converted to glucose to provide fuel for respiration.

Respiration must not be confused with breathing, which is the mechanical action by which animals obtain oxygen and rid their bodies of carbon dioxide. All plants and animals are *aerobic* (air-breathing), but some bacteria are *anaerobic* and use a different respiration process. Aerobic organisms use oxygen to oxidize glucose, a reaction that releases energy. Carbon dioxide and water are by-products of the reaction. This is respiration and it is the direct opposite of photosynthesis:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \textit{energy}$$

Plants have a problem, however, arising from *photorespiration*. Unlike ordinary respiration, photorespiration wastes energy rather than releasing it. It occurs because the enzyme rubisco can attach itself to oxygen as well as to carbon dioxide. If rubisco attaches to carbon dioxide it catalyzes the carboxylation of RuBP, but if it attaches to oxygen it catalyzes the oxidation of RuBP, triggering a sequence of reactions that end by releasing carbon dioxide but without releasing energy.

Whether rubisco attaches to oxygen or carbon dioxide depends on the relative concentrations of these gases in air. At one time, when the atmospheric concentration of carbon dioxide was higher than it is now, photorespiration may have been unimportant, but today, when the air contains approximately 365 parts per million of carbon dioxide, enough oxygen attaches to rubisco to significantly reduce the efficiency of photosynthesis. Certain groups of plants. known as *C4* and *CAM* plants, have adapted to the low atmospheric concentration of carbon dioxide by modifying the reactions at the start of the light-independent stage (see the sidebar on page 84).

C4 photosynthesis involves more steps than the C3 pathway, and C4 plants use much more energy than C3 plants. Because they avoid photorespiration, however, they use carbon dioxide more efficiently than do C3 plants.

Their improved efficiency gives C4 plants an advantage in dry climates. When water is scarce, plants close their stomata to reduce losses, but with their stomata closed they cannot

C3, C4, and CAM plants

In many plants the light-independent stage of photosynthesis begins with the addition of a molecule of carbon dioxide to a molecule of ribulose biphosphate (RuBP). RuBP is a sugar containing five carbon atoms. Adding a carbon atom produces a six-carbon sugar. This is unstable and breaks into two molecules of 3-phosphoglycerate, a three-carbon sugar. Plants in which photosynthesis uses this reaction are known as *C3 plants.* The efficiency of photosynthesis in C3 plants is often reduced by high rates of photorespiration.

Other plants, mainly tropical and subtropical grasses including corn (maize) and sugarcane, use a different reaction. Carbon dioxide enters *mesophyll* cells lying just below the leaf cells that contain chlorophyll. There the enzyme PEP carboxylase catalyzes a reaction that attaches carbon dioxide to phosphoenolpyruvate, producing the four-carbon compound oxaloacetate, which is then converted to another four-carbon compound. PEP carboxylase has no affinity for oxygen. Plants using this reaction are known as *C4 plants.*

The four-carbon compound leaves the mesophyll cells through passageways called *plasmodesmata* to enter *bundle-sheath cells* that are packed tightly around leaf veins. There the four-carbon compound gives up its carbon dioxide, which combines with rubisco and enters the light-independent stage. Because carbon dioxide accumulates in the bundle-sheath cells its concentration is always high enough to ensure that it wins the competition with oxygen for rubisco, thus preventing photorespiration.

Certain desert plants have evolved a further modification that minimizes the loss of moisture when leaf *stomata* (pores) are open to exchange gases with the air. This modification was first identified in plants belonging to the stonecrop and houseleek family, Crassulaceae, and it is known as *crassulacean acid metabolism,* usually abbreviated to *CAM.*

CAM plants open their stomata at night, when the air is cool and the rate of evaporation is low. Carbon dioxide enters the mesophyll cells and oxygen departs, but little moisture is lost. The carbon dioxide combines with an organic acid and the resulting compound is stored in *vacuoles* (small spaces) inside the mesophyll cells.

Photosynthesis is impossible at night, but at dawn the CAM plants close their stomata and keep them closed until nightfall. During the day they use the carbon dioxide they collected overnight to enter the light-independent stage of photosynthesis.

exchange gases with the air. Carbon dioxide cannot enter leaf cells and oxygen cannot leave them. Consequently, inside the cells where photosynthesis takes place the concentration of oxygen increases, that of carbon dioxide decreases, and the rate of photorespiration rises until sometimes it exceeds the rate of photosynthesis. This is less of a problem for C4 plants than it is for C3 plants. In temperate climates, however, C4 plants are often at a disadvantage compared with C3 plants. Water is usually plentiful in temperate climates and droughts seldom last long, so plants can afford to lose moisture through their open stomata. This favors C3 plants, and because C4 plants use more energy they are often at a disadvantage.

Why plants need water

Photosynthesis, the sequence of chemical reactions by which green plants make sugar, uses carbon dioxide as a source of carbon and water as a source of hydrogen. If a plant had no access to water, photosynthesis would be impossible and the plant would die. Only a small fraction of the water inside a plant is used for photosynthesis; nevertheless, water is an essential raw material for the process that gives a plant the energy it needs to grow, repair its tissues, and reproduce.

Plants also absorb mineral nutrients from the soil. They need relatively large amounts of the elements nitrogen, potassium, phosphorus, sulfur, calcium, magnesium, and iron, and very small amounts of a range of others, including boron, copper, manganese, molybdenum, and zinc. Nitrogen and sulfur are essential ingredients of all proteins, for example. These elements are present in a fertile soil, where they are dissolved in water. They enter plant roots in solution, and this is the only way the plant can obtain them. The plant needs water as a solvent for the mineral nutrients it requires.

Once they have entered the root system, the mineral nutrients must be transported to all the parts of the plant where they are needed—to the leaves, buds, flowers, and fruits, and to every branch, twig, and stem. The nutrients travel along vessels—visible as the veins in leaves—flowing in the form of a solution; they are dissolved in water. The plant needs water to transport nutrients.

The vessels that transport nutrients form *xylem* tissue. Other vessels, comprising *phloem* tissue, transport the sugars made by photosynthesis from the leaves to every part of the plant. The sugars also travel in solution, so the plant needs water to carry sugars to tissues that need the energy they supply.

Plant cells are filled with fluid that is mainly water. The fluid keeps the cell walls rigid, like the air in a tire, and when all the plant cells are rigid so is the whole plant. Plants need water to maintain their rigidity—the scientific term is *turgor.* If they lack water the cells lose their turgor and the plant wilts. Its leaves hang limply, and in nonwoody plants the stem also becomes limp and the plant collapses. Provided it has not been without water for too long, a wilting plant recovers quickly when its roots once more have access to water, but prolonged wilting is fatal.

Plants absorb water through the fine hairs lying just behind the tip of every branch of their roots. Water enters the *root hairs* because the pressure inside the hair is lower than the pressure outside. Inside the root, the water enters the xylem tissue that transports it to the rest of the plant.

Xylem consists of bundles of hollow, approximately cylindrical cells arranged end to end. The cells are dead, but they form continuous tubes leading all the way to the leaves.

Leaves have tiny pores, called *stomata,* through which the gases involved in photosynthesis enter and leave the plant. When the stomata are open for gas exchange, moisture evaporates from inside the mesophyll cells just below the leaf surface. This loss of water is called *transpiration.* As water molecules escape, adjacent molecules cling strongly to depressions in the mesophyll cell walls, and at the same time the mutual attraction of water molecules pulls the water into the shape with the smallest possible surface area. The combined effect is to lower the pressure inside the cell to below the atmospheric pressure, and the difference in pressure causes water to move from the leaf xylem and into the mesophyll cells. Water molecules are drawn through the xylem tissue behind the molecules moving into the mesophyll cells, and this pressure, starting at the stomata, is transferred down through the plant all the way to the root hairs. The pressure is so strong that on a hot day, when the rate of transpiration is high, the sides of the xylem cells are pulled inward and a tree trunk becomes measurably narrower.

Typical plants of subtropical deserts

Cacti, the most famous of all desert plants, cope with the dry conditions in several ways. They dispense with leaves or have only very small leaves. The green swollen structures that are typical of cacti are stems, not leaves. Photosynthesis takes place in the stems and the stems also store water. The bulbous shape of the swollen stems reduces water loss, prevents the plant from overheating, and stores water. This is because the swollen stems have a smaller surface area in relation to their volume than they would have if they were not swollen. The volume of the stem determines the amount of water it can store, and the surface area determines the amount of warmth it can absorb and water it can lose by transpiration.

Naturally, desert animals might like to steal the water and to prevent this most cacti protect themselves with viciously sharp spines. In some species the spines are tiny, barbed, easily detached, and grow in bunches, so that any animal

Spines on a prickly pear cactus (Opuntia *species*) *grow from sunken depressions called areoles.* (Courtesy of Fogstock) brushing against them has to spend a long time picking them out of its skin. Most cacti have shallow roots, but in larger species these spread a long way horizontally. The roots are adapted to absorb water rapidly just below the ground surface. All cacti are CAM plants (see the sidebar "C3, C4, and CAM plants" on page 84).

The spines of cacti, and also their branches and flowers, grow from sunken cushions called *areoles.* These are set singly on raised lumps called *tubercles* or in rows along ridges or ribs, as in the saguaro or giant cactus (*Carnegiea gigantea*). The biggest of all cacti, the saguaro can grow to a height of 65 feet (20 m) and a diameter of two feet (60 cm). Its flowers are pollinated by birds and insects during the day and by bats at night.

Unrelated plants and animals that live in extreme environments such as deserts often come to resemble one another (see the sidebar "Parallel evolution and convergent evolution" on page 116). There are plants in the African deserts that look almost identical to the cacti of American deserts. They are not cacti, however, but members of the spurge family (Euphorbiaceae). *Euphorbia echinus,* from southern Morocco, grows as bunches of cactuslike, swollen stems up to three feet (90 cm) tall with sharp ridges bearing spines. *E. heterochroma* is similar in appearance, but up to six feet (1.8 m) tall and from East Africa. Abyssinian spurge (*E. abyssinica*) has vertical ridged stems with spines and grows up to 15 feet (4.5 m) tall, and Canary Island spurge (*E. canariensis*) can be 20 feet (6 m) tall. Milk barrel (*E. cereiformis*) from South Africa grows as clusters of ridged stems up to three feet (90 cm) tall and

A saguaro cactus (Carnegiea gigantea) *silhouetted against the night sky.* (Courtesy of Fogstock)

A barrel cactus (Ferocactus *species*) *growing in the Joshua Tree National Park* (Courtesy of Rodolfo Arpia)

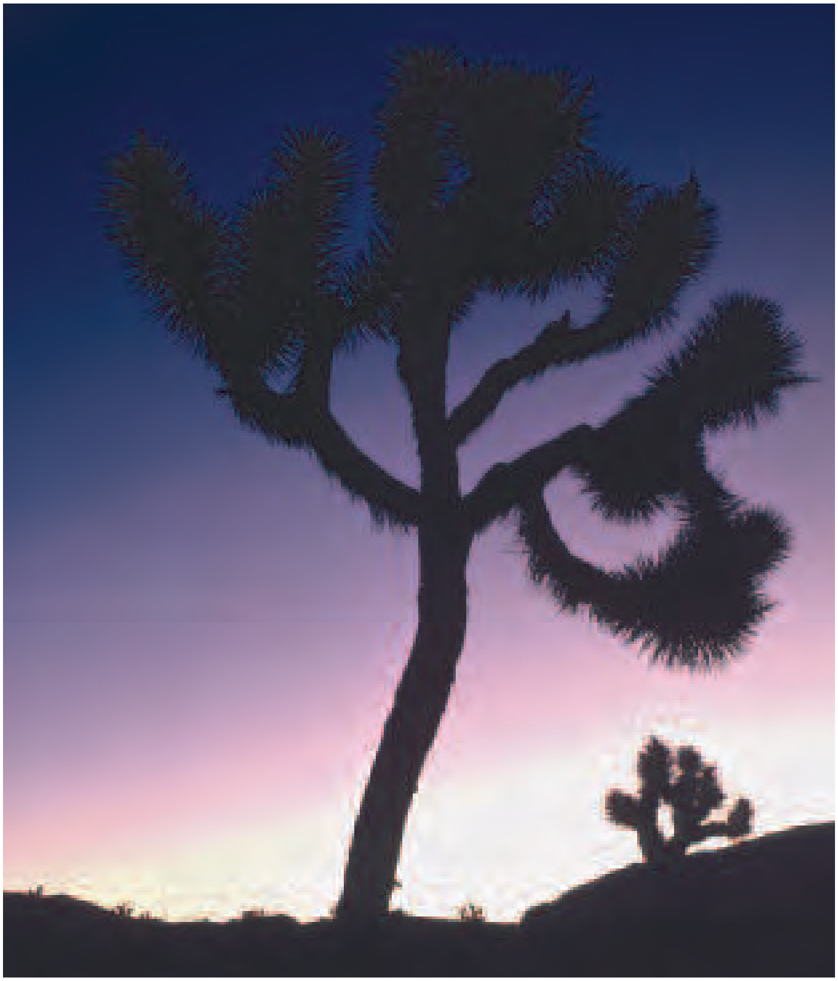
up to two inches (5 cm) thick. It resembles *Cereus* cacti so closely that it was given the name *cereiformis,* meaning "cereus shaped." There are differences between euphorbias and cacti, of course. Unlike cacti, euphorbias produce a very poisonous sap. Euphorbias bear their spines in pairs, whereas cacti bear theirs either singly or in bunches. While cacti are CAM plants, euphorbias are C3 plants (see the sidebar "C3, C4, and CAM plants" on page 84).

Thorn trees (1,200 *Acacia* species), known in Australia as wattles, also bear spines. Australia has the largest number of species, but thorn trees also grow in the African and Asian deserts, and the bullhorn acacia (*A. cornigera*) is found in Central America. Its thorns are swollen at the base, and each thorn houses a colony of ants that protect the tree in return for food supplied by the plant.

Many agaves (family Agavaceae) look like cacti. They have thick leaves, up to 10 feet (3 m) long in some species, with prickles along the edges. Agaves grow in many parts of the world, but the century plant (*Agave americana*) is American. Its name refers to the mistaken belief that the plant flowers only once in every century. In fact it flowers every 10–20 years.

Yuccas also belong to the agave family, and all 30 species are American. Some yuccas are the size of small trees. The biggest of them all is the Joshua tree (*Yucca brevifolia*) of the Mojave Desert, which can grow to 35 feet (10.7 m).

Creosote bushes (*Larrea divaricata tridentata*) are the most abundant plants over large areas of the North and Central American deserts. These are shrubs up to five feet (1.5 m) tall, which can survive for a year without rain. Their leaves smell of creosote, hence the name.



Joshua trees (Yucca brevifolia) (Courtesy of Fogstock)

Camel thorn (Alhagi maurorum) *seen here in the Namib-Naukluft National Park, Namibia, has branches that exude a sap that hardens into lumps called manna.* (Courtesy of Gerry Ellis/Minden Pictures)

All of these are perennial plants, always present in the desert and able to survive for long periods without water. Cacti, euphorbias, agaves, and yuccas store water in their succulent (moisture-conserving) leaves. Thorn trees and creosote bushes have tiny leaves to minimize water loss and remain dormant between rains. Other plants survive as seeds that germinate when they are moistened.

Tumbleweeds are the most famous of these. There are several unrelated species, and tumble grass (*Schedonardus paniculatus*) is typical. The plant dies after producing seeds. As it withers, it curls up into a ball with the seeds on the inside. The wind blows the ball along, scattering seeds as it goes.

Many other plants survive as seeds in the ground. Following rain, the seeds germinate and the plants grow, flower, and set seeds before the ground dries out. Evening primrose (*Oenothera* species) of California produces seeds that can wait 50 years or more for conditions that allow them to germinate. When it rains the desert blooms, but within a few weeks the flowers are gone, the plants have died, and the desert appears barren as a new crop of seeds awaits the next rain.

Typical plants of cold deserts

Gobi is a Mongolian word that means “waterless place.” Although it is a desert, however, the Gobi is not devoid of plants. Succulent grasses grow in the warmer areas, especially *Echinochloa* species, a type of millet. Elsewhere on the Gobi plateau there are feather grasses (*Stipa* species), with blades folded into tubes, so the stomata are on the inside. This minimizes the loss of water by transpiration and is an adaptation to dry conditions. These include Gobi feather grass (*S. glareosa*) and timuriya (*S. villosa*). Around the desert margins there are snakeweeds (*Cleistogenes* species), including Dzungarian bridlegrass (*C. soongorica*).

There are also shrubs. In places the soils are salty, so many of the woody plants are *halophytes* (tolerant of salt) as well as *xerophytes* (tolerant of drought). Yellow khotir, also called yellowwood beancaper (*Zygophyllum xanthophyllum*), has edible flower buds that are used as a substitute for capers. The nitre bush (*Nitraria sibirica*), a member of the same family (Zygophyllaceae), has a fruit that some animals eat because it is rich in salt. Tamarisks are shrubs or small trees that often grow on sandy soils near coasts. Dzungarian reaumuria (*Reaumuria soongorica*), a member of the tamarisk family (Tamaricaceae), is a small halophytic shrub found in the low-lying Dzungaria basin of northwestern China. Yellow ephedra (*Ephedra prezewalskii*) is a xerophytic shrub or small tree.

Winter fat (*Krascheninnikovia lanata*), a member of the sugar beet family (Chenopodiaceae), also grows in North America where it is known as white sage. It is a small bush that is covered with a dense mat of pale-colored hairs. Gobi kumarchik (*Agriophyllum gobicum*) belongs to the same family, but is an annual herb with seeds that are an important Mongolian food.

Saxaul (*Haloxylon ammodendron*) is a shrub about 10 feet (3 m) tall that grows in the sandy parts of the desert where the sand is stable. In many of the less arid places saxaul plants grow so close together they form “forests” that bind the soil together and prevent erosion. There are also peashrubs (*Caragana bungei* and *C. leucocephala*), small shrubs that are the dominant plants over large areas.

In contrast, the Taklimakan Desert of western China is extremely dry and plants are very few and far between. In depressions, where there is groundwater within 10–15 feet (3–4.5 m) of the surface, there are sparse thickets of tamarisk shrubs and nitre bushes, but over most of the desert the shifting sands make it impossible for plants to gain a secure anchorage. There are more plants near the edges of the desert.

Patagonia, in southern South America, has a much richer plant life. There are forests along the western border. On the tableland to the east of the mountains the plants are xerophytic, adapted to the combination of low rainfall and constant drying winds. Few plants grow in the driest areas, but there are wetter areas completely covered by plants. In the desert proper, where plants cover up to 15 percent of the ground surface, there are halophytes such as saltbushes (*Atriplex* species) and other members of the sugar beet family (Chenopodiaceae).

In the moister areas, where almost half the ground is covered in plants, the predominant species are cushion plants, often growing between rocks, and dwarf shrubs. Cushion plants are typically one to four inches (2–10 cm) high, most with tiny but bright flowers. Many are widely cultivated as alpines, including *Benthamiella, Brachyclados,* and *Nassauvia* species. Among the shrubs and cushion plants there are tufts of feather grass (*Stipa* species) and meadow grass (*Poa* species).

Where the desert merges into the pampas grassland, shrubs cover more than half the ground. They include *Chuquiraga* species, up to 20 inches (50 cm) tall, and *Berberis* species, which grow as small trees up to 10 feet (3 m) tall.

Typical animals of hot deserts

Loose desert sand moves like a liquid and there are animals that swim through it as though they were in the sea. Some lizards swim through the sand (see “Snakes and lizards” on pages 110–114) and so do the golden moles that are found in southern Africa and nowhere else.

All moles have poor eyesight, but golden moles are really blind. Skin covers their eyes and fur covers the outside of their ears. This does not make them deaf, however, because the bones of the inner ear are very large and highly sensitive to vibrations. Golden moles are not closely related to other moles, despite resembling them and living in a similar fashion. They swim just below the surface of the sand foraging for insects, and they will eat any legless lizard that comes their way. Grant's golden mole (*Eremitalpa granti*) swims up to three miles (5 km) a night in search of food.

Desert hedgehogs (*Paraechinus aethiopicus*) of the Sahara and both Brandt's hedgehog (*P. hypomelas*) and the long-eared hedgehog (*Hemiechinus auritus*) of the Central Asian deserts feed mainly on invertebrate animals such as insects, but they will sometimes eat an animal the size of a mouse. These hedgehogs have large ears that work like radiators to keep their owners cool. Blood flowing through them comes very close to the surface and loses heat to the air before returning to the heart. Big ears are a common adaptation to life in the hot desert. Jackrabbits, which are really hares (*Lepus* species) rather than rabbits, also have large ears, and so does the caracal or caracal lynx (*Felis caracal*), a cat up to 2.5 feet (75 cm) not counting the long tail, which hunts it. The biggest ears of all, however, belong to the fennec fox (*Vulpes zerda*) of North Africa, Sinai, and Arabia. It is the smallest of all the foxes. A full-grown adult weighs only 2–3.3 pounds (0.8–1.5 kg). Fennec foxes spend the day in burrows in the sand, emerging at night to hunt for mice, birds, lizards, and insects.

Ears are meant for hearing, of course, and desert animals with big ears have acute hearing. Many predators hunt by night, locating their prey by the slightest sound. Prey species rely on their hearing to detect the approach of a hunter.

How heat kills and how animals stay cool

If your body temperature rises just a few degrees above 98.6°F (37°C) you will become ill and feverish. If it rises above 109°F (43°C) and remains there for more than a few minutes you will suffer brain damage. A high temperature can kill. People are not unique in this respect. No vertebrate animal can tolerate too high a body temperature. In mammals and birds the temperature inside the body, known as the *core temperature,* is between approximately 97°F and 104°F (36–40°C). Birds have a higher core temperature than mammals.

The reason animals tolerate only a limited range of body temperatures is partly chemical. All the functions of a living body, such as respiration, digestion, and muscular activity, involve chemical reactions that are catalyzed by enzymes. The speed with which these reactions take place increases as the temperature rises, approximately doubling for every 18°F (10°C) rise in temperature, but there is a temperature above which they slow down. This means there is an optimum temperature—about 104°F (40°C)—at which enzymes work best, and the optimum temperature for enzymatic reactions determines the normal body temperature. The core temperature remains below the optimum enzyme temperature in most species because at temperatures only slightly above the optimum, the chemical bonds holding enzymes together begin to break and the enzymes degrade. When that happens, ordinary bodily functions start to fail. Survival in the hot desert depends on being able to stay cool.

Reptiles, such as snakes and lizards (see pages 110–114), keep cool by finding shade or burrowing below ground during the heat of the day. Their body temperature falls at night, and just as there is a temperature above which enzymatic reactions slow down there is also a temperature below which they are very slow. When its body is cold a snake or lizard can barely move its muscles. It must start each day by warming up, which it does by basking in the morning sunshine. Animals that bask in the sunshine to raise their core temperature and seek shade to lower it are called *ectotherms*. *Ectos* is the Greek word for "outside," and an ectotherm regulates its core temperature by external means.

Mammals and birds are *endotherms—endos* is the Greek word for "within." They regulate their core temperature internally, by such means as sweating, panting, shivering, and constricting or dilating blood vessels just below the skin. In reality it is not quite so simple, because endotherms also seek shade and bask in the sunshine—and people wear different clothes in hot and cold weather. Small desert rodents, for example, retreat to a burrow when it is too hot for them. Lying in its burrow, the rodent ceases to move. Its breathing and heartbeat slow, its temperature falls, and the animal falls into a torpor—a kind of deep sleep. A few hours later, when it is cooler above ground, the rodent rouses itself and resumes the search for food.

Endotherms can be active at night and first thing in the morning, and they can live in cold climates, but they pay a price for this flexibility. Endothermy uses energy, so an endotherm must eat more than an ectotherm of similar size. A person uses 30 times more food energy than an alligator of about the same size.

Sweating and panting cool the body by allowing moisture to evaporate from the surface. Rodents do not sweat, but instead they lick their fur, which has the same effect. Evaporation is an efficient way to lose surplus heat, but only if the lost moisture can be replaced quickly. An animal that keeps cool in this way but is unable to drink water to compensate will soon begin to suffer from dehydration.

The water that is lost is taken from the fluid surrounding cells. Only pure water is lost and, consequently, the salts dissolved in the body fluid become more concentrated. When the solution surrounding cells is stronger than the solution inside cells, water flows out of the cells, through the cell walls, to reduce the difference in concentration. This increases the concentration inside the cells. At first the effect is to accelerate cellular activity, because in a more concentrated solution molecules will collide more frequently with the active sites on enzyme molecules to which they bond. Eventually, however, all the active sites will be occupied; the cell will be unable to manufacture more enzymes; and cellular function will be disrupted. Cells will then start to die. People suffering severe dehydration become very confused and lose bodily coordination.

In most mammals, including humans, dehydration also thickens the blood, because blood plasma crosses the walls of blood vessels to replace fluid lost by sweating or panting. As the blood thickens, the heart has to pump harder to circulate it and eventually the circulation slows. The most important mechanism by which endotherms lose heat involves dilating blood vessels in the skin. Warm blood flowing close to the surface loses heat and returns to the heart at a lower temperature. If the circulation slows, however, this process also slows and the core temperature then rises rapidly and uncontrollably. Death follows swiftly when the animal has lost

The camel: "ship of the desert"

The dromedary, or single-hump camel (*Camelus dromedarius*), has been known to go 17 days without drinking in summer. In winter some camels do not drink at all and after two months without drinking they may still refuse water. When it does drink, however, a camel can swallow 27 gallons (103 l) of water in 10 minutes.

A camel survives for so long without drinking by using water very efficiently. Its kidneys extract much of the water from its urine, allowing the animal to excrete as little as one quart (1.14 l) of water a day.

Many animals, including humans, keep cool by sweating. But a camel does not sweat until its body temperature exceeds 105°F (40.5°C). If it has no access to water, at night its body temperature falls, sometimes as low as 93°F (34°C). Consequently, it takes several hours for its temperature to rise during the day. Its temperature varies much less in winter and in summer if water is available.

A camel's body warms very slowly because its thick coat traps a layer of air next to its skin. The outer part of the coat absorbs heat, preventing it from reaching the skin, and when the camel does sweat its perspiration evaporates into the layer of air by the heat of the skin, not the heat of the Sun.

The camel's hump is made of fat and is a food store. Over the rest of its body the layer of fat beneath the skin is very thin. The hump provides insulation from the Sun, and the thin layer of fat elsewhere allows heat to escape from the body.

When a camel loses body fluid it does so from its saliva and moisture in its lungs, and not from its blood, replacing the lost water from other body fluids and fluids in its tissues. This allows the volume of blood to remain constant, avoiding explosive heat death, but the loss of other fluids makes the animal thinner. It can lose up to 25 percent of its body weight through fluid loss while remaining perfectly healthy—despite being so emaciated its ribs are clearly visible—and continuing to eat even though it cannot drink. When it drinks its body fills out again at once.

A camel's hind legs are attached to its pelvis only at the top of the femur (thigh bone); in most animals they are attached by muscles extending all the way to the knee. This

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mode of attachment gives a camel its long-legged look, but it also allows it to tuck its hind legs completely beneath its body when it lies down, thus reducing the area of body surface that is exposed to the heat. When camels lie down they usually lie close together, so they shade each other, and they all face the Sun to minimize the area of their bodies exposed to direct sunlight. As the Sun moves during the day, the camels change their positions to follow it.

A camel has very broad feet. These spread the weight of its body and help prevent the camel from sinking into soft sand. It has long eyelashes and each row of lashes is double. These help keep sand out of its eyes. Long hairs also protect its ears, and it is able to close its nostrils. These are all adaptations that equip the camel for life in the desert.

"Ships of the desert" (Camelus dromedarius) *at Oasis Dakhia, in the Egyptian desert* (Courtesy of Gerry Ellis/Minden Pictures)

between 10 percent and 20 percent (about 12 percent in humans) of the water in its body. This is known as *explosive heat death*.

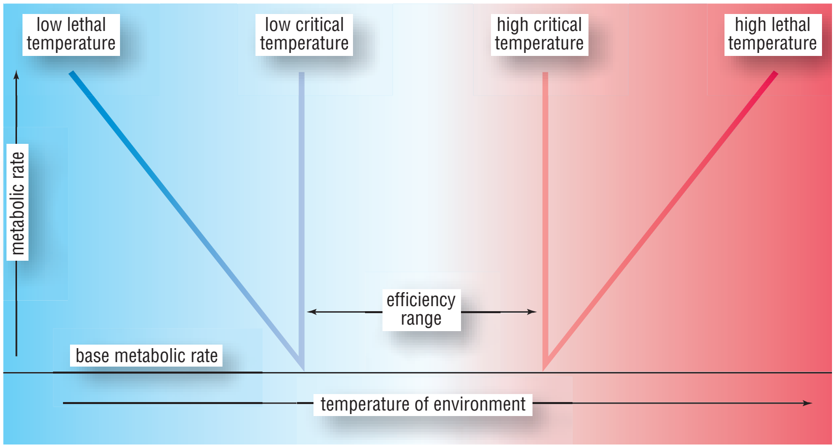
Some animals are better adapted to life in a hot climate than others, and the camel is probably the most highly equipped of all (see the sidebar on pages 97–98). It avoids explosive heat death and is renowned for its ability to go for long periods without water. A camel can walk 25 miles (40 km) a day carrying a load of 500 pounds (227 kg) and can carry a rider more than 100 miles (160 km) in a day at a steady speed of about 10 MPH (16 km/h). Not for nothing is the camel called "the ship of the desert."

How freezing kills and how animals keep warm

Walk into a room where the temperature is 84°F (29°C) and it will feel warm. It would not be long, however, before a person who was naked and remained motionless in such a room began to feel cold. It may seem warm to someone who is fully clothed, but 84°F (29°C) is 14.6°F (8°C) lower than the normal core temperature of a human body, 98.6°F (37°C).

No animal likes to feel cold. Cold can kill. In an environment at 84°F (29°C) a motionless, bare human body would not sweat at all. If the air temperature slowly fell from 84°F (29°C), blood vessels in the skin would constrict to reduce heat loss from inside the body, making the person look pale. Goose bumps would appear, caused by the contraction of skin muscles. If humans had more body hair, this contraction would make it rise to trap a layer of air next to the skin as thermal insulation. Soon after this the person would begin to shiver uncontrollably.

When the air temperature fell below the *low critical temperature* of about 79°F (26°C) these mechanisms would no longer be sufficient to maintain the core temperature. Cell respiration would then accelerate to drive the body's metabolism faster, "burning" carbon to release energy and consuming more oxygen to fuel the oxidation reaction. Respiration would continue to accelerate as the temperature fell lower, but a point would be reached beyond which the chemical reactions involved in respiration began to fail. The person would then become confused, feel dizzy, and suffer from cramps. If the person's core temperature fell below the *low lethal temperature* of about 90°F (32°C) he or she would die.



Temperature and metabolic rate. There is a temperature range within which a particular animal functions most efficiently. Outside this range, beyond the low or high critical temperature, the animal's metabolic rate increases to raise or lower the core body temperature. Eventually this proves impossible, and when its core temperature reaches the low or high lethal temperature, the animal dies.

All animals have a range of temperatures within which their bodies function most efficiently, and they will die if their body temperature exceeds or falls below certain limits of tolerance. The diagram above shows the relationship between temperature and metabolic rate.

Frostbite occurs when tissues cool to below freezing. Blood vessels in the skin constrict to reduce heat loss and the tissue begins to freeze. Ice crystals form in the fluid between cells, increasing the salt concentration in the fluid. This draws water out of surrounding cells, causing cell dehydration and eventual death. It can also cause the breakdown of proteins.

Low critical temperatures vary from one species to another, reflecting the climate to which each is adapted. The low critical temperature for rodents living in hot deserts, such as the Sahara, is about 88°F (31°C). For the arctic fox (*Alopex lagopus*) it is –40°F (–40°C). This does not mean, however, that the arctic fox can tolerate temperatures much lower than –40°F (– 40°C). At this temperature the amount of energy the fox needs to generate by respiration is close to the maximum possible. Even if there were a limitless supply of food, the fox simply could not digest it fast enough to generate the necessary warmth. Therefore the gap between the low critical and low lethal temperatures is narrow.

The fox, like all the big animals of cold climates, relies on insulation to keep out the cold, just as Inuit people, fully at home in subzero temperatures, wear thick, windproof clothes. Marine mammals, such as seals, dolphins, and whales, have a thick layer of fat, called *blubber,* just below the skin that doubles as insulation and a store of energy-rich food. Land animals, such as the fox and polar bear (*Ursus maritimus*), have thick coats. Small animals, such as rodents, are not big enough to have really thick coats, and a small animal has a much greater surface area in proportion to its volume than a bigger animal has. Heat is lost through the body surface, so the greater the surface area the more heat an animal loses. Small animals lose body heat readily, and the only way they can survive the winter cold is to hibernate (see "What happens during estivation and hibernation" on pages 102–105).

Animals living in cold climates often have small ears. These reduce heat loss in the same way that the big ears of animals in hot climates maximize heat loss to help them keep cool (see "Typical animals of hot deserts" on page 93–94).

Arctic insulation is extremely effective. The fact that the low critical temperature for the arctic fox is so low shows that it is not until the temperature falls to –40°F (–40°C) that the fox begins to feel cold. Its body fat and thick fur keep it warm.

That is not quite the whole story, however. The fox's nose is naked, and the fur is much thinner on the lower part of its legs and its paws than elsewhere on its body. Practically speaking, it must not mind its feet being cold. If its feet were at its core temperature they would melt the snow and ice the fox stood on, which might be dangerous. But if its feet and nose are almost at freezing temperature, how does the fox avoid transporting cold blood from them into its body and reducing its core temperature? The bodies of arctic birds raise this question even more dramatically: There are no feathers at all covering their lower legs and feet.

The solution lies in *countercurrent exchange.* Close to where a bodily extremity, such as a leg, joins the main part of the body, arteries and veins run side by side and very close together, forming a network of small blood vessels called the *rete mirabile* or "wonderful net." This configuration permits heat exchange. Warm blood from the heart flowing through the arteries toward the extremity warms the cold blood flowing in the opposite direction through the veins. The blood approaching the heart is made warmer than it would otherwise be, greatly reducing the amount of energy the animal must expend in maintaining its core temperature. At the same time, blood flowing toward the extremity is chilled, so the extremity remains cool. When the air temperature is –22°F (–30°C), an arctic fox's paws are at about 32°F (0°C), its ankles at 57°F (14°C), and its nose at 41°F (5°C). Its shoulder muscles are at 99°F (37°C), however, and its chest muscles are at 95°F (35°C). The wonderful net allows animals to live comfortably in temperatures that are far below freezing.

What happens during estivation and hibernation

When the heat becomes unendurable, most desert animals seek shade. Some find shelter beneath rocks while others retreat into their burrows and there they wait until the cool of the evening. While waiting, these animals fall into a deep sleep. This way of escaping the heat for part of the day is called *diurnation.*

The Mojave ground squirrel (*Spermophilus mohavensis*) has a burrow, but when it retreats to its burrow it stays there—by night as well as by day. It lives only on the western side of the Mojave Desert in California and is rare because of disturbance to its habitat, but even allowing for its rarity not many people have ever seen it. That is because not only does it sleep through the heat of the desert summer, it also sleeps through the winter. It emerges above ground in February and disappears in August. If food is scarce it may go back to sleep as early as April.

There is a great deal this small squirrel must do while it is active. It must mate, and males travel up to one mile (1.6 km) a day in search of mates. That is a long way for an animal measuring about nine inches (23 cm) in length, including its tail. The young are born in March, weaned in May, and soon after that are independent. While all this is happening, the squirrel must eat voraciously, almost doubling its weight before the searing heat shrivels all the food plants and it is time to sleep once more.

Its long sleep is no ordinary sleep. As it dozes off, the squirrel's body temperature falls until it is only a degree or two higher than the air temperature in its cool burrow. All its bodily functions slow down. Its breathing and heartbeat slow and occasionally its breathing stops altogether for a time. In this condition, with its body's needs reduced to an absolute minimum, the fat its body stored in spring and early summer provides enough energy—with a wide safety margin—to sustain the squirrel until the first leaf buds open the following spring. Then, when its body senses the lengthening days and rising temperature, its breathing accelerates. After 15–20 minutes of fast breathing its muscles have enough oxygen to become active. The squirrel starts shivering. Shivering generates body heat and about half an hour later the squirrel is awake, alert, and active.

Animals that become dormant during hot weather are said to be *estivating,* from the Latin *aestus,* meaning "heat," and the Mojave ground squirrel is not the only desert species to avoid the heat in this way. Many ground squirrels and all desert frogs and toads do so. Frogs and toads absorb oxygen and release carbon dioxide through their skins. This is called *cutaneous respiration* and it means that frogs and toads have highly permeable skins that lose water readily. Estivation allows them to survive for long periods below ground where the air is moist and there is no risk of desiccation. Couch's spadefoot toad (*Scaphiopus couchii*) of the North American deserts remains dormant for 10 or 11 months of the year and arouses itself only when it hears the sound of falling rain.

An animal that survives cold weather by becoming dormant is said to be *hibernating—hibernus* is the Latin word for "wintry." Many mammals hibernate, and so does the common poorwill (*Phalaenoptilus nuttallii*) of southern California. It is the only bird that is known to hibernate for any length of time. The Hopi Indians call it *hölchoko*—"sleeping one." While it is hibernating the poorwill's temperature, normally about 104°F (40°C), falls to about 65°F (18°C).

Only small animals are able to hibernate, and these include many species found in continental deserts where winters are cold. The arctic ground squirrel (*Spermophilus undulatus*) hibernates. A close relative of the Mojave ground squirrel, this animal occurs in the North American and Eurasian arctic and is known in Russia as the long-tailed souslik.

Marmots (*Marmota* species), which are also squirrels, are the largest animals to hibernate. The bigger an animal is, the longer it takes for it to enter hibernation and awaken from it and the greater the amount of energy that is needed for arousal. This is because the body of a small animal has a large surface area in relation to its volume and therefore loses heat rapidly, and its small size also allows it to warm up rapidly. A marmot weighs an average 11 pounds (5 kg) and this is probably the upper limit for the size of a true hibernator.

Although many people believe that bears hibernate, in fact their long winter rest is not true hibernation. A bear's normal body temperature averages 100°F (38°C). During its winter rest its temperature falls only to about 93°F (34°C) and is rarely lower than 88°F (31°C). In contrast, the arctic ground squirrel's normal body temperature of 100°F (38°C) falls to within a degree or two of freezing during its hibernation. If a bear weighing 440 pounds (200 kg) were to hibernate, allowing its temperature to fall to 40°F (4°C), raising its temperature to 100°F (38°C) would take several days and require as much energy as the bear uses in approximately 3.5 days of ordinary activity. It would be impossible for the bear to eat sufficient food prior to hibernation for it to lay down a layer of body fat thick enough to sustain it through the winter and then allow it to revive.

There is an additional risk. If its body temperature falls below a certain danger threshold a hibernating animal needs to arouse itself. It wakes, warms itself by shivering and moving about, and then eats food from its winter store to replace the energy this activity used. Small animals wake several times during the winter. Under these circumstances it is unlikely that an animal the size of a bear could arouse itself quickly enough to prevent its temperature falling so low as to cause serious harm, and it could not possibly replace the energy this used by snacking from its winter hoard. Only small animals are able to hibernate.

Scorpions, spiders, and insects

Most people are scared of scorpions. The raised tail—in fact the *postabdomen* and not really a tail—with its fearsome sting has earned the scorpion a bad reputation that is partly warranted. All scorpions sting, but they do so in order to subdue their insect prey before eating it. Most of the 700 or so species deliver a sting that is extremely painful to people but one from which they make a full recovery.

There are exceptions, however. *Androctonus* species are very dangerous, and the fat-tailed scorpion (*A. australis*) of Old World deserts is possibly the worst of all. Up to four inches (10 cm) long and with extremely potent venom, it can deliver a lethal sting. It hides under rocks and crevices but also in cracks in the stone and brick walls of houses.

American scorpions are less dangerous. The striped scorpion (*Centruroides vittatus*) is the one people encounter most often. It is about 2.5 inches (6.4 cm) long and hides in cool, damp places. Its sting is very painful but is fatal only to persons allergic to the venom. The related and slightly larger—three inches (7.5 cm) long—bark scorpion (*C. sculpturatus*) is the only American species with a sting that can kill. Children, elderly persons, and those with respiratory illnesses are especially vulnerable. Unlike most scorpions, the bark scorpion never digs burrows, but lives entirely in trees. The desert hairy scorpion (*Hadrurus arizonensis*) is the biggest American species. It is 3.75 inches (9.5 cm) long and lives among rocks.

Despite their reputation, scorpions will sting only if they are handled or touched. Then they grip their molester with their claws, just as they would grip prey, and sting repeatedly. If a scorpion grabs you, tear it away immediately.

All scorpions are nocturnal. That is why they are seldom seen but pose a risk to people out after dark in bare feet or wearing sandals. Their eyesight is poor, but they are able to detect vibrations in the air or ground and are quick to attack once they have located prey.

Wind scorpions are more visible, because they are active by day. They have many names, including sun spiders, false spiders, camel spiders, and jerrymanders. Solitary hunters, they look like balls of thistledown as they race across the desert sand in pursuit of prey. Some have bodies no more than 0.6–0.8 inch (1.5–2.0 cm) long, and the largest are about 2.75 inches (7 cm) long or six inches (15 cm) when the legs are included. They hunt insects, scorpions, spiders, small reptiles, mammals up to the size of a mouse, and each other—they are highly antisocial. They will also eat carrion.

Despite their names, they are neither scorpions nor spiders, although they do possess eight legs and large *chelicerae,* which serve as claws, as well as long *pedipalps,* which look like legs but are appendages used for examining and manipulating objects. They are solifugids (order Solifugae), organisms related to spiders and scorpions but distinct from them. There are about 900 species of solifugids found mainly in hot deserts throughout the world. Some species are nocturnal. These are usually larger and less brightly colored than the solifugids that are active by day.

Wolf spiders really are spiders. They hunt by running their prey down and overpowering it. They have keen eyesight—with two large eyes and four smaller ones below them—and can detect the slightest movement that might betray a potential victim. There are also jumping spiders in the desert. They stalk their prey and jump on it as soon as they are within range.

Tiger beetles (family Cicindelidae) are about one inch (2.5 cm) long and often brightly colored. Active by day, they chase their prey, but their larvae use a different hunting strategy. The larva digs a vertical burrow where it waits. When an insect comes within its reach it grabs its victim and holds tight until the prey is subdued.

Ant lions (family Myrmeleontidae) and worm lions (family Rhagionidae) dig pitfall traps. An ant lion digs a conical pit in the sand and waits at the bottom, buried except for its *mandibles*—mouthparts it uses to seize food. When an insect, commonly an ant, reaches the edge of the pit the ant lion throws sand, triggering a landslide that carries the victim into the pit and to the waiting mandibles.

Insects are plentiful in all deserts. Each shower of rain brings forth butterflies and moths. Every plant harbors vegetarian flies and beetles. The abundance of edible insects means there is ample food for the hunters.

Darkling beetles (family Tenebrionidae) have few enemies, however, despite being active by day. They respond to threats either by releasing a highly offensive smell or by pretending to be dead. Most predators will leave a dead beetle alone.

Locusts

There are venomous snakes that lie hidden beneath the sand, poised to strike. There are deadly scorpions lurking in dark crevices, solifugids that bite, and insects that sting. Yet none of these can inspire the dread conveyed by the name of a particular kind of big grasshopper: locust.

Locusts are grasshoppers. Most of the time they avoid each other and are harmless, but when food is abundant they congregate into vast swarms that devour farm crops. (Courtesy of Rafal Zdeb)

Locusts are strict vegetarians. They do not bite or sting. They transmit no diseases to people. Yet they regularly kill thousands and have been doing so throughout history (see the sidebar on page 109). An adult locust is about two inches (5 cm) long with a wingspan of about four inches (10 cm), and it weighs approximately 0.07 ounces (2 g). The weight is important, because that is roughly the amount of food it eats every day. The amount is small, but one ton of locusts eat as much food each day as 2,500 people, and a locust swarm contains many tons of insects. In 2004 locust swarms swept across large areas of Queensland and parts of New South Wales, Australia, and also devastated food crops in Mauritania and Western Sahara in Africa. A locust invasion of Madagascar began in 1939 and it was 1957 before the swarms disappeared.

Locusts are among at least 10,000 species of short-horned grasshoppers (family Acrididae). All of them feed on leaves, but only about 12 species periodically form swarms. Swarming involves a dramatic change in the insects' behavior and appearance, and it is this ability to change that distinguishes locusts from other grasshoppers. The change is so great that it was not until 1921 that the Russian entomologist Boris P. Uvarov (1889–1970) recognized that what until then had been thought of as two distinct species were in fact two forms of the same species.

Species of locusts occur in various parts of Africa, the Near East, Asia, and Australia. All of them are highly destructive. The South American locust (*Schistocerca paranensis*) is the most serious locust pest of Central and South America, and between 1874 and 1877 swarms of Rocky Mountain locusts (*Melanoplus spretus*) covered 125,000 square miles (324,000 km^2) of the United States to a height of 5,000 feet (1,525 m). During that outbreak, some people tried to protect their crops by covering them with blankets. The locusts ate the blankets and then devoured the crops. The Rocky Mountain locust became extinct soon afterward and the last known specimen was found in 1902 in Canada. Scientists believe that farmers inadvertently destroyed them by plowing the areas where the locusts laid their eggs.

The most destructive species of all, and the likely culprit in most of the great plagues of history, is known simply as the desert locust (*Schistocerca gregaria*). It lives in the deserts and dry grasslands of Africa and Asia, wherever the average annual rainfall is less than eight inches (200 mm). Like all locusts, desert locusts live for most of the time as harmless

Locust plagues

In 1986 swarms of locusts began to move across northern Africa. By 1989, when the swarms finally disappeared, the locusts had devastated crops in approximately 30 countries. In 2004 the rains that ended a prolonged drought triggered a locust plague that swept across eastern Australia.

Along the southern edge of the Sahara, in the region known as the Sahel, 100,000 people died between 1931 and 1932, during an outbreak lasting from 1926 to 1934, because locusts had devoured all the food. There were also severe outbreaks between 1940 and 1948, 1949 and 1963, and 1967 and 1969.

Locust outbreaks are often called plagues and they have occurred in Africa throughout history. The eighth of the plagues of Egypt, described in the Old Testament (Exodus 10:14–15), was a swarm of locusts that, according to the biblical account, darkened the sky for three days. Historians believe this was a real event that took place in about 1470 B.C.E. in the Nile Delta.

More recently, a plague afflicted North Africa, especially Algeria, in 1724 and 1725. Louis de Chénier (1722–96), the French consul in Morocco from 1767 until 1782, was in Rabat in 1779. He described seeing many peasants who had died from starvation, parents selling their children, and women and children running behind camels in the hope of finding grains of undigested barley in their droppings. Morocco suffered again from 1813 to 1815.

Many Greek and Roman authors told of the devastation locust swarms caused in classical times when they moved north from Africa, across the Mediterranean and into southern Europe. Carried by the wind, swarms have crossed the Mediterranean several times. In 1954 a swarm from North Africa was swept all the way to Britain, and in October 1988 a swarm crossed the Atlantic, landing on several Caribbean islands and the South American coast.

During a plague the swarms may cover 11 million square miles (28.5 million km^2)—more than one-fifth of the land area of the Earth. Early in 1954, 50 locust swarms invaded Kenya. One of those swarms covered 77 square miles (200 km^2) and consisted of an estimated 10 billion locusts.

grasshoppers. They can fly but seldom do so, and although they are often present in large numbers where food is abundant, the gray, brown, or green insects avoid one another. They mate and lay eggs in moist soil below the surface. After about two weeks the eggs hatch and the young, known as *hoppers,* emerge to feed. Hoppers cannot fly, but within two to four months they mature into adults that can fly.

Locusts continue to live in this way until heavy rain is followed by a greatly increased amount of vegetation. Females then lay more eggs to take advantage of the increased abundance of food and the locust population increases. That is when a change comes over the juvenile insects. Their color changes to pink, sometimes with black, yellow, or orange stripes, and they no longer avoid one another. Instead, when two individuals meet they tend to remain together and when pairs meet they also stay together, so that the locusts form bands that steadily increase in size. Insects can grow only by discarding their external skeleton, and after they have molted for the fifth time the locusts are mature and yellow in color. They roost in trees and shrubs at night and feed all day. Before long their food supply is exhausted and that is when they start to migrate, flying by day as an immense swarm that is carried along by the wind and landing wherever there is food. A locust swarm may contain 40 million–80 million insects.

Snakes and lizards

Lizards thrive in deserts. They bask in the morning sunshine until they are warm enough to start looking for food, and when the heat becomes too intense they find shade or bury themselves. Desert lizards eat small animals, the size of the prey depending on the size of the lizard. Most eat insects, but some hunt small mammals and a few eat the eggs of ground-nesting birds. The chuckwalla (*Sauromalus obesus*), found in the southwestern United States, is unusual in being a vegetarian. It is about 16 inches (40 cm) long and has very loose skin that hangs in folds.

Most lizards are fairly small, but the fiercely carnivorous monitor lizards (family Varanidae) are the exception. Gould's monitor, also called the sand monitor (*Varanus gouldi*), lives

Anchieta's desert lizard (Meroles anchietae) *on the side of a sand dune in the Namib-Naukluft National Park, Namibia* (Courtesy of Gerry Ellis/Minden Pictures)

in the Australian deserts. It is about five feet (1.5 m) long and when threatened it rises onto its hind legs, hissing loudly. It is a highly agile lizard that can outrun a man over a short distance. Like all monitors it hunts by day.

The only venomous lizards in the world are two species related to the monitors. The gila monster (*Heloderma suspectum*) inhabits the southwestern United States, and the Mexican beaded lizard (*H. horridum*) is found in western Mexico. Both lizards are about two feet (60 cm) long and they use their venom to subdue prey. Their bite is painful to humans, but rarely fatal.

Many desert predators hunt lizards, and most lizards are small and unarmed. Armor and bluff are their best means of defense. The Texas horned lizard (*Phrynosoma cornutum*) has big horns behind its head, a collar of spikes around its neck, and spines along its back and sides. It looks fierce but is only seven inches (18 cm) long and feeds on ants.

The thorny devil (*Moloch horridus*) of the Australian deserts is about six inches (15 cm) long, moves slowly, and eats ants

Sidewinders

Snakes cross a surface by muscular movements that use their scales to push against small irregularities. This is a highly successful method, but it works only on solid surfaces. A snake travels with difficulty in loose sand, because when it pushes with its scales the sand slides away and the snake barely moves.

A snake finding itself on loose sand moves in a different fashion, by *sidewinding.* Most snakes will use this form of locomotion when they need to do so, but some have specialized in it—although they do not use it to cross solid surfaces.

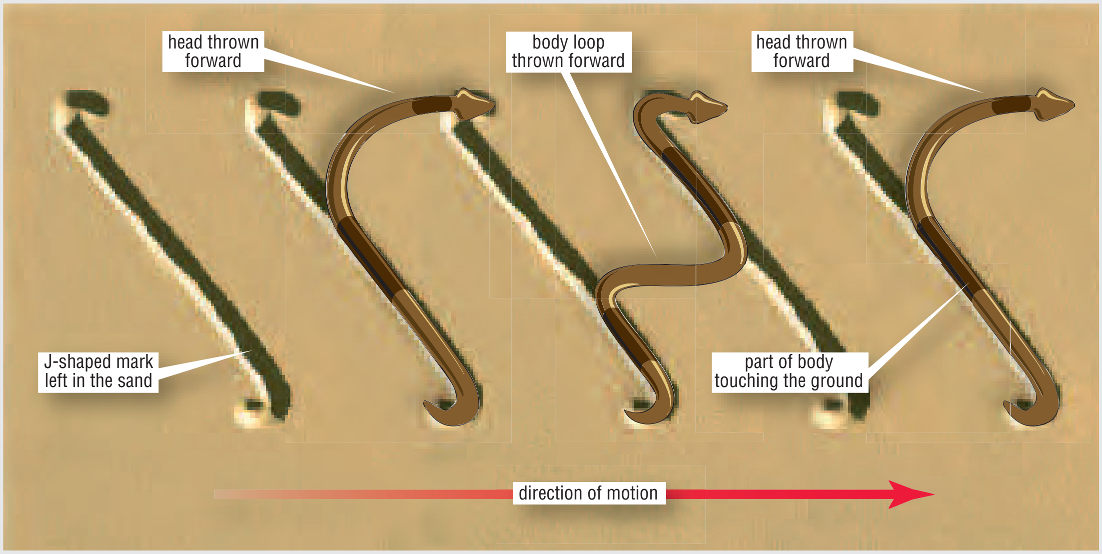
The most famous sidewinding snake is the sidewinder (*Crotalus cerastes*), a small rattlesnake found in the American deserts. The horned viper (*Cerastes cerastes*), carpet viper (*Echis carinatus*), and desert sidewinding viper (*Bitis peringueyi*) are sidewinders found in African, Middle Eastern, and Indian deserts, respectively. Its potent venom, excellent camouflage, and bad temper make the carpet viper, also known as the saw-scaled viper, possibly the most dangerous snake in the world.

While sidewinding, only two or three sections of the snake's body press against the ground at any time and these press downward, so the sand does not slide away. First, the snake presses with the middle part of its body to raise the forward part upward and throw it to the side. It then presses with the upper and lower parts of its body to throw a loop of its body to behind the head and bring the rest of its body behind it. Repeating this sequence (illustrated in the drawing on page 113) carries the snake across the sand at an angle of about 45° to the line of its body and leaves behind a distinctive set of J-shaped depressions in the surface.

and termites. Its appearance is terrifying. Its entire body is covered in modified scales that look like spines, with a really big spike over each eye. The princely mastigure (*Uromastyx princeps*) has a thick tail covered in spines that it lashes furiously at any animal threatening it. This lizard is about nine inches (23 cm) long and lives in the Eastern Sahara. If its spines fail to deter an attacker the armadillo lizard (*Cordylus cataphractus*) of Southern Africa rolls into a tight ball with its tail in its mouth.

Most skinks (family Scincidae) have very short legs and some are legless, yet these lizards move through desert sand

Sidewinding works only for small snakes. The desert sidewinding viper is only about 10 inches (25 cm) long and the sidewinder and carpet viper are both up to 30 inches (75 cm) long.



Sidewinding. The dark areas show the parts of its body that the snake presses against the ground for support as it throws its head forward, followed by a loop of its body and then the remainder of its body. The snake leaves a characteristic pattern of marks in the sand.

with such a smooth swimming motion that one species, *Scincus philbyi* of the Arabian Desert, is known as the sandfish. It has strong legs and can walk over the sand surface, but it hunts for millipedes and other small invertebrates just below the surface, swimming through the sand like a fish.

Snakes also thrive in the desert. Most shelter beneath overhanging rocks or in crevices, and some live in burrows. There are also snakes that lie in wait for prey, buried in the sand with just their eyes and nostrils showing. McMahon's viper (*Eristocophis macmahonii*) of the Sahara and Middle East is one of these. A small, highly venomous snake, about 30 inches (75 cm) long, it sweeps its body from side to side, sinking vertically until only its shape in the sand betrays its presence. There it waits for any passing lizard or small mammal that comes within its striking distance. It is easy to step on a snake that hides in this way, and this makes them dangerous.

Although there are snakes in sandy desert, they are more likely to be encountered in rocky areas, where there is plenty of shelter and the ground surface is solid. Snakes find it difficult to move across loose sand and usually do so by throwing their bodies in a series of loops, a method called *sidewinding*. Certain species have specialized in this manner of locomotion, making them fully at home in sandy desert (see the sidebar on pages 112–113).

Cobras are among the most feared of all venomous snakes. The Egyptian cobra (*Naja naje*) is up to eight feet (2.5 m) long and inhabits deserts throughout Africa. The most dangerous American snake, the western diamondback rattlesnake (*Crotalus atrox*), also lives in deserts. It can grow to 6.5 feet (2 m). The Mojave (*C. scutulatus*), tiger (*C. tigris*), and sidewinder (*C. cerastes*) rattlesnakes also inhabit American deserts. In addition, there are several nonvenomous species, some of which eat other snakes. As well as hunting small mammals and lizards, the Californian kingsnake (*Lampropeltis getulus californiae*), found in the deserts of the western United States, eats rattlesnakes, copperheads (*Agkistrodon contortix*), and coral snakes (about 40 *Micrurus* and *Micruroides* species) and is immune to their venom. This snake is three to six feet (0.9–1.8 m) long.

Rattlesnakes are pit vipers. Heat-sensitive organs located in pits between their eyes and nostrils allow them to detect a prey animal by the warmth of its body compared with the background. This ability makes them able to hunt in total darkness. Coral snakes, kingsnakes, and the harmless milk snake (*Lampropeltis triangulum*) are also nocturnal.

Desert mammals

Where water is scarce, animals adopt extreme measures to conserve it. These measures are so efficient that certain desert mammals never drink liquid water.

Gerbils are rodents, most of which live in the deserts of Africa and Asia. There are more than 80 species, some resembling mice and some rats, but all of them are very economical in their use of water. They do not sweat, and the species that live in deserts spend the daytime in their burrows, often with the entrance sealed, emerging at night to forage mainly for seeds. These are often moistened by dew and so they contain some water. The gerbils carry them to their cool burrows, where the air is moister than the air above ground, further increasing the moisture content of the food. When the gerbil digests its meal, its kidneys extract almost all of the water from it, so the gerbil excretes only a few drops of urine each day. The efficiency of an animal's kidneys is measured by the concentration of its urine. If human kidneys have an efficiency (or urine concentration) of one, and those of a dromedary (see the sidebar "The camel: ship of the desert" on pages 97–98) have an efficiency of 1.96, those of a gerbil measure 3.85.

The Australian hopping mouse (*Notomys alexis*) has kidneys that are possibly the most efficient of all, measuring 6.55 on the scale, but most small desert animals survive without ever taking a drink. Meriam's kangaroo rat (*Dipodomys merriami*) has kidneys (efficiency 3.25) that can extract the salts from seawater. It lives in Arizona and Death Valley, California, where it feeds on seeds that have absorbed water while being stored below ground, but it does not collect the seeds itself. Meriam's kangaroo rat steals food from the burrows of the bannertail kangaroo rat (*D. spectabilis*).

The kowari (*Dasyuroides byrnei*) is about half the size of a kangaroo rat, but otherwise very similar. It has big ears, a long, bushy tail, and hind legs that are longer than its front legs. It is not a rodent, however, but a marsupial that inhabits the Australian deserts. Other marsupial mammals of the Australian deserts also resemble rodents, but marsupials and rodents are not closely related. The similarities are superficial between these marsupials and *eutherian* mammals—the group that includes all the native mammals of Africa and Eurasia and most of those of North and South America. They arise through convergent evolution (see the sidebar on page 116).

It is not only small rodents that have no need to drink. The dorcas gazelle (*Gazella dorcas*), native to the deserts from the Sahara to India, also obtains all the moisture its body needs from the food it eats, although it will drink if water is available, and it loses weight on a completely dry diet. The addax

Parallel evolution and convergent evolution

When two species of animals resemble each other and behave in similar ways it is natural to assume they are related. This is often the case. A domestic cat shares many features with a sand cat, for example, and a German shepherd dog bears a close resemblance to a wolf. Domestic cats and sand cats are closely related, and so are domestic dogs and wolves. Saying that two species are related implies that they are descended from a common ancestor.

Sometimes, though, appearances can be deceptive. Kangaroo rats (*Dipodomys* species) of the North American deserts and jerboas (*Jaculus* species) of the Sahara and Arabian Desert look similar and live in the same way, yet they are not closely related. They share a common ancestor, but the evolutionary lines leading to the modern animals diverged 57 million years ago. That ancestor probably had long hind legs and hopped, and both kangaroo rats and jerboas have retained these features because they live under similar conditions. Consequently, they are as alike as their remote ancestors were. This is an example of *parallel evolution:* If two species with a common ancestor separate, but both continue to live in the same way, they may continue to resemble one another.

The kowari (*Dasyuroides byrnei*) might pass for a kangaroo rat, except for being about half the size, and the pygmy planigale (*Planigale maculata*) looks very much like a house mouse (*Mus musculus*), but smaller. They look very similar, but kowaris and pygmy planigales inhabit the Australian deserts and are marsupials, the group of mammals that includes koalas and kangaroos. Mice and rats are *eutherian* mammals, along with cats, dogs, cattle, and most other mammals. Marsupials and eutherians diverged about 100 million years ago, so these apparently similar animals are very distant relations. They resemble one another because they live in almost identical environments, but the similarities are superficial. Desert rodents eat a mainly vegetarian diet, but marsupial “mice” are carnivores.

This is an example of *convergent evolution:* Over many generations, two or more unrelated species that live under similar environmental conditions may evolve to resemble one another.

Gemsbok (Oryx gazella), *a species of antelope found throughout the drier regions of Africa. These animals are resting in a circle, constantly alert for predators approaching from any direction.* (Courtesy of Jasen Leathers)

(*Addax nasomaculatus*) and Arabian oryx (*Oryx leucoryx*) are antelopes that live far from water, the addax in the Sahara and the Arabian oryx in the Arabian Desert. Neither animal needs to drink.

Antelopes are vegetarians. So are rodents, but gerbils will also eat insects and any small animals they can catch, and three species of grasshopper mice (*Onychomys*) are meat eaters, feeding on grasshoppers and other insects, as well as scorpions, lizards, and small mammals. Grasshopper mice live in the deserts and semiarid regions of North and Central America.

Pumas (*Felis concolor*), also called cougars and mountain lions, sometimes venture into North American deserts to hunt. The puma is the only cat to be found in American deserts, but several cat species inhabit the African and Asian deserts. These include lions (*Panthera leo*) in the Sahara and Kalahari Desert and cheetahs (*Acinonyx jubatus*) in deserts from the Sahara eastward to northern India.

There are also several small cats. The sand cat (*Felis margarita*) inhabits deserts from the Sahara to Central Asia, and

A caracal (Felis caracal) *at rest in the Harnas Wildlife Reserve, Namibia* (Courtesy of Michael and Patricia Fogden/ Minden Pictures)

Pallas's cat (*F. manul*) is found from Iran to western China. Both cats are slightly bigger than a domestic cat and both hunt only at night. The caracal, or caracal lynx (*F. caracal*), usually hunts in twilight, but it hunts by day in winter and by night in very hot weather. Larger and heavier than either the sand cat or Pallas's cat, the caracal resembles a small, long-legged puma with large, pointed ears ending in prominent tufts of dark hair. It pursues prey up to the size of a young deer in dry, open country and deserts from Africa to India.

Desert birds

Birds have several advantages over mammals when it comes to living in the desert. In the first place, their core body temperature is higher, at about 104°F (40°C), so they are troubled by the heat for fewer hours each day. Most birds fly, which takes them into air that is much cooler than the air close to the ground, and because they are moving through the air they experience wind chill. Finally, birds can fly to distant sources of water that are far beyond the reach of mammals.

Mourning doves (*Zenaida macroura*) fly 40 miles (64 km) or more across the North American desert every morning to water holes where they congregate in large numbers. When the birds have drunk their fill they separate to forage for food or return to their young, waiting secure in nests that are constructed in cactus plants and protected by spines. The young cannot make the journey to the water hole and so their parents must carry liquid to them. Mourning doves are pigeons and all pigeons, male as well as female, regurgitate a liquid called *pigeon milk* to feed their young. Pigeon milk is nutritious, but 65–81 percent of it by weight is water, and the young continue to receive it almost until they have all of their adult feathers, even though by this time their parents are bringing them solid food.

Sandgrouse (family Pteroclididae), which are small, ground-nesting birds of the African and Asian deserts, carry water differently. Each morning the adult female sets off for the nearest water hole, up to 20 miles (32 km) distant. When she returns to the nest the male departs. On arriving at the water hole he rubs his belly on the dry, sandy ground to remove the natural oils in his feathers, then walks into the water to drink. The feathers on his belly are modified to act like a sponge, soaking water while he is drinking. When he has drunk his fill the sandgrouse flies back to the nest. Some of the water evaporates from his "sponge" during the flight, but enough remains to satisfy the needs of the young. When they are satisfied he rubs his belly on the ground to dry the feathers, and then all the family starts looking for food.

Pigeons and sandgrouse eat very dry food and so they need water. Meat-eating birds obtain water from their food. Not all of them are airborne hunters. The greater and lesser roadrunners (*Geococcyx californicus* and *G. velox* respectively) of North America are long-tailed members of the cuckoo family (Cuculidae) that hunt by running at up to 15 MPH (24 km/h) and stopping abruptly when they spot prey. They will eat insects, scorpions, lizards, small mammals, birds, and snakes, even rattlesnakes.

Roadrunners have another curious talent, and in this respect they resemble reptiles. Desert nights can be very cold and daytime temperatures are high. Most birds cope with the low temperatures by increasing the rate at which they use energy to keep warm, but the roadrunner is different. It allows its core temperature to fall. By dawn the roadrunner is too cold to be very active, so it begins the day by basking in the sunshine, helped by a patch of dark feathers on its back that it can raise. The dark color of the feathers absorbs warmth, and the raised feathers trap a layer of air.

The secretary bird (*Sagittarius serpentarius*) is a ground-dwelling hunter of the semiarid grasslands and desert edge of Africa south of the Sahara, named for the long feathers at the back of its head, which resemble the quill pens that office clerks once carried behind their ears. It is a bird of prey that flies well and nests in acacia trees, but it hunts on the ground for small animals, including snakes, which it kills by stamping on them.

The greater roadrunner (Geococcyx californianus) *feeds on invertebrate animals and lizards. This bird is in the Bosque del Apache National Wildlife Refuge, New Mexico.* (Courtesy of Gerry Ellis/Minden Pictures)

Other birds of prey hunt from the air. These include three desert falcons—the lanner falcon (*Falco biarmicus*) of Africa and Arabia, the saker falcon (*F. cherrug*) of Central Asia, and the laggar falcon (*F. jugger*) of India. Falcons are no more than 15–20 inches (40–50 cm) long, but they are powerful and highly maneuverable hunters of small birds.

Vultures are the birds many people associate with deserts, but most vultures—including all the American species—avoid deserts. Lappet-faced vultures (*Torgos tracheliotus*) forage over the Sahara, alone or as groups of up to four birds. The lappet-faced is the biggest of the vultures—up to 45 inches (1.1 m) from the tip of its bill to the tip of its tail, with a wingspan of nine feet (2.7 m), and weighing 15 pounds (6.8 kg). The powerful bill of a lappet-faced vulture can rip through the hide of a rhinoceros. Not surprisingly, other vultures leave them in peace while they are feeding. The griffon (*Gyps fulvus*), white-headed (*Trigonoceps occipitalis*), and hooded (*Necrosyrtes monachus*) vultures have ranges that overlap that of the lappet-faced vulture. All of these vultures feed only on carrion, but the Egyptian vulture (*Neophron percnopterus*) also eats vegetable matter, garbage, and small live animals. It is found from Egypt eastward as far as India.

Animals of the Arctic

Lemmings are small rodents, about four inches (10 cm) long with a short tail and longer hair than voles and mice. There are nine species, all but one of which live in the arctic tundra. In winter the arctic or collared lemming (*Dicrostonyx torquatus*) grows a white coat. Other lemmings are uniformly brown through the year, except for the Norway lemming (*Lemmus lemmus*). It has a dark back and pale underside.

Despite the cold, lemmings do not hibernate. Instead they burrow beneath the snow where they are sheltered from the wind, moving freely through the grasses and sedges at the bottom of trenches that separate blocks of ice. Throughout the winter they feed on the plants around them, emerging in spring when the snow starts to melt, flooding their trenches.

All lemming populations fluctuate over a cycle of three or four years. When their numbers reach a maximum the lemmings produce fewer young and many of the young die from stress and hunger, reducing the population to such a low level that it takes three or four years for the population to recover.

It is not true that from time to time Norway lemmings commit mass suicide by leaping over cliffs into the sea, but it is true that they sometimes move in large numbers and may run into the water where many drown. Norway lemmings are quarrelsome animals that usually live alone, but when their numbers increase encounters become unavoidable. Then the older and stronger animals drive out the younger and weaker ones, which move away in all directions until a natural barrier, such as a river or shore, halts their progress. As lemmings continue to arrive, small groups merge into vast crowds of individuals, all of them trying to drive one another away. The resulting stress leads to panic, which sends the lemmings rushing headlong, sometimes into a lake or the sea.

Weasels (*Mustela nivalis*) and stoats (*M. erminea*) hunt lemmings. With their small, slender bodies they are able to follow the rodents through their winter tunnels.

Lemmings are also the principal food for snowy owls (*Nyctea scandiaca*), but these big, white owls must wait until their prey is forced onto the surface. Unlike most owls, snowy owls hunt by day. When the lemming population crashes, the owls move south, sometimes as far as the northern United States.

Ptarmigans (three *Lagopus* species) are the only other birds that remain in the Arctic through the winter. They nest on the ground and feed on berries and other plant material. In fall they shed their brown plumage and grow white feathers that camouflage them against the winter snow.

The arctic fox (*Alopex lagopus*) also grows a white coat in winter; the animal's long, thick fur was once highly prized for making fur coats. These foxes take birds' eggs and ground-nesting birds, but lemmings are their principal food. When the lemming population crashes so does that of the arctic fox.

Tundra wolves (*Canis lupus tundarum*) also hunt in the Arctic. The biggest of all wolves, they will eat eggs, birds, rodents, carrion, and even berries, but they prefer larger prey, especially caribou (*Rangifer tarandus*), known in Europe as reindeer. Caribou undertake long seasonal migrations, always following the same routes that take them northward in spring and south to the shelter of the pine forests in the fall.

Wolves will attack a solitary musk ox (*Ovibos moschatus*), but musk oxen usually live in herds and these are impregnable. When threatened, the musk oxen form a circle, facing outward with their calves inside. They have big, solid horns that are formidable weapons, and the circle turns continually so that the attackers face the horns of the biggest, strongest ox. Any wolf that comes too close will be killed by the horns, and a wolf that penetrates the circle will be trampled to death. Musk oxen feed on grass, leaves, lichens, and other plant material and they will dig through the snow to find it. Their long, thick coats provide such good insulation that snow falling on their backs does not melt.

The polar bear (*Ursus maritimus*) is the biggest and most famous of all the arctic hunters, and the biggest of all land-

A polar bear (Ursus maritimus) *running across the ice at Ellesmere Island, Canada* (Courtesy of Jim Brandenburg/ Minden Pictures) dwelling carnivores—bigger than a lion or tiger. An adult male is almost 10 feet (3 m) long and weighs 1,400 pounds (635 kg) or more; females are only slightly smaller. A polar bear can run faster than a caribou over a short distance and can kill a musk ox, but polar bears also eat smaller mammals, birds, and some plant material. Seals are their main food, however. Seals are mammals and must surface for air, so the bear waits beside a small area of open water or the breathing hole many seals make in the ice. When the seal appears the bear grabs it and hauls it ashore. Alternatively, a bear will stalk seals that are resting on the ice. It will not attack seals in the water, because although polar bears are strong swimmers, seals can outmaneuver them.

Animals of the Antarctic

No land mammals dwell in Antarctica. The continent is too remote for any to have reached it and too inhospitable to allow any that managed the journey to survive. The only land animals are about 100 species of invertebrates, half of which are parasites of seals or birds—the only permanent residents.

Penguins are the most famous inhabitants and they are superbly adapted to the Antarctic cold. Their small feathers lie in three layers, providing a thick and completely waterproof coat, and most penguins also have a thick layer of insulating fat just below the skin. A few of the 18 species live farther north, but most inhabit Antarctica and the nearby islands and, of course, they are instantly recognizable. They were given the name "penguin" in the 16th century by the first European explorers to encounter them, because they resembled the great auk (*Pinguinus impennis*), a North Atlantic seabird that is now extinct. Penguins range in size from the little blue or fairy penguin (*Eudyptula minor*), 16 inches (41 cm) tall, to the emperor penguin (*Aptenodytes forsteri*), about four feet (1.2 m) tall.

On land, penguins walk with a comical hopping or waddling gait and sometimes they toboggan on their fronts, but in the water they are fast and highly maneuverable. They feed on fish, squid, cuttlefish, and krill.

Krill resemble shrimp, but are only distantly related to them. There are 85 species, but the most abundant in Antarctic water is the whale krill (*Euphausia superba*). It is only about two inches (5 cm) long, but krill occur in such vast numbers that many birds and mammals depend on them, including whales. A blue whale (*Balaenoptera musculus*) eats about four tons (3.6 tonnes) of krill a day. No one knows just how many krill there are, but their population has been estimated as 500 trillion individuals (5 followed by 14 zeros). If the estimate is correct, krill are the most numerous animals on Earth.

There is no large land predator to hunt penguins, but a fearsome hunter awaits them in the ocean. About 10 feet (3 m) long and weighing 770 pounds (300 kg), leopard seals (*Hydrurga leptonyx*) are the largest of all seals. Their bodies are slender, with a long neck, and spotted like a leopard's coat. On land they move slowly and clumsily like all seals, and penguins ignore them, but in the water they are fast, formidable hunters and penguins provide about one-quarter of their diet. Leopard seals also feed on fish, squid, other seals—and krill, of course.

Leopard seals are plentiful, but they are not the most abundant species. Crabeater seals (*Lobodon carcinophagus*) are the most numerous of any seal species, with a population of 15 million–40 million. They are smaller than leopard seals and faster on land, but both leopard seals and killer whales (*Orcinus orca*) hunt them in the water. Crabeaters feed almost entirely on krill.

The Weddell and Ross Seas form deep bays in the Antarctic coast, and the Weddell seal (*Leptonychotes weddelli*) breeds on the permanent ice shelf of the Weddell Sea. It feeds on squid, bottom-dwelling fish, and invertebrate animals and dives up to 1,800 feet (550 m) below the surface in search of food. The Ross seal (*Ommatophoca rossi*), found in the Ross Sea, feeds mainly on squid.

CHAPTER 5

HISTORY AND THE DESERT

When deserts grew crops

Today Tassili-n-Ajjer, Algeria, lies deep inside the Sahara. The nearest city, Tamanrasset, lying a few miles to the south at 22.78°N, 5.50°E, has an average annual rainfall of 1.8 inches (46.7 mm). It is one of the driest places on Earth. Caves at Tassili-n-Ajjer (the name means "Plateau of the Chasms") have paintings on their walls that were made by the people who lived there from about 8000 B.C.E. until 4000 B.C.E. The paintings depict scenes from the everyday life of a people who lived by hunting. Other cave paintings in the same region show a very similar way of life. The hunters pursued buffalo, elephants, rhinoceroses, and hippopotamuses. Hippopotamuses are animals that spend most of their time in water, and in the cave paintings people are seen hunting them in canoes. Clearly, in those days that part of Algeria was not a desert. Until 6000 B.C.E. southern Libya had an average annual rainfall of eight to 16 inches (200–400 mm). Today it rarely rains at all.

As recently as Roman times North Africa was a land of farms producing food for export. It was known as "the granary of Rome," and in some places the outlines of fields are still visible from the air. In about the year 120 C.E., the astronomer, mathematician, and geographer Ptolemy (Claudius Ptolemaeus) recorded that it rained every month except August in the city of Alexandria, where he lived. Alexandria, on the Egyptian coast, now receives an average of seven inches (178 mm) of rain a year.

Climates change over time and, as they do so, deserts appear and disappear—and not only in Africa. Petra, about 16 miles (26 km) northwest of the town of Maʿān, Jordan, now lies in ruins, but from about 300 B.C.E. until 100 C.E. Petra was a flourishing city and a center for the caravan trade.

Its people had a reliable water supply and were fed from the produce of surrounding farms.

The annual rainfall at Sukkur, Pakistan, averages 3.2 inches (81.5 mm). Sukkur lies in the valley of the Indus River and is on the edge of the Thar Desert. It is not far from the ruins of Mohenjo Daro, a city that flourished from about 2500 B.C.E. until 1700 B.C.E. Farmers grew cereals, dates, and melons there to feed the citizens of Mohenjo Daro, and they may have grown cotton and raised livestock as well.

A few miles to the east of St. Louis, Missouri, Cahokia Mounds State Park contains the remains of the biggest Native American city north of Mexico. When the city was at its peak, between 1050 C.E. and 1250 C.E., its population may have been as high as 40,000 or even 50,000. Farms around the city produced enough food for all of those people. The city was abandoned when the climate changed and the area turned to desert. It is not desert now, because since then the climate has changed again.

Desert civilizations

Mighty empires once prospered in parts of the world that are now barren deserts. The earliest of these lay to the south of modern Baghdad, Iraq, and produced the first written language—Sumerian. The oldest surviving inscriptions written in Sumerian were made in about 3100 B.C.E. The people who made them had arrived about two centuries earlier in the region, which came to be known as Sumer. They were not the earliest inhabitants, however. Sumer was settled between 4500 B.C.E. and 4000 B.C.E. by people who drained the marshes, established industries, and lived in villages set in a landscape that supplied them with all of their food. Clearly the land around them was not a desert. The Sumerians displaced the original inhabitants and developed a civilization based on 12 or more city-states. These eventually fell under the control of Sharrukin, or Sargon, who ruled Akkad, the region to the north of Sumer, from 2334 B.C.E. until 2279 B.C.E. Sumerians invented wheeled vehicles, the potter's wheel, writing, and written laws.

The land lying between the Red Sea and the eastern bank of the Nile River from approximately Aswān south as far as Khartoum is known today as the Nubian Desert, an extension of the Sahara. It was not always so desolate. A stone-age culture had developed there by 6000 B.C.E., and in about 2613 B.C.E. the Egyptians under Pharaoh Snefru raided the region and brought back cattle and prisoners. The Egyptians knew the country as Cush (or Kush) and the Greeks called it Ethiopia, though it lies to the north of modern Ethiopia, in Sudan. It is also called Nubia.

At one time Egypt formed part of the Nubian Empire. The Nubian king Piankhi, who lived around 730 B.C.E., annexed Egypt, styling himself king of Cush and Egypt. Piankhi's successor, Shabaka, also called Sabacon, who ruled from about 719 or 718 B.C.E. to 703 B.C.E. and founded the 25th Egyptian dynasty, is believed to have moved his capital to Memphis, about 14 miles (22 km) south of Cairo. Although the expanding Assyrian Empire drove the Nubians from Egypt in about 650 B.C.E., their own kingdom survived for a further 1,000 years.

In Yemen, in the southwestern corner of the Arabian Peninsula, there once lived a people known as the Sabaeans. Their kingdom was called Saba, and it appears in the Old Testament under the name of Sheba. The first historical mention of the Sabaeans is a record of tribute sent by the king of Saba to the king of Assyria in about 715 B.C.E.

The Sabaeans appear to have been a prosperous people, but little is known about them until the second century C.E., when they joined with Cush to form the kingdom of Aksum. Migrants from Saba had settled in the Tigre region of modern Ethiopia around the town of Aksum (14.08°N, 38.7°E). They traded with Greece, Rome, Cush, and Egypt, and in the third century their descendants conquered Saba. The Aksum Empire had been born, and in 320–350 C.E. it conquered Cush and appropriated that kingdom's considerable wealth. Until about 400 C.E. Aksum was an important meeting point for trade routes between Africa, India, and the Mediterranean. The Aksum Empire began to decline in importance from about 900 C.E.

More recently a large and important empire covered much of West Africa. At its peak in the early 14th century, the Mali empire extended across most of modern Mali, Guinea, Senegal, Gambia, Guinea-Bissau, and Mauritania, and its influence was felt in Sierra Leone, Burkina Faso, Niger, and Algeria. It was not the first West African empire. Until the middle of the 11th century the Ghanaian Empire ruled most of the region. As that empire declined, several short-lived kingdoms competed for its territories, and at the Battle of Kirina in 1235 armies led by Sundiata Keita, king of Kangaba, defeated those of the king of Susu. Both kingdoms then united under Sundiata and the resulting Mali Empire expanded northward to the salt and copper mines of the Sahara. Its capital was at Niani, now a village in northeastern Guinea. Gao, Djenné, and Timbuktu were important commercial centers.

There were rich farmlands on the floodplain of the Niger River, at the heart of the Mali Empire, and there were gold mines nearby. Gold also passed through Mali on its way from mines in countries to the south to Mediterranean ports and from there to Europe, and it was taxed in Mali. By the reign of Mansa Mūsā, from 1307 to perhaps 1337, the empire's wealth was legendary. In 1324–25 Mansa Mūsā made a pilgrimage to Mecca, taking with him 100 camels laden with gold. A pious man, Mansa Mūsā felt obliged to distribute gold to less fortunate fellow Muslims he encountered along the way. He distributed so much gold in Cairo that it caused marked inflation.

Internal strife and rebellion weakened the empire from the second half of the 14th century, and by the 15th century Mali was in decline. The Songhai people, originally from northwestern Nigeria, dominated the surrounding states and had established themselves in Gao by 800, and were themselves dominated by the Mali Empire. As that empire weakened, the Songhai achieved independence, and in 1471 Sonni 'Alī (reigned 1464–92) occupied Djenné. His son, Sonni Baru, was deposed by Muhammad ibn Abī Bakr Ture (also known as Askia Muhammad Touré, reigned 1493–1528), who captured Timbuktu and restored it to its former prosperity. This established the Songhai Empire, which reached the peak of its power and influence in the 15th and 16th centuries. In 1590–91 the Songhai army was defeated by a Moroccan expedition. The Moroccans occupied Gao, Djenné, and Timbuktu, ending the Songhai Empire.

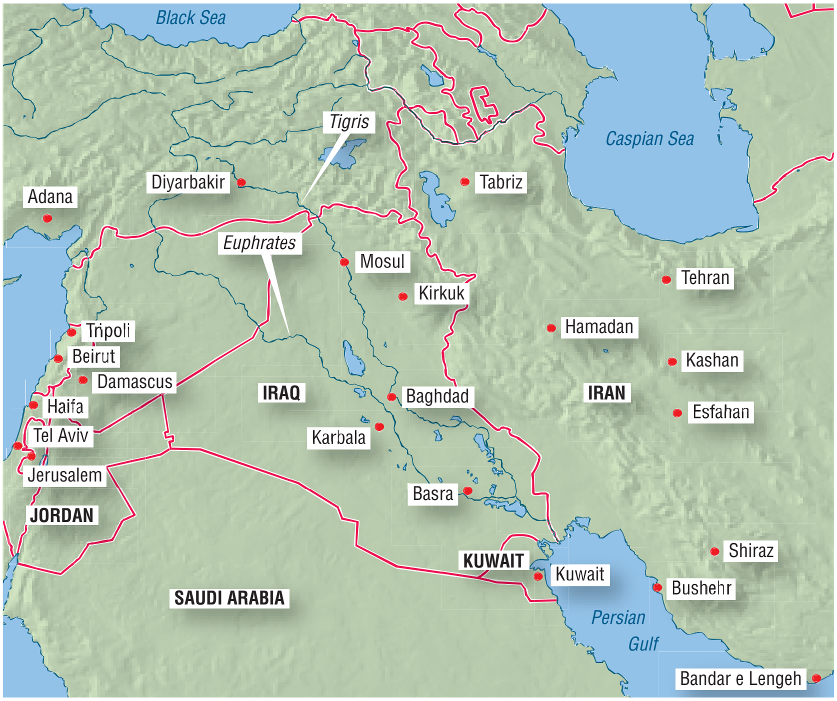
The Middle East: birthplace of Western civilization

Western civilization was born approximately 8,000 years ago on the Anatolian Plain, in southern Turkey. That is where people first discovered the way to select seeds from the best of the plants they liked to eat and to grow more plants from them. At about the same time, people began to capture animals they formerly hunted and breed young animals from them in captivity. They had invented farming and were domesticating a range of food plants and livestock. There is archaeological evidence of farming in Turkey in about 6200 B.C.E.

People who live by gathering plant foods and hunting game move about, living in temporary camps as they follow the migrations of animals between seasonal pastures. Farmers need to live in one place, and as farming spread, villages appeared to accommodate farming communities. The most ancient cities appeared at about this time. This marks the literal beginning of civilization, because our words *civilization* and *citizen* are derived from the Latin *civitas,* which means "city."

One of the most ancient and most famous of these Anatolian cities is called Çatalhüyük (pronounced: chatalHOO-yook). The city consists of rectangular houses made from mud bricks and built without spaces between houses, so people walked across the roofs and entered their homes from above. Inside, the walls were decorated with paintings and the homes were well furnished. The citizens were prosperous. Çatalhüyük was occupied from about 6500 B.C.E. to 5800 B.C.E. and several thousand people lived there.

Knowledge of agriculture spread from Anatolia southward into Egypt (see pages 132–134) and eastward into the lands between the Tigris and Euphrates Rivers in modern Turkey, Syria, and Iraq. As the map on page 131 shows, the region has a crescent shape, and the American historian James



The Fertile Crescent lies between the Tigris and Euphrates Rivers, in what are now Syria and Iraq.

Henry Breasted (1865–1935) gave it the name *Fertile Crescent,* by which it is still often known today. The land between the rivers was more often known by its Greek name of Mesopotamia, "the land between the rivers," from *mesos* (between) and *potamos* (river).

It was in Mesopotamia that the empire of Sumer and Akkad arose, and it is there that the Assyrian and Babylonian Empires flourished from about 1800 B.C.E. The city of Babylon lay close to the modern town of Al Hillah in southern Iraq. Nineveh and Nimrud were two of the most important Assyrian cities. Both lay close to modern Mosul in northern Iraq.

Not far away, the Phoenicians were flourishing at the same time, but they had arrived in Phoenicia—modern Lebanon—in about 3000 B.C.E. Tyre and Sidon (modern Saida) are Phoenician cities mentioned in the Old Testament. From their port of Byblos (modern Jubayl, north of Beirut), the Phoenicians exported paper made from papyrus, and *byblos* became the Greek word for "papyrus." Our word *bible* means "papyrus book." People were living in Byblos by 3000 B.C.E. and the city is inhabited to this day. Byblos-Jubayl has been continuously occupied probably for longer than any other city in the world.

Egypt

Egypt has a desert climate. Cairo receives an average 1.1 inches (28 mm) of rain a year. Yet it is a large, bustling city—by far the biggest city in Africa or the Middle East—and there has been a major city in that area since at least 3100 B.C.E.

Ancient Egypt was originally two countries. Upper Egypt extended from Aswān (24.2°N), where a waterfall known as the First Cataract marks the southern limit of the navigable river, to Cairo. The region from Cairo northward to the Nile Delta and the Mediterranean comprised Lower Egypt. According to tradition, the ancient city, located 14 miles (22.5 km) to the south of modern Cairo, was founded by Menes, the first king of the united kingdoms of Upper and Lower Egypt. The god of the city was Ptah, to whom a vast temple was built. The city was called Memphis, a Greek name derived from Menefer, an alternative name for Pharaoh Pepi I, but the city was also known as Hikupta—"mansion of the soul of Ptah." The Greek version of that name was Aegyptos and they applied it to the entire country.

Memphis was the capital of the Old Kingdom from its founding until about 2258 B.C.E and it remained an important city until Roman times. Its influence declined as that of Alexandria rose, and the Arabs finally destroyed Memphis in the seventh century C.E. The Arab conquerors used much of its stone to build their new city of Al Fustāt, which was the Arab capital of Egypt from 641 until 969, and very little of Memphis now remains.

Farmers were tilling the soil in El Fayyûm, a low-lying area to the southwest of Cairo, long before Memphis was built. They grew wheat and barley for food, cotton and flax for making cloth, and they raised sheep, goats, and pigs. The first farmers arrived in the region in about 4000 B.C.E. and settled because in those days the land was not desert, but grassland. Elephants, rhinoceroses, and giraffes lived there. Farther south a different people were raising livestock near the modern town of Asyūt. By the time knowledge of farming had spread northward to the Nile Delta, in about 3600 B.C.E., however, the climate was becoming drier.

Egypt became home to one of the world's most important civilizations and has thrived ever since. Its success was due to the fact that its farms did not rely directly on the rainfall. Instead, they received their water from the Nile River. Every year, when the snows melt in the distant mountains of Uganda and Ethiopia, the water level rises, first in the Blue Nile flowing from Ethiopia and, as that level starts to subside, then in the White Nile flowing from Uganda. The two rivers meet at Khartoum, and between June and September the combined Nile used to overflow its banks, flooding the land on either side all the way northward to the sea. As well as bringing water, the flood brought fertile soil washed from the Ethiopian hillsides. Today the Aswān High Dam regulates the flow of water and the annual flood no longer occurs.

The flood was never entirely dependable, and when it was late or failed famine was the likely consequence. It was famine that brought down the Old Kingdom in about 2134 B.C.E. and the Middle Kingdom in about 1640 B.C.E.

Fields on either side of the river were on low-lying ground and separated from one another by high banks. Canals leading from the river allowed the floodwater to fill each field. The fields remained under several feet of water for a few weeks, during which the mud settled. Between floods the fields were irrigated by water lifted from the river by a bailing device known as a *shadoof,* or *shaduf,* and poured into the canals. It may have been Egyptian farmers who invented irrigation.

Egyptian farming was highly organized, with a ministry of agriculture overseeing the proper management of the resources. Between them the pharaoh, temples, and wealthy aristocrats owned all of the land, and the farmers were tenants paying a rent that was fixed by law. Seed and oxen for plowing were loaned to the farmers and the loans were repaid from the harvest.

Ordinary people ate mainly bread, beans, and onions. They were the first to use yeast to leaven bread and to bake bread in ovens, rather than on a flat stone over an open fire. They also used yeast to make beer, their staple drink. Wealthier people also enjoyed salads, lentils, peas, and other vegetables and fruit, and also beef, poultry, game, and fish. They loved cakes, some of which were sweetened with honey and fried. The farmers grew grapes, kept bees, and by 1200 B.C.E. were producing olive oil.

Peoples of the Sahara and Arabian Deserts

Deserts are empty and barren, but they have never been entirely uninhabited. People cross them carrying goods for trade, and there are permanent settlements wherever an oasis exists naturally or can be made by sinking a well (see “Oases and wells” on pages 47–51). Traders have meeting places where goods are exchanged and deals done, and towns often grow up in such places.

Tunis, the capital of Tunisia, was once known as Carthage, and in ancient time it was occupied by Phoenicians from what is now Lebanon. The local people, called Numidians, allied themselves with the Phoenicians and so became involved in the Punic Wars between Carthage and Rome, which led to the destruction of Carthage and Roman occupation. The Romans knew the region as Barbary, a name they took from the Greek word *barbaros,* meaning “foreign.” A “barbarian” originally meant a person who spoke a foreign language. The Romans gave the name *Berber* to the people living in Barbary, and this is still the name by which outsiders know them, although they prefer to call themselves the Imazighen, or “free men.”

Over the succeeding centuries some Berbers became Christians who spoke Latin; others adopted Judaism, and many of their descendants now live in Israel; but most converted to Islam and learned to speak Arabic. Their ancient languages still survive, however, and there are still Berber people who speak no Arabic.

The true desert people are the Tuareg, often called “the blue people” because their men wear blue robes and turbans—although the Regui-Bat, another nomadic tribe, also dress in blue. Most Tuareg live in Niger and Mali, but others are scattered throughout North Africa. The Tuareg are another branch of the Berber people. At one time they lived around oases as peasant farmers, but in the 12th century they were dispersed by Bedouin Arabs and since then they have lived as nomads. They were once feared. No one knew the desert better than they did, and they would appear suddenly, riding horses or camels and heavily armed, to raid travelers. They also traded and exacted taxes from caravans crossing the desert they regarded as their own.

Today the Tuareg live in peace, but modernization has disrupted their way of life. The Tuareg came to dominate desert freight haulage and as recently as the 1940s they owned and operated approximately 30,000 caravans transporting goods across the desert. Camel caravans cannot compete against surfaced roads and diesel trucks, however, and as transport changed the Tuareg lost their means of livelihood.

Farther south, in West Africa, the Fulani were also nomads. They came originally from eastern Sudan, but the expansion of the Ghanaian Empire forced them to move. Eventually they were dispersed across the region between Cameroon and Senegal. They began expanding eastward from Senegal in the 14th century, and by the 16th century they were moving into Hausaland. Many Fulani continued to live a nomadic life but some, especially in Hausaland, settled down in the towns and converted to Islam. In the 1790s Usman dan Fodio, an Islamic cleric living in the state of Gobir, in northern Hausaland, accused the Hausa rulers of being little better than pagans and urged the people to revolt. The uprising of Hausa and Fulani people began in 1804, and by 1808 the rebels had conquered Hausaland and also engulfed Adamwa (northern Cameroon), Nupe, and Yorubaland in the south, and Oyo and the emirate of Ilorin in the northeast. By the end of the 19th century the Fulani Empire had weakened. Its decay made it easier for the British to gain control of what then became Northern Nigeria.

Arab is an Arabic word that means “those who speak clearly”—in other words, in Arabic. Consequently an Arab is anyone whose first language is Arabic. The Arabs came originally from Arabia, and it is probably they who domesticated the

Bedouin people with their camels (Camelus dromedarius)*, seen at sunset near Oasis Dakhia, among the sand dunes of the Sahara in Egypt* (Courtesy of Gerry Ellis/Minden Pictures)

dromedary (see the sidebar "The camel: 'ship of the desert' " on pages 97–98), originally for military use.

Severe droughts led to the failure of many farms throughout the Mediterranean region during the fourth century C.E., and people who had been farmers became nomads. The Arabic name for nomads is *badw* (singular *badawi*). The *badw* are the people known in English as Bedouin, and they are the traditionally nomadic people found throughout the desert lands. Most Bedouin speak Badawi, which is their own dialect of Arabic. Bedouin who have adopted a settled way of life on the edge of the desert are known as *fellahin.*

Many Bedouin have now settled down, but some continue to live as nomads, driving their camels, sheep, and goats across the desert from one area of seasonal pasture to another. They live in low, rectangular black tents, the size of the tent reflecting the social position of its owner.

Peoples of the Asian deserts

The Gobi Desert lies partly in Mongolia and partly in the Inner Mongolian Autonomous Region of China. The people of the Gobi are Mongols. Parts of Mongolia are farmed, but the dry climate makes farming precarious, and most of the farmers are descendants of Chinese immigrants. Although nowadays most Mongolians live in towns and villages, the Mongols are traditionally nomads who raise camels, horses, cattle, sheep, and goats. Some also raise yaks (*Bos grunniens*), which are sturdy cattle from Tibet.

Their camels are the two-humped Bactrian camels (*Camelus bactrianus*). People ride camels during very severe winter weather, but they are used mainly as pack animals. Camels also give milk, and their long coats supply the wool that is used to make Mongolian garments and blankets.

Meat and milk are the staple foods. Some of the milk is used to make dried curd and cheese. Mare's milk is fermented to make the national drink, called *airag*. People also drink tea, made in a large bowl with added milk and salt. Mongols do not eat vegetables or fish.

The traditional Mongol dwelling is a circular structure made from wooden poles covered with skins, woven cloth, or more commonly felt. It is known variously as a *ger, yurt,* or *yurta* and is furnished with brightly colored rugs. There is a hearth near the center and a hole in the roof to allow the smoke to escape.

There is never just one ger, but always at least two and sometimes as many as six. These make up the herding camp that is the basis of Mongol society. Families agree to join a herding camp for one year and at the end of the year they decide whether to remain together. A camp must not grow so large that it makes managing the livestock and pastures difficult. Every camp has sheep, managed as a single flock. The families keep other livestock only if there are enough people to look after them and the pasturage will sustain them.

Spring and summer are spent on the pastures. Every morning the livestock are taken out from the camp, returning in the evening. When they have grazed one area of pasture they are taken to the next, starting close to the camp and moving a little farther away each day. When the journey to the pasture becomes inconveniently long it is time for the families to move on. They pack their gers and possessions onto camels and travel to the next site, allowing their animals to make the best possible use of the food and water they find along the way.

Mongolian winters are harsh, and as the weather turns colder the families move to their permanent winter campsites, where the authorities provide fodder and there is shelter for the animals. That is when animals that are unlikely to survive are slaughtered and their meat dried or frozen to provide food during the time when there is no milk.

No one lives in the Taklimakan Desert. It is too dry there for plants to grow, and with no plants, the desert provides nothing for animals to eat.

People live in parts of the Thar Desert, mainly along the northern margin, in the valley of the Indus River. Farming is possible there in the rainy season, and local people have learned to collect and store water and to use it efficiently.

Caravans and the Silk Road

No one should attempt to cross the desert alone. It is extremely dangerous, even today. People who need to cross a desert have always sought companions and experienced guides who will make sure they follow the best route and who will protect them from robbers. A group of people traveling together across a desert is called a *caravan.* A modern caravan might comprise a number of cars, trucks, or buses. A traditional caravan used strings of up to 40 camels linked by ropes. Caravans in the Middle East and North Africa sometimes comprised hundreds or even thousands of camels moving three or four strings abreast. There is safety in numbers, and the more hazardous the route the bigger the caravan.

The camels carried loads of about 350 pounds (160 kg) of goods or of passengers. Passengers rode in *panniers*—large bags or baskets—slung on either side of the animal.

Caravans traveled by day except in extremely hot weather, when they might travel by night, resting at the end of each section of the journey. They moved at a steady two to three MPH (3–5 km/h) and covered 16–40 miles (26–64 km) before stopping to rest. When possible, day caravans rested overnight in a *caravansary.* This was a public facility enclosed by thick, high walls and located, because of its size, outside a town or large village. It offered secure shelter for animals, storage space for goods and supplies, and bedrooms for the travelers. There was a well to supply water and a communal hearth for cooking, but travelers had to provide their own food, bedding, and fodder for their animals. The caravansary remained open from dawn until dusk, when the resident porter closed and locked the only entrance.

Today there are roads across deserts, but the former absence of roads did not mean camel caravans wandered just anywhere. Caravans followed particular routes that were developed to take pilgrims to Mecca and goods from one trading center to another. There were also salt routes. The most important salt routes in the Sahara led to Timbuktu, and there was also a salt route from southern Arabia to the Mediterranean. Routes often went from oasis to oasis. The modern roads often follow the old caravan routes.

The most famous caravan route of all led from China to Alexandria, Egypt, and to Antioch (modern Antakya) in southern Turkey. It is called the Silk Road, and it was once used to transport silk and spices from Asia and gold, silver, precious stones, and woolen cloth from Europe. Although it is no longer used as a trade route, sections of it are now open to tourists. There are plans to restore the entire Silk Road as the Trans-Asian Highway.

When the first Chinese silk cloth reached Europe it was literally worth its weight in gold. No one knew how it was made: The Chinese kept its method of manufacture a closely guarded secret. Demand for this fabulous material was huge, and the Silk Road first opened to export it in about 100 B.C.E.

Smaller trade routes converged on the city of Xi'an (also spelled Sian), where the Silk Road began. From there it went north as far as the Great Wall, then followed the Wall past the Nan Shan Mountains and skirted the southern edge of the Gobi Desert. At the lake of Lop Nur the road divided. One branch passed to the north of Lop Nur and along the northern edge of the Tarim Basin at the center of the Taklimakan Desert, and the other passed to the south of the lake and basin. The road crossed the Pamir and Karakoram Mountains, turned south to Islamabad, Pakistan, then north again to Samarqand, Uzbekistan. It then crossed northern Iran, passed to the south of the Caspian Sea, crossed northern Iraq and Syria, going through Damascus, and finally reached the ports of the eastern Mediterranean. Goods were taken by sea from there to southern Europe.

It is not only goods that travel along roads as important as the Silk Road. Ideas also travel. Information about China, much of it highly unreliable, traveled to Europe. Buddhism traveled northward from India and spread eastward. Nestorian Christianity, a version of Christianity developed in the Near East in the fifth century, traveled to China. And in central Asia, where western and eastern ideas met along the Silk Road, there are Buddhist statues with European faces.

Peoples of the American desert

At some time around 300 B.C.E. people settled in Arizona and lived by hunting game and gathering wild fruits and beans. They also grew corn and dug a canal three miles (5 km) long that carried water from the Gila River to irrigate their fields. Very little is known about where these people came from or why they disappeared. They are known as the Hohokam, a name given to them by the Akimel O'odham (or Pima) people, who may be descended from them and who occupied part of what had been Hohokam territory. The name means "those who have disappeared" in the Akimel O'odham language.

The Akimel O'odham, whose name means "river people," were farmers who settled along the river valleys and used river water to irrigate their crops. Harvests were never reliable, however, and the Akimel O'odham obtained some of their food by hunting and gathering wild plants.

The Hohokam and all of their descendants lived in permanent villages built either from blocks of baked mud called *adobe* or from stone. Dressed stone came into use between 1050 and 1300 C.E. This is stone that has been shaped into squared blocks that fit snugly together to produce a much more solid construction. Using dressed stone, Native Americans built apartment buildings up to four stories high and with up to 1,000 rooms. Rooms on the ground floor often had only one entrance, in the roof, and each upper story was set back from the story below, so that every room had a terrace. The floors between stories were made from a thick layer of adobe laid over rush matting that rested on massive timber beams. Each apartment block was a complete village.

These villages, constructed in and beside the North American desert, are known by the Spanish word for villages—*pueblos*—and their occupants are called Pueblo Indians. Some pueblos were built on ledges and in alcoves along the sides of canyons and mesas (see "Mesas, buttes, and other desert landforms" on pages 43–45). Many pueblos also had underground rooms that were used for important religious ceremonies.

The Anasazi were among the first Pueblo peoples and contemporaries of the Hohokam. Their name means "ancient ones" in the Navajo language. They lived in the Four Corners region to the east of the Wasatch Range, where present-day Utah, Colorado, New Mexico, and Arizona meet. The Anasazi lived by hunting and gathering, and they also cultivated corn and pumpkins.

Part of the Sonoran Desert is known as the Yuma Desert, and it is home to the Yuma people, who once lived along the floodplains of the lower Colorado River. They lived by fishing, hunting, and gathering wild plants, and also by farming. The Yuma farmers had no need for irrigation, because every spring the melting of the snow in the mountains made the river overflow its banks, soaking the fields and leaving behind a deposit of fertile silt.

Farther upstream, the Tohono O'odham—their name means "desert people"—inhabited a much drier area. They relied on farming much less than other Pueblo peoples and lived a partly nomadic life. Heavy summer rains would cause floods, and when these subsided the Tohono O'odham (also called the Papago) planted their seeds in the silt. While their crops of corn, beans, pumpkins, and cotton were growing, the Tohono O'odham lived in villages nearby, but the ground dried after harvesttime and the people moved to other villages in the hills where there was water and game.

The Pueblo Indians still survive, but nowadays most of them live in reservations. The Hopi, one of the best-known groups, live in eastern Arizona on a large reservation surrounded by the Navajo Reservation. The Hopi villages are built on top or at the foot of three mesas, known as the First, Second, and Third Mesas, that project like fingers from the much larger Black Mesa to the north. Oraibi, the unofficial Hopi capital, is built on top of the Third Mesa, about 6,500 feet (1,980 m) above sea level. People have been living in Oraibi since 1100 C.E. and Oraibi may be the oldest continually inhabited settlement in the United States, although the present village is not the original one, which lay at the foot of the Third Mesa.

Peoples of the Arctic

In 1999 an area of 733,400 square miles (1.9 million km^2) in the Northwest Territories of Canada became the self-governing territory of Nunavut, with a population of about 22,000, of which about 17,500 are Inuit. Greenland is also a self-governing Inuit territory, known officially as Kalaallit Nunaat. The Inuit population of Kalaallit Nunaat, accounting for about 85 percent of the total population of 59,000, is descended from Canadian migrants.

Amerindian peoples live in the far north of North America, but the true desert people of the far north are the Inuit—the name means simply "the people." Both Amerindians and Inuit are descended from Asian ancestors, but the two groups are not closely related.

Inuit peoples inhabit the Arctic Regions of Alaska, Canada, Greenland, and Siberia. The Aleuts, living in the Aleutian Islands and western Alaska, are close relatives. The Aleut and Inuit languages are also related, but their speakers have been separated for so long that the languages have diverged and are now about as alike as English and Russian.

Inuit are fully adapted to the arctic climate. Their short and stocky build, with short arms and legs, conserves warmth by reducing the surface area of the body in relation to its volume. The shape of their skulls also minimizes heat loss. Their fingers and toes remain warmer than those of non-Inuit people when exposed to extreme cold, and Inuit people have a high tolerance for pain associated with the cold. Inuit rarely shiver, because their metabolic rate—the speed with which the body generates warmth—is up to 45 percent higher than that of non-Inuit due largely to the Inuit diet. This consists of fish, red meat, and blubber (whale and sea fat) and is very high in fat, calories, and protein. Their diet supplies the Inuit with sufficient vitamins and most minerals, but they do tend to suffer from a deficiency of calcium and an excess of phosphorus. Besides retaining heat due to their physique and diet, Inuit dress in very warm clothes and live and sleep in dwellings that are well insulated, but also well ventilated.

During the winter Inuit communities traditionally spent the winter together. The men caught fish through holes in the sea ice and stalked seals that lay resting on the surface or waited on the ice for them to surface at their breathing holes. In spring the communities dispersed. Some families fished in lakes or rivers, some traveled farther afield in pursuit of seals, and some hunted bowhead whales (*Balaena mysticetus*). They hunted on water in *kayaks*—canoes that carry a single person. The families moved inland in summer, traveling by dogsled and living by hunting large land animals, such as bears and caribou. Animals provided the Inuit with everything they needed. They used bones where other people used wood: to make the framework for houses and boats and to make tools and weapons, such as arrowheads and harpoon heads. Skins were used for clothing, tents, and the outer covering of boats. Seal oil was used as fuel for lighting and heating.

This traditional way of life began to change in North America when European whalers arrived in the 19th century and established trading stations that supplied the Inuit with manufactured goods in exchange for skins, furs, and ivory from walrus tusks. Missionaries opened schools and many Inuit settled in villages. More recently, oil and mining companies have provided jobs for local people and towns have grown up to accommodate them. Most Inuit in Kalaallit Nunaat have permanent houses and live by fishing and sheep farming. Fish processing, handicrafts, fur preparation, and shipbuilding provide additional employment, and in years to come the mining industry may also employ local people. People who hunt now use rifles, snowmobiles, and boats with outboard motors. Inuit life has changed and living conditions have improved in many ways, but not everyone has benefited. Like other Native Americans, some Inuit have found it difficult to adapt to rapid changes and to be accepted into the predominant Western culture.

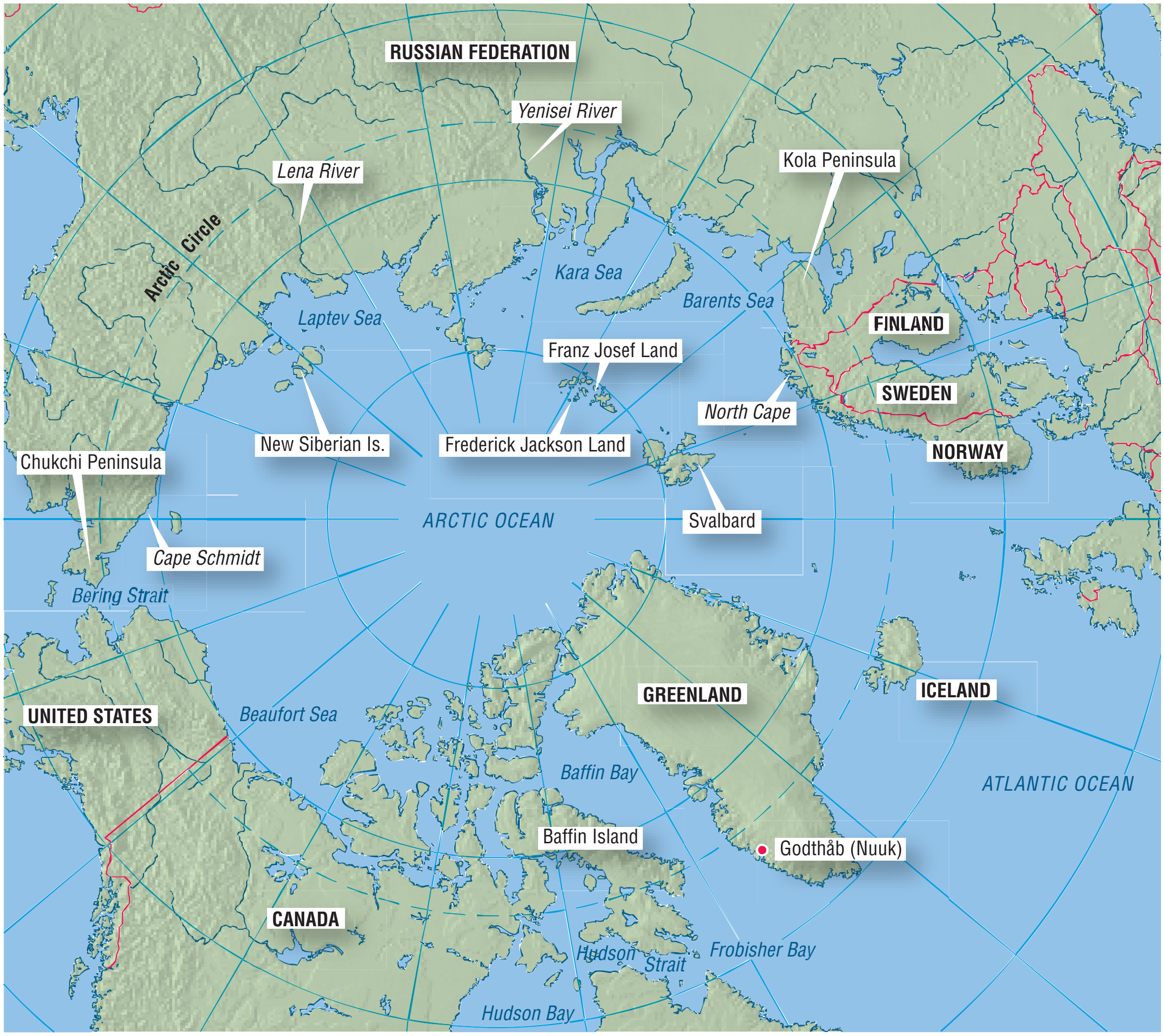
DESERT EXPLORATION

Explorers in the Far North

English and Dutch merchants were trading extensively with Asia by the 16th century, but the only sea routes involved a long and dangerous journey around the southernmost tip of either Africa or South America. In addition to the storms sailors could expect as they rounded the Cape of Good Hope or Cape Horn, they risked being boarded and having their cargoes seized. Portugal controlled the route around Africa and Spain controlled the route around South America, and naval ships of both countries would attack foreign ships. It was possible to travel overland to Asia, but that journey was even harder.

The merchants sought an alternative route to the north. If ships could sail eastward, around the North Cape of Norway and across the Arctic Ocean, they would reach the Asian ports. This route was called the Northeast Passage. Several attempts were made to find it, but all of them failed. Most reached no farther than the Kola Peninsula and the Barents Sea. It was not until 1778 that the English navigator and scientist James Cook (1728–79) proved that Asia and North America were separate. Cook sailed northward through the Bering Strait as far as Cape Schmidt and could see land on both sides of the Strait. This was progress, but still no one had found the Northeast Passage. The map on page 146 shows the location of these places.

Finally, in 1878–79, an expedition led by the Swedish explorer Baron Nils Adolf Erik Nordenskjöld (1832–1901) found the Northeast Passage. Nordenskjöld sailed eastward in the *Vega* accompanied by three cargo ships. Two of these were bound for the Yenisei River, flowing into the Kara Sea, and the other for the Lena River, flowing into the Laptev Sea. The *Vega* continued to the Chukchi Peninsula at the



The Arctic. The North Pole lies near the center of the Arctic Ocean, and the Arctic region is mainly covered by sea, surrounded by North America, Greenland, and Eurasia.

northern end of the Bering Strait, where the sea ice forced it to spend the winter.

The alternative to a Northeast Passage was a Northwest Passage, passing to the north of North America. The search for this route also began in the 16th century, and the first expedition to enter the Arctic sailed in 1576, led by the English explorer Sir Martin Frobisher (c. 1539–94). After enduring terrible storms, Frobisher reached Baffin Island and sailed some distance along the inlet that bears his name. This was the first of many attempts, including four made by the

English navigator Henry Hudson (his year of birth is not known), in the course of which Hudson discovered the bay, strait, and river that bear his name. On his last attempt, when he set sail from London on April 17, 1610, in the *Discovery,* Hudson surveyed the eastern shore of Hudson Bay and spent the winter locked in the ice. When the ice began to melt in spring his crew mutinied, and on June 22, 1611, Hudson, his young son, and seven crew members who remained loyal were cast adrift in a small boat. Hudson and his companions were never seen again.

The Northwest Passage was eventually found to exist. The British explorer Commander Sir Robert John le Mesurier McClure (1807–73) traveled the route in 1850–54. McClure commanded HMS *Investigator,* which sailed part of the route before being abandoned. The crew then proceeded on foot before being rescued and returned to Britain.

The *Investigator* was one of four ships composing an official search party that set out in 1848 to search for members of the expedition led by Rear Admiral Sir John Franklin (1786–1847). Franklin had sailed in 1845 to seek the Northwest Passage with HMS *Erebus* and HMS *Terror.* The party disappeared and despite several searches their fate was not discovered until 1859. It was found that Franklin had traveled the Northwest Passage, but it had cost his life and that of his crew. The discovery of the passage is now attributed to both McClure and Franklin. Neither of them sailed the whole of the passage, however. The first person to achieve that was the Norwegian explorer Roald Amundsen (see the sidebar on page 153) in 1906.

Interest in the Northwest Passage became intense between about 1890 and 1910, because there was a widespread belief that the Arctic Ocean was free of ice and it appeared that the ice might be breaking up around the coasts. This did not happen, and the ice thickened again in the early 20th century, but the expeditions it inspired resulted in detailed studies of the coastlines and islands of the Arctic Ocean.

Henry Hudson had attempted to reach the North Pole in 1607, but he was searching for a route to Asia, as were other explorers, and it was not until the late 18th century that adventurers headed for the Pole as a goal in its own right. On

April 6, 1909, Commander Robert Edwin Peary (1856–1920) of the U.S. Navy claimed to have reached the Pole. Hardly had Peary made his claim, however, than Dr. Frederick Albert Cook (1865–1940) challenged it. Cook, a physician who had served as surgeon on one of Peary's earlier expeditions, declared that he had reached the Pole on April 21, 1908—a year before Peary. Cook's evidence that he had reached the Pole at all failed to convince most geographers, and Peary is generally credited with having been the first person to reach the North Pole.

Along with the searches for sea routes and the race to reach the Pole, other expeditions were engaged in scientific studies

Fridtjof Nansen

Fridtjof Nansen (1861–1930) was a Norwegian explorer, scientist, and statesman who won the 1922 Nobel Peace Prize for his humanitarian work with the League of Nations and the International Committee of the Red Cross.

Nansen was born on October 10, 1861, at Store-Fröen, on the outskirts of Christiania (now Oslo). He studied zoology at Christiania University. An avid outdoor sportsman, Nansen was an accomplished skater and skier and developed a strong physique and stamina. He first visited the Arctic in 1882 as a member of the crew of the *Viking,* a sealing ship that sailed close to Greenland. The encounter gave Nansen the idea of crossing the Greenland ice cap. He recruited a party for the trek and set out in August 1888 from the east coast, reaching the west coast almost six weeks later. The group spent the winter at Godthåb (now Nuuk), where Nansen spent his time studying the Inuit people.

This experience led to his most famous expedition. With financial support from the Norwegian government and private subscriptions, a ship called the *Fram* (Forward) was built to Nansen's design and on June 24, 1893, it sailed for eastern Siberia with a crew of 13. Nansen's idea was to allow the ship to be enclosed by sea ice and then to drift with the ice in order to track the direction of the ocean currents. The *Fram* withstood the pressure of the ice and drifted slowly northward.

Nansen left the ship when it reached 84.07°N and headed north by dogsled and kayak accompanied by the Norwegian explorer Frederic Hjalmar Johansen (1867–1923), reaching 86.23°N, the highest latitude anyone had then reached, before making for Franz Josef Land. The two men were forced to spend the winter, from August 1895 of the ocean and its currents. The most famous of these was led by the Norwegian scientist and explorer Fridtjof Nansen (see the sidebar starting on page 148). Nansen believed that the currents carried sea ice from the New Siberian Islands in the Laptev Sea to Svalbard, and he designed a ship, the *Fram,* that would be strong enough to drift with the ice. Nansen's calculations proved correct.

Discovering Antarctica

It is possible that Polynesian sailors glimpsed the icy cliffs of Antarctica long before the first Europeans arrived there, and

until May 1896, on Frederick Jackson Land (Ostrov Dzheksona in Russian), the northernmost island of Franz Josef Land, which Nansen named after the English explorer Frederick George Jackson (1860–1938) whom he met there. Nansen and Johansen built a hut and hunted polar bears and walrus for food and fuel oil. They finally returned to Norway on August 13, 1896. The ice released the *Fram* to the north of Svalbard in 1896, just as Nansen had predicted it would, and the crew returned safely to Norway.

Nansen was also an eminent scientist. In 1896 he was appointed professor of zoology at Kristiania University (the spelling had been changed), but in 1908 this appointment was changed at his request to professor of oceanography. He took part in several scientific cruises, making discoveries about wind-driven ocean currents and the circulation of ocean water.

He took an active part in negotiations over the dissolution of the union between Sweden and Norway, which established Norway as an independent nation, and he became the first Norwegian minister in London. During World War I he headed the Norwegian mission in the United States. Nansen headed the Norwegian delegation to the first assembly of the League of Nations, where one of his tasks was to arrange the repatriation from Russia of almost 430,000 German and Austro-Hungarian prisoners of war. He led the efforts by the Red Cross in 1921 to bring relief to Russia, then stricken by famine, and he proposed a scheme, adopted internationally in 1922, to issue identification documents to refugees. He devoted his Nobel Prize money to furthering international relief work.

Nansen died at his home at Lysaker, near Oslo, on May 13, 1930.

Phoenician ships may have visited the continent as long ago as 1000 B.C.E. Modern exploration did not commence until the 18th century, however.

For centuries European explorers had been sailing ever farther south, and in 1488 the Portuguese navigator Bartolomeu Dias de Novais (c. 1450–1500) became the first European sailor to round the Cape of Good Hope. Ferdinand Magellan (1480–1521), another famous Portuguese explorer, discovered the Magellan Strait, between the southern tip of South America and Tierra del Fuego, in 1520. In 1578 the English sailor Sir Francis Drake (c. 1543–96) discovered the Drake Passage, between Cape Horn and the tip of the Antarctic Peninsula.

The ancient Greeks believed there must be land far to the south to balance the lands in the Northern Hemisphere, and Europeans continued to believe this despite the fact that no one had ever seen this mysterious land. It was shown on maps as *Terra Australis Incognita* ("Unknown Southern Land"), and the European nations were anxious to claim it because they also believed it to be rich in resources and suitable for habitation. Unfortunately, it was also very remote and surrounded by thick sea ice that made it unapproachable.

On January 17, 1772, Captain James Cook (1728–79) became the first sailor to cross the Antarctic Circle (66.5°S), and on January 30, 1774, Cook reached 77.17°S, the closest anyone had ever been to the South Pole. Cook proved that if a large southern continent existed, it lay to the south of latitude 60°S and was a land of perpetual ice and snow. A Russian expedition led by Fabian Gottlieb von Bellingshausen (1778–1852) was the next to cross the Antarctic Circle, but not until 1820. At one point Bellingshausen came within 20 miles (32 km) of the coast.

A French expedition led by Captain Jules-Sébastien-César Dumont d'Urville (1790–1842) sailed with two ships from Toulon in 1837 and mapped the coast of the northern part of the Antarctic Peninsula. Dumont d'Urville named the region Terre Adélie, after his wife. Adélie penguins are also named after her. A United States expedition commanded by Charles Wilkes (1798–1877) explored the coast from 1838 until 1842 and saw land, now called Wilkes Land, several times. The Scottish seaman James Clark Ross (1800–62) was also in the area at that time with HMS *Erebus* and HMS *Terror,* the ships that would later be used in the search for the Northwest Passage (see “Explorers in the Far North” on pages 145–149). Ross found the edge of what came to be called the Ross Ice Shelf, covering much of the Ross Sea. A British seal hunter, James Weddell (1787–1834) had discovered the Weddell Sea, on the opposite side of the Antarctic Peninsula, in 1823.

By the start of the 20th century explorers were starting to venture farther inland. Captain Robert Falcon Scott (1868–1912) led an expedition from 1901 until 1904 that crossed the Ross Ice Shelf. Scott’s third lieutenant on that expedition was Ernest Shackleton, destined to become one of the most renowned of all Antarctic explorers (see the sidebar on page 152).

In 1910 Scott left England at the head of an expedition that would attempt to reach the South Pole. They set up a base camp at Cape Evans, on Ross Island, and on October 24, 1911, a party of 12 men headed south, transporting their equipment and supplies on motorized sledges and sledges pulled by ponies and dogs. The motorized sledges broke down and had to be abandoned, and the ponies could not cope with the conditions and had to be shot. When the team reached 83.5°S the dogs could go no farther and they were sent back. From that point the men had to haul the sledges themselves. Five of them—Scott, E. A. Wilson, H. R. Bowers, L. E. G. Oates, and Edgar Evans—reached the Pole on January 18, only to learn that Roald Amundsen (see the sidebar on page 153) had arrived there a month earlier. On the return journey, the party encountered weather that was unusually severe, even for Antarctica. By that time, their supplies of food and fuel were low and all of them perished from cold and exhaustion. Scott, Wilson, and Bowers, the last to die, were only 11 miles (17.7 km) from a depot where they had left stores that would have saved them.

Explorers in the deserts of Africa, Arabia, and Asia

The 15th century was an age of European exploration. That is when ships began venturing north and south and it is also when Europeans first began to visit African shores, although at first they did not travel very far inland.

Ernest Shackleton

Ernest Henry Shackleton (1874–1922) was one of the most famous of Antarctic explorers, greatly admired for his courage, optimism, and ability to inspire confidence and devotion in those he led. Born at Kilkea House in County Kildare, Ireland, on February 15, 1874, he was educated at Dulwich College, London. He entered the merchant navy at the age of 16, sailing from Liverpool in the *Hoghton Tower,* a full-rigged sailing ship bound for Valparaiso via Cape Horn.

Shackleton first traveled to Antarctica as third lieutenant on the 1901–04 expedition led by Captain Robert Falcon Scott (1868–1912). He took part in the sledge crossing of the Ross Ice Shelf and reached latitude 82.28°S, but the journey made him ill and he left Antarctica in March 1903 on a supply ship.

His next journey to the continent was in January 1908 as leader of the British Antarctic *Nimrod* expedition. On that visit Shackleton led a sledge party that came within 97 miles (156 km) of the South Pole, and another party, led by T. W. Edgeworth David, reached the Magnetic South Pole. On their return to London, Shackleton was knighted and made a companion of the Royal Victorian Order.

He set forth again in March 1914 at the head of the British Imperial Trans-Antarctic Expedition. The aim of that expedition was to cross from a base on the Weddell Sea, past the South Pole, to McMurdo Sound on the Ross Sea. It was not to be. Shackleton's ship, the *Endurance,* became trapped in the ice and drifted for 10 months until the ice finally crushed it. Shackleton and his men drifted on ice floes for another five months, finally escaping in boats to Elephant Island, in the South Shetland Islands. From there Shackleton and five companions sailed in an open whaling boat across 800 miles (1,287 km) of the Southern Ocean, through bitter cold and mountainous seas, to South Georgia Island. They then walked across the island—the first people ever to do so—to find help from the whaling station at Stromness, 17 miles (27 km) distant. Shackleton then led four rescue expeditions from South Georgia until finally he was able to rescue his men, all of whom survived. His reputation rests largely on his heroism, determination, and refusal to abandon his men.

His expeditions and the effort needed to raise funds to finance them exhausted him. Shackleton died at Grytviken, South Georgia, on January 5, 1922, while preparing for yet another Antarctic expedition.

Diogo Gomes, a Portuguese explorer who flourished between 1440 and 1482, sailed far up the Gambia River in 1456 and met men from the remote city of Timbuktu, then an important trading center in the Mali Empire (see "Desert civilizations" on pages 127–130). The name Timbuktu and stories about its wealth became a magnet attracting later

Roald Amundsen

One of the greatest of all polar explorers, Roald Engelbregt Gravning Amundsen (1872–1928) was born on July 16, 1872, at Borge, to the south of Christiania (now Oslo), Norway. He began to study medicine, but in 1897 he joined a Belgian Antarctic expedition sailing in the *Belgica.* This was the first expedition ever to spend the winter in Antarctica.

In 1903 Amundsen sailed into arctic waters with a crew of six in the *Gjöa.* Their voyage was the first to navigate the Northwest Passage.

He then planned to drift across the North Pole in Nansen's old ship, the *Fram,* but in 1909 he learned that Robert E. Peary (1856–1920) had reached the Pole. Amundsen continued with his preparations, but when he sailed from Norway in June 1910 only his brother knew that the expedition was heading south rather than north. The *Fram* anchored in the Bay of Whales, on the eastern side of the Ross Sea and close to the edge of the ice shelf, 60 miles (96.5 km) farther south than the Scott camp at Cape Evans. Amundsen began the trek to the Pole on October 19, 1911, accompanied by four men, 52 dogs, and four sledges, and arrived there on December 14. They left the Pole on December 17 and arrived back at their base on January 25, 1912. They were the first people to reach the South Pole.

The success of this expedition brought Amundsen enough money to set up a shipping business, and he built a new ship, the *Maud,* in which he planned to pursue his original plan of crossing the North Pole. He departed in 1918 and sailed the Northeast Passage to the Bering Strait, but there he was forced to abandon the voyage. Instead, he attempted to reach the North Pole by air. He and the American explorer Lincoln Ellsworth (1880–1951) came within 170 miles (273.5 km) of the Pole in 1925, and in 1926 Amundsen crossed the Pole with the Italian explorer Umberto Nobile (1885–1978) in the airship *Norge,* flying from Spitzbergen, Svalbard, to Alaska. The crossing led to a bitter dispute between Amundsen and Nobile over who should be credited with leading the expedition.

In May 1928 Nobile made a second flight in the opposite direction, this time without Amundsen, in the airship *Italia.* He crossed the Pole successfully but crashed at Spitzbergen. Nobile and his crew survived and a major international rescue operation was launched. Amundsen flew from Norway to join in the rescue, but his aircraft crashed into the sea on June 18 and Amundsen was killed.

adventurers, but centuries passed before a European set eyes on the city. The first to do so was a Scottish explorer, Alexander Gordon Laing (1793–1826), who traveled from Tripoli, Libya, was injured in a fight in Tuareg country (see "Peoples of the Sahara and Arabian Desert" on pages 134–136), and entered Timbuktu on August 18, 1826. He stayed there until September 24, then left heading north, but died on September 26, murdered by his guide. René-Auguste Caillé (1799–1838) was the first European to visit Timbuktu and return safely. This French explorer traveled from the West African coast and reached the city on April 20, 1828. He remained there for two weeks before heading north to Morocco and back to France.

Other travelers were exploring the Sahara at about this time. In 1823 a party led by Hugh Clapperton (1788–1827), a Scottish naval officer, reached Lake Chad and continued into what is now Northern Nigeria. The most important scientific study of North and Central Africa took place between 1850 and 1855. James Richardson (1806–51), an English explorer, Heinrich Barth (1821–65), a German geographer, and Adolf Overweg (1822–55), a German geologist and astronomer, traveled southwest from Tripoli into northern Nigeria and around Lake Chad. Richardson led the party, but he died in Nigeria and Barth took command. Overweg died in September 1852 and Barth continued alone, eventually reaching Timbuktu where he remained for six months before returning to Tripoli and from there to London, having covered approximately 10,000 miles (16,000 km). Barth was well equipped for the journey. An accomplished linguist, he spoke fluent Arabic, and he had thoroughly explored the North African coast before attempting to cross the desert.

The first European to study the Tuareg was a French explorer, Henri Duveyrier (1840–92). He met Barth, was inspired by him, and also learned to speak Arabic. He was only 19 years old when in 1859 he embarked on a three-year journey through the northern Sahara, spending much of the time living with the Tuareg. Friedrich Gerhard Rohlfs (1831–96) explored the Atlas Mountains and Morocco in 1862 disguised as an Arab, in 1864 he reached the Fezzan region of central Libya, and in 1865 he crossed the desert from Tripoli to northeastern Nigeria and traveled from there to the West African coast. In 1874 he crossed the Sahara again, this time from Tripoli to Egypt. This colorful German adventurer had joined the French Foreign Legion in 1855 and learned Arabic. In 1885 he was appointed German consul in Zanzibar.

Arabia was much less accessible than the Sahara. The first European expedition was sent by King Frederick V of Denmark and set out in 1762, led by a German surveyor, Carsten Niebuhr (1733–1815). That team explored the coast, but penetrated only a short distance inland. It was 1876 before the next serious attempt was made, this time by an English traveler, Charles Montagu Doughty (1843–1926). He wanted to visit Mecca. Although he never reached that city, he visited several inland towns in the mountainous region of Jabal Shammar and the port of Jidda, not far from Mecca.

The most famous European to be associated with Arabia was not an explorer at all, but an English scholar and soldier. T. E. Lawrence, who became known as Lawrence of Arabia (see the sidebar on pages 156–157), wore Arab dress, spoke fluent Arabic, and fought alongside Arab troops against Turkish forces in World War I. Lawrence was a truly romantic hero, who was not interested in money or social position.

It was Sir Wilfred Thesiger (1910–2003) who did more than anyone else to keep alive the romance of the desert during the latter years of the 20th century. This English soldier, travel writer, and photographer was born in Addis Ababa, Ethiopia, and lived there until he was nine years old. As an adult, he lived with the Bedouin, made several crossings of the Rub'al-Khali—the "Empty Quarter" of the Arabian Desert—and made a special study of the Marsh Arabs of southern Iraq. He also explored Afghanistan and Pakistan.

European exploration of the Asian deserts began in the late 19th century. The Swedish explorer Sven Anders Hedin (1865–1952) spent five years traveling over the Ural and Pamir Mountains, past Lop Nur, and to Beijing along the old Silk Road (see "Caravans and the Silk Road" on pages 138–140). The geographer and geologist Ferdinand Paul Wilhelm, Freiherr von Richthofen (1833–1905), who was

Lawrence of Arabia

Thomas Edward Lawrence (1888–1935) was born on August 15, 1888, at Tremadoc, Caernarfon, Wales. His family moved to Oxford in 1896, and Thomas attended school in that city and completed his education at Jesus College, University of Oxford. He visited Palestine and Syria in 1909 to study the architecture of crusader castles, which was the subject of a thesis he submitted the following year for his degree in modern history. Lawrence then joined several archaeological expeditions to the Middle East.

The last of these expeditions, early in 1914, was to Sinai, and its secondary purpose was to gain military intelligence about preparations for war on the Turkish side of the border with Egypt. Lawrence was still working in Sinai at the outbreak of World War I, but he later moved to the map department of the War Office in London. When Britain and France declared war on Turkey on November 5, 1914, Lawrence was attached to the intelligence staff in Egypt concerned with Arab affairs.

In October 1916 Lawrence accompanied the diplomat Ronald (later Sir Ronald) Storrs (1881–1955) to the Hejaz province of Arabia, where Husain ibn 'Ali, the emir of Mecca, had proclaimed a revolt against the Turks, who occupied parts of Arabia. Storrs held discussions with Husain's son Abdullah and then returned to Egypt, but Lawrence was permitted to visit Abdullah's brother, Faisal, who was leading an army near Medina. Lawrence returned to Cairo, but he was sent back to join Faisal's army as political and liaison officer.

For the remainder of the war Lawrence fought alongside the Arab army, encouraging the soldiers and planning many of its operations. He invariably wore Arab dress, and when Turkish forces captured him in November 1917 they did not know the identity of their prisoner. Lawrence escaped and took part in several other military operations. By the end

born in Upper Silesia (then in Prussia and now in Poland), traveled extensively through China and it was he who coined the name "Silk Road."

The explorer and archaeologist who did more than anyone to rediscover the route of the Silk Road was Sir Aurel Stein. Mark Aurel Stein (1862–1943) was born in Hungary, but he became a British citizen in 1904 and was knighted in 1912. In 1900, 1906, and 1913 Stein went on expeditions through the Xinjiang Uygur autonomous region of China that lasted a total of seven years. He followed the old caravan routes for about 25,000 miles (40,200 km), discovering the Jade Gate of the war Lawrence held the rank of lieutenant colonel and was highly decorated. He was a member of the British delegation to the Paris peace conference in 1919 and an adviser on Arab affairs at the Colonial Office in 1921 and 1922, but then he left government service. “Lawrence of Arabia” had become very famous and he began to write his account of the war.

In August 1922 Lawrence enlisted in the Royal Air Force (RAF), giving his name as John Hume Ross. A newspaper exposed him, however, and in January 1923 he was discharged. In March 1923, using the name T. E. Shaw, to which he changed his name legally in 1927, Lawrence enlisted in the Royal Tank Corps. He transferred to the RAF in 1925 and remained in service until his death on March 19, 1935, following a motorcycling accident.

As well as being a war hero, Lawrence was a distinguished classical scholar and also a skilled mechanic, who was keenly interested in aviation and designed a seagoing motorboat for the RAF. His popularity also rested on his renunciation of his army rank to enlist as an ordinary airman and soldier, his indifference to money, and his sense of fun—but he could be extremely rude to people he despised.

Lawrence published several books, the most famous being *Seven Pillars of Wisdom.* He wrote this over many years and to help with the printing costs in late 1926 he published 200 copies, each bound differently, of an abridged version. These books were sold by subscription but were so beautifully illustrated that they cost much more to produce than subscribers paid for them. To recover the costs Lawrence authorized publication of an even more abridged version called *Revolt in the Desert.* The subscribers’ edition appeared in the summer of 1935, soon after Lawrence’s death. This was so successful that it prevented publication of the full text, 200 pages longer than the abridged version, which finally appeared in 1997, 75 years after Lawrence finished writing it.

that once stood at the Chinese border and the walls built to prevent nomads from entering China. He carefully excavated ancient sites, discovering ancient cities and—his most famous discovery—the Cave of a Thousand Buddhas (see the sidebar on page 158). In one of the caves Stein found a hoard of approximately 60,000 paper manuscripts and other documents dating from the fifth to 11th centuries that had been walled up in 1015. Written in Chinese, Sanskrit, Tibetan, Uighur, and other languages, they included scriptures, stories, and ballads from Buddhist, Taoist, Zoroastrian, and Nestorian Christian traditions.

The Cave of a Thousand Buddhas

Dunhuang is a small oasis town in northwestern China, on the edge of the Gobi Desert and on the Silk Road. Buddhist monks traveled the Silk Road on their way to China from Central Asia and India, and monks and Buddhist disciples from different parts of Asia met at Dunhuang. Buddhist communities were established there in the third and fourth centuries.

In 366 C.E., a Buddhist monk carved himself a temple inside a cave, and other monks later added to his work until every corner was covered with pictures of the Buddha. It came to be known as "the Cave of a Thousand Buddhas."

In subsequent years Buddhists decorated other caves in the area. Today there are 492 decorated Caves of a Thousand Buddhas, containing religious paintings and sculptures. It is the largest ancient Buddhist site in China, known officially as the Mogao Caves.

The illustrations depict stories from the Buddhist sutras (sacred texts), representations of Buddhas, Boddhisattvas (individuals who have attained enlightenment but choose to continue helping and teaching others rather than enter Nirvana), and other religious figures, as well as portraits of people who have made important donations to the collections. Work on the caves continued until the 12th century, when the site fell into decline until it was rediscovered early in the 20th century.

In 1987 the area was designated a World Heritage Site by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). Many of the caves are open to the public.

DESERT INDUSTRIES

Oil and modern desert economies

Herodotus was a Greek historian who lived in the fifth century B.C.E. The exact years of his birth and death are not known, but what is known is that he was born in Halicarnassus, a Greek city on the Mediterranean coast of Asia Minor (modern Bodrum, Turkey) that was ruled by the Persians. Herodotus was a great admirer of the Persian Empire, and he was also a great traveler. He claimed to have walked the entire length of the Royal Road that ran for about 1,500 miles (2,413 km) from the city of Susa, in the country of Elam near the Zagros Mountains in what is now southwestern Iran, to the coast of the Aegean Sea. What is interesting about his walk is that Herodotus said the road was surfaced with asphalt. Wheeled vehicles, especially horse-drawn chariots, could move rapidly over a hard, smooth surface, and many Assyrian and Persian roads were surfaced in this way.

Asphalt is liquid when hot, but sets hard when it is cold, making it an ideal substance for surfacing roads. It may also have been used almost 6,000 years ago at Mohenjo Daro, in the Indus Valley, to seal the brick walls of a reservoir. In India it was called "earth butter." It was not difficult to obtain asphalt. There are many places where it oozes from the ground. It would be surprising if people had failed to notice that it sets hard when it cools and to conclude that this property might make it useful.

Also known as *pitch* and *bitumen,* asphalt is a petroleum product that remains as a residue after the lighter oils have evaporated. Asphalt was used as mortar, as cement for laying mosaic floors, and as an adhesive for setting jewels and attaching the handles of tools and weapons. Lighter oils were also used widely in the ancient world for lighting and for cleaning clothes. In the Arabic and Persian languages this oil is known as *naft* from which we derive our word *naphtha.*

Petroleum was especially abundant in the United States and in the desert lands of western Asia and Arabia. It was always a valuable natural product, but it was only in the 20th century that it came to dominate the world economy. As demand for oil increased, exploration intensified, and oil was discovered in places where it had not previously been known to exist. Oil was discovered in Libya in the 1950s, in Algeria, Tunisia, Oman, and Nigeria in the 1960s, and in Yemen in the 1980s. Nearly half of the world's known reserves of petroleum are located in the Middle East. North America has the next largest reserves, with approximately 14 percent of the total.

Oil has brought wealth to some desert lands but not to all of them. Economists measure the prosperity of a country by its *gross domestic product,* or GDP. This is the total value of all the goods and services produced in that country in a year, excluding income from investments overseas. The *per capita GDP* is the GDP divided by the size of the population. The per capita GDP does not represent average earnings, but it does make it possible to compare countries of different sizes. The resulting figure is nevertheless misleading, however, because currencies are sometimes overvalued or undervalued in relation to one another. To resolve this, the per capita GDP is often converted to its *purchasing power parity* (PPP) in U.S. dollars. This figure is obtained by spending a given amount of local money on a range of everyday items, such as groceries, rent, and transportation, then finding out what the same goods and services would cost in U.S. dollars. The table on page 161 shows comparable figures for a selection of desert countries, although the PPP is not known for all of them.

The table lists desert countries in descending order of wealth and shows that most oil-producing countries are much richer than countries without oil. The apparently huge discrepancies between the per capita GDP of the United Arab Emirates (UAE), Kuwait, and Qatar and those of the other countries are due mainly to the small size of their populations—3.1 million in the UAE, 2.2 million in Kuwait, and 0.5 million in Qatar. In contrast, the population of Tunisia is 9.7 million. Comparing a country such as Tunisia, which has oil,

Per capita GDP and purchasing power+

Country	Per capita GDP (US$)	PPP (US$)
United States	31,910	31,910
Kuwait*	22,110	(not known)
United Arab Emirates*	17,870	(not known)
Qatar*	11,600	(not known)
Bahrain*	7,640	(not known)
Saudi Arabia*	6,900	11,050
Libya*	6,700	(not known)
Mexico*	4,440	8,070
Tunisia*	2,090	5,700
Iran*	1,810	5,520
Jordan	1,630	3,880
Algeria*	1,550	4,840
Egypt	1,380	3,460
Morocco	1,190	3,320
Mongolia	390	1,610
Mauritania	390	1,550
Yemen*	360	730
Nigeria*	260	770
Mali*	240	740
Chad	210	840
Niger	190	740
Ethiopia	100	620

(*oil-producing countries)
+figures are for 1999

with one such as Chad, which does not, demonstrates just how economically important oil is to some desert nations.

Solar energy

Not every desert country possesses oil reserves, but there are two things that all the subtropical deserts have in abundance: warm sunshine and empty space. If they can capture the sunshine and put it to work, perhaps their economies will be able to develop without being hindered by the cost of imported fuel.

Some of the devices needed to capture solar energy are familiar and widely used. Solar panels, solar cells, and wind turbines are the best known. *Wind turbines* are driven by the wind, of course, but it is solar energy that produces the differences in air pressure that generate winds, so wind power is derived from solar energy.

Deserts are windy places and therefore suitable for *wind farms*. Wind farms must be large if they are to produce useful amounts of energy, but deserts can provide the space they need.

Unfortunately, wind power is unreliable because, even in the desert, there are times when the wind is too weak to set the blades turning or too fierce, so they have to be shut down to protect them from damage. In practice, a wind turbine spins for less than 40 percent of the time.

Solar panels absorb solar heat and use it to provide hot water or central heating. Their usefulness is limited in high latitudes, where the sunshine is weak for much of the year, but they are very useful in subtropical deserts, where people need hot water and central heating might be welcome on cold desert nights.

Solar cells convert sunlight directly into electricity. They absorb light, not heat, so they work just as well in winter as in summer, but of course they work only during the hours of daylight. If they are to be useful, therefore, they need to generate surplus electricity during the day that can be stored in batteries to provide a supply through the night. Power generated in this way is not cheap, because the cells are made from costly materials and are not very efficient, which means that a large number are required. The price is falling, however. One day it should be possible in desert countries to fit solar panels and cells to commercial premises, apartment buildings, and small factories with low power requirements, making them self-sufficient in solar-heated water and giving enough electrical power to cook and operate electronic equipment.

Solar ponds also use sunshine to heat water, but they do so on a bigger scale than solar panels. A solar pond exploits the fact that salt water is denser than freshwater and the two do not mix readily. The pond has a large surface area and is usually several feet deep. Its bottom and sides are lined with black plastic to absorb radiant heat, and the pond is partly filled with water saturated with salt. Freshwater is then poured in very carefully to form a layer that floats above the denser salt water. Heat from the Sun passes through the water and is absorbed by the plastic. As the temperature of the plastic rises, the salt water in contact with it grows warmer. Convection currents then transport heat throughout the salt water, but they do not penetrate the overlying layer of freshwater, so there is nowhere for the heat to escape. When the temperature reaches approximately 200°F (93°C) salt water is piped to a heat exchanger in a tank of freshwater. It warms the freshwater and then returns to the pond. The freshwater layer has to be replenished from time to time to replace water lost by evaporation, but evaporation losses can be greatly reduced by covering the entire pond with transparent plastic. Warm water from a solar pond can be fed into industrial boilers to raise steam to drive generating turbines, greatly reducing the amount of fuel needed to boil it.

It is possible to use solar heat to generate much higher temperatures using a *solar furnace*. A large, flat mirror called a *heliostat,* driven by a computer-controlled motor, tracks the Sun across the sky, reflecting its image—and also its radiant heat—onto a parabolic mirror. The parabolic mirror reflects the heat to a focal point where there is a target. The arrangement is just like the reflector dish and aerial used to receive satellite TV, only much bigger. The parabolic mirror concentrates the heat, producing temperatures high enough to melt steel. There are experimental solar furnaces in many countries that receive abundant sunshine, but the world's largest is at Odeillo, France. It generates temperatures up to more than 12,600°F (7,000°C).

A *solar chimney* combines the principles of the solar panel and the wind turbine by absorbing solar heat and using it to warm air that spins a generating turbine (see the sidebar on page 164). The structure itself is extremely large and therefore both costly and technologically challenging, but its operating costs are low, and in years to come solar chimneys might provide desert countries with plentiful cheap electricity.

Minerals, metals, and textiles

Economists describe mining and quarrying for industrial minerals and metallic ores as a *primary industry.* A primary industry performs only the first stage in the series of processes culminating in manufactured goods. Each of those stages

Solar chimney

The most ambitious scheme for converting sunshine into electrical power uses air warmed by solar energy to drive several turbines fitted inside a vertical cylinder that is open at both ends. The device looks like a chimney and, like a chimney, it removes warm air. Unlike an ordinary chimney, however, it extracts energy from the rising air.

A circular, transparent roof made from glass or plastic covers a large area of ground. The roof rises gently from the edge, so that the center is higher than the circumference. A cylinder rises vertically from the center of the covered area.

Sunlight warms the air below the transparent roof. The warm air rises up the slope of the underside of the roof and then flows up the chimney, accelerating all the time, and more air is drawn in at ground level to replace it. As it rises up the chimney, the air spins a turbine that generates electrical power.

A solar chimney works throughout the night as well as during the day, because during the night the ground radiates the warmth it absorbed by day, thus warming the air. In some designs, black plastic tubes filled with water cover the ground to enhance this effect. The black plastic absorbs solar heat during the day, heating the water inside the tubes, and the water releases its warmth at night.

In order to work, a solar chimney needs to be very large indeed. An experimental prototype built in 1983 at Manzanares, Spain, worked successfully for several years. Its chimney was 640 feet (195 m) tall and its roof covered an area of about 486,000 square feet (45,250 m^2). An operational solar chimney would be at least 3,000 feet (1 km) tall and its roof would cover approximately 40 square miles (104 km^2). There are proposals to build solar chimneys in India, South Africa, Australia, and elsewhere. Constructing a chimney as tall as this and a “greenhouse” covering such a large area will be highly challenging from an engineering point of view.

Solar chimneys are very costly to build, because of their size, but their running costs are low, their “fuel” is free, and their lifetimes are very long, so they might generate electricity cheaply. They are not very efficient, however, extracting no more than three percent of the solar energy falling on them. Efficiency can be improved by making the chimney taller to reduce the air pressure at the top, and by increasing the covered area, which increases the air pressure at the bottom of the chimney. Refinements to the design could also reduce energy losses considerably and make solar chimneys much more efficient.

adds to the value of the commodity being processed, and it follows that its value is least at the initial stage of being extracted from the ground. Consequently, primary industries produce large quantities of cheap raw materials. Few nations that depend economically on primary industries are wealthy. In order to increase national prosperity, governments aim to perform as much of the processing and manufacturing as possible within their own borders, so that the added value accrues to local people.

Mineral resources are not distributed evenly. The table below lists desert countries that exploit mineral resources, with the approximate yearly value of their output of metals and nonmetals, in U.S. dollars.

It is not easy to separate figures for metals and nonmetals because countries do not all measure them in the same way. Consequently, for most countries the two are combined, but Bahrain and Libya produce only nonmetals. Some countries, including Chad, Mongolia, and Western Sahara, possess neither oil nor minerals.

Merging the data for metals and nonmetals hides the richness of some of the African reserves. Tunisia has some of the

Mineral output in desert countries (millions of U.S. $ per year)

Country	Metals	Nonmetals	Not differentiated
Bahrain		12.6	
Egypt			51.5
Eritrea			0.5
Ethiopia			54.2
Iran			1,223.2
Jordan			239.3
Libya		599.4	
Mali			81.7
Mauritania			105.9
Morocco			746.5
Namibia			382.8
Niger			62.5
Nigeria			168.6
Oman			44.6
Saudi Arabia			597.9
Sudan			27.4
Tunisia			249.0

(Source: *Britannica Book of the Year, 2005*. Chicago: Encyclopaedia Britannica, Inc.)

largest reserves of phosphate rock in Africa. Phosphate rock is used to make industrial chemicals and fertilizer, which Tunisia exports. Morocco has ores of copper, iron, lead, manganese, and zinc, as well as common salt. Mauritania has ores of copper and titanium, as well as phosphate rock and gypsum. Libya has iron, manganese, and gypsum. Niger is one of the world's most important producers of uranium, and it also possesses high-quality iron ore.

Reserves may exist without being exploited. Mali has copper, iron, manganese, nickel, and bauxite—the most common aluminum ore—but gold is the only metal it exports. Minerals may be located in places that are too remote to be exploited economically. This is because the cost of transport forms a significant proportion of the overall cost; the farther the minerals travel, the higher their price will be. In a highly competitive market, remoteness can make them too expensive. The reserves may also be in places where access is difficult. This also increases the cost of bringing in the heavy machinery used in mining and quarrying and taking out the heavy, bulky rock that is the mineral product.

Desert peoples have always raised sheep and goats. These are kept partly to supply milk and meat, but they also produce wool, and many of the world's finest cloths and carpets are made in desert countries. Iran (formerly Persia), Afghanistan, Turkey, and Bukhara are among the places famous for their carpets.

Carpets are woven or made by knotting colored threads to a woven base. Both techniques, and the resulting products, are well suited to people leading a nomadic life. Looms are easily dismantled and assembled again, wool and dyeing materials are easy to carry, and decorated carpets can transform a tent into a splendid dwelling. In the 16th century European explorers and merchants—often the same individuals—recognized the potential market for Asian carpets and the export trade began. Only the wealthy could afford them and they were much too expensive to be laid on floors. Instead, their owners hung them on walls or over balconies or laid them across chests and tables. They displayed them without risking damage to them.

Persian carpet making reached its peak in the 15th and 16th centuries, and Persian designs and techniques influenced carpet makers in neighboring countries, especially those in Egypt, Turkey, and the Caucasus. Caucasian carpets are still made and exported by nomadic peoples living near the Caspian Sea.

Bokhara, also called Bukhara or Buxoro, is the principal city in Buxoro, province of Uzbekistan, but although it gives its name to Bokhara carpets it is not the place where they are made. Bokhara carpets are made over a wide area of Turkistan. Turkistan is not a country, but an area of more than 1 million square miles (2.6 million km^2) in Central Asia bounded by Siberia, Tibet, Afghanistan, India, and Iran. Its name refers to its people, who are Turkic nomads.

The finest woolen garments are made from cashmere, which is a fine soft wool obtained from the Kashmir breed of goats. Iran and Turkey produce some cashmere wool, but most comes from China, Mongolia, and Iran. Only a small amount of cashmere wool is produced, because a Kashmir goat yields no more than one pound (0.5 kg) of wool a year. The demand for it is high, and consequently cashmere is very expensive.

Cashmere was first used to make shawls, which became very fashionable in the late 19th century. Early in the 20th century European factories began making imitation cashmere shawls. These were attractive and much cheaper than the real thing but of poorer quality. Today cashmere is made into sweaters, suits, dresses, and overcoats.

Traditional carpets and garments are luxury items that command high prices, but the supply is limited, and that restricts the contribution their production can make to national economies. Their manufacture can be industrialized, but while increasing the output does not necessarily imply reducing the quality of the product, increasing the supply inevitably lowers the price and, with it, the perceived value. People might come to think the factory-made carpets and garments were only slightly better than equivalent goods made closer to home and sold at lower prices.

Tourism

Deserts are romantic places, full of legends and mystery. They contain ancient cities with magical names such as Timbuktu and Petra—a once-important city that now lies in ruins and abandoned, except by the busloads of tourists that travel to visit it. When Europeans with an adventurous spirit began to travel to new places in the 19th century, the deserts of North Africa and the Middle East attracted them strongly. People today want to vacation in desert lands, so it is no surprise that tourism makes an important contribution to desert economies.

Egypt and North Africa are easily accessible from North American and European airports. Tourists visit Egypt to see the Pyramids, the Sphinx, the Nile, and ancient temples, and while they are in the country they can try riding a camel and explore desert culture. As the table on page 170 shows, tourism earns Egypt $4.3 billion a year.

Visitors to North Africa can examine archaeological remains from the time when this region formed part of the Roman Empire. They can visit the site of Carthage, now a suburb of Tunis, and ports that were built by the Phoenicians. Tunisia earns almost $1.5 billion a year from tourism, and Libya earns $24 million—a figure that is likely to increase in years to come.

Not every country benefits from tourism, however, and the list of tourist destinations could be lengthened. Yemen earns $64 million a year from visitors, but part of Yemen was once the kingdom of Sheba, a fact that might attract more people than it does. Frankincense, the plant resin used in incense, was once exported throughout the Middle East and Mediterranean region from Oman, a country that has been inhabited for at least 10,000 years and that was once the center of an empire extending through much of East Africa. Tourism brings in $120 million a year, but it might bring in more.

Three of the world's major religions originated in the Near East and Arabia, and many of the visitors are pilgrims traveling to sites of religious importance. Pilgrimage is especially important in Saudi Arabia, Israel, and Palestine and might increase if conflicts in the region were resolved.

Now that the more adventurous and wealthy tourists have explored the more accessible parts of the world, they are beginning to look farther afield. It is possible to travel part of the Silk Road (see pages 138–140), with stops at Tashkent, Samarqand, and Bukhara. Mongolia welcomes tourists, offering them the opportunity to meet the descendants of the famed Mongol warriors of old, to join in traditional festivities, and to visit a traditional nomad camp and enter a ger (see "Peoples of the Asian deserts" on pages 136–138).

Polar deserts also attract visitors. Antarctica is extremely remote, but cruise ships visit the Antarctic Peninsula each year, allowing passengers to see icebergs and ice cliffs and enjoy time ashore. The Antarctic Heritage Trust is trying to raise funds to restore huts that were erected and occupied by famous explorers, such as Scott and Amundsen, and that would provide an additional attraction for visitors. In 2001–02 more than 11,500 tourists landed on Antarctica.

Greenland has magnificent scenery and a national park covering 289,500 square miles (750,000 km^2) in the northeast of the country. The number of visitors is controlled, but it increases each year. In 2003 Greenland had 29,712 tourists. The number may seem small, but in January 2004 the population of Greenland was 56,854, so the country receives a large number of tourists in relation to the size of its population.

Tourism brings in foreign currency, but the improvements in travel facilities that make it possible work both ways: They also allow citizens of the tourist destinations to become tourists in their own right, and when they travel they spend money abroad. This means that the income from tourism is partly offset by the money tourism takes out of a country and by the cost of providing facilities for visitors. When account is taken of both figures, the profitability of tourism may be greatly reduced or even reversed. Yemen earns $64 million a year from tourism but loses $83 million a year, and Nigeria earns $200 million but loses $730 million. Mexico has one of the biggest tourist industries. Each year it earns $8.3 billion, mainly from visitors from the United States, but it loses $5.5 billion.

There is a further disadvantage, in that tourism tends to provide low-paid, seasonal jobs, many of them unskilled. If their economies are to develop, the desert nations need modern industries that require highly skilled workers, and educational and training institutions to supply them.

Tourism in desert countries (million U.S. $ per year)

Country	Income from visitors*	Expenditure*
Algeria	133 (2002)	193 (2000)
Bahrain	741 (2002)	378 (2002)
Burkina Faso	39 (2002)	23 (1994)
Chad	23 (2001)	56 (2001)
Djibouti	4 (1998)	4 (1998)
Egypt	764 (2002)	1,278 (2002)
Eritrea	73 (2002)	—
Ethiopia	77 (2002)	45 (2002)
Iran	1,249 (2002)	2,514 (2002)
Jordan	786 (2002)	416 (2002)
Kuwait	119 (2002)	3,021 (2002)
Libya	75 (2002)	548 (2002)
Mali	71 (2000)	41 (2000)
Mauritania	28 (1999)	55 (1999)
Mexico	8,858 (2002)	6,060 (2002)
Mongolia	167 (2002)	119 (2002)
Morocco	2,046 (2002)	444 (2002)
Namibia	219 (2002)	56 (2002)
Niger	28 (2002)	16 (2002)
Nigeria	263 (2002)	950 (2002)
Oman	242 (2002)	771 (2002)
Qatar	not available	not available
Saudi Arabia	3,420 (2002)	7,356 (2002)
Sudan	62 (2002)	91 (2002)
Syria	1,366 (2002)	610 (2002)
Tunisia	1,422 (2002)	260 (2002)
United Arab Emirates	1,328 (2002)	not available
Yemen	38 (2002)	78 (2002)

*The figure in parentheses is the year to which the amount refers.
(Source: *Britannica Book of the Year, 2005*. Chicago: Encyclopaedia Britannica, Inc.)

THREATS TO DESERTS

Depleting the water below ground

Deserts are dry places where people learn to use water very carefully. Despite their traditional thriftiness, as the populations of desert nations increase so, inevitably, does their demand for water. People need only a small amount of water for drinking, cooking, washing, and hygiene. They need very much more to grow food, and in North Africa and the Middle East crop irrigation accounts for 90 percent of all the water used. It requires about 1,500 tons of water to produce one ton of wheat grain. Industry also uses water. Some, known as *process water,* is incorporated into products and much more is used for cooling. Cooling water is returned to the system, but each time it is used, a proportion is lost by evaporation.

Over the world as a whole, the average amount of water available annually to each person for all uses, including agriculture and industry, is approximately 18,500 gallons (70,000 l), but it is not distributed evenly. In North Africa and the Middle East each person has little more than one-sixth of the global average—an annual 3,200 gallons (12,000 l)—and even that is an average figure that conceals a wide disparity. People in Iran have an average 4,755 gallons (18,000 l) a year, but those living in Jordan and Yemen have less than 530 gallons (2,000 l). The situation is deteriorating. Experts fear that by 2025 the average amount of water available annually to each person throughout the region may be little more than 1,300 gallons (4,900 l).

People take water from rivers, but those living far from any river use wells (see “Wells and oases” on pages 47–50). Wells take water from below ground and in many deserts, especially the Sahara, there is a very large amount of groundwater.

Saharan groundwater is of three types. There are *alluvial aquifers*—reserves lying close to the surface that are filled by water from major rivers, such as the Nile. Along the Mediterranean coast, where the climate is wetter, there are *coastal aquifers* that are filled by rainwater (see "What happens when it rains" on pages 45–47).

Alluvial and coastal aquifers are recharged from rivers and rainfall, respectively, but increased demand for water has raised fears that water is being removed from them faster than it is replenished. In Egypt, water is being removed four times faster than Nile water is entering the aquifer to recharge it, and water is being removed from the coastal aquifer in Libya five times faster than the aquifer is being recharged. There is a risk that some years from now regions dependent on the coastal and alluvial aquifers may face shortages of water unless they find alternative sources such as desalination (see pages 205–207).

By far the biggest aquifer, however, is the *Nubian Sandstone Aquifer* (NSA), which is estimated to hold 89,500 cubic miles (373,000 km^3) of water. The NSA covers approximately 770,000 square miles (2 million km^2) beneath Egypt, Sudan, Chad, and Libya, and it adjoins the *Continental Intercalaire* aquifer, extending over 48,250 square miles (125,000 km^2) from southwestern Algeria to central Libya.

Both the NSA and Continental Intercalaire aquifer contain water they accumulated long ago. Scientists have calculated, for example, that the Continental Intercalaire was intensively recharged between 45,000 and 23,500 years ago but has received little water since. Water in the NSA is much more ancient. These are aquifers holding "fossil" water, and water that is taken from them is not replenished.

Water is being removed from the North African deep aquifers at an estimated rate of 210 gallons (795 l) every second. This rate has increased steadily over the years and is now more than six times what it was in 1950. Abstraction lowers the water table in the vicinity of the well, and the water table is now 65–130 feet (20–40 m) lower than it was in 1950—but only in the area around each well. No one knows whether the water table is falling elsewhere, but the time may come when it is too expensive to deepen the wells sufficiently to maintain the supply of water for irrigation.

People living in and close to the North American deserts are also increasingly concerned about the reliability of their water supply. In the future they may need to increase their reliance on desalination. Other deserts, such as the Namib, Atacama, and Taklimakan, are too dry to support agriculture of any kind, and no one lives in them.

Waterlogging and salination

Ironically, in some areas where farmland is heavily irrigated, the water tables are rising. That is what can happen when the irrigation system is inefficient.

Irrigation water should soak downward at a rate of 0.1–3 inches (2.5–75 mm) per hour. At this rate plant roots are able to absorb the moisture they need, and if irrigation continues over a 24-hour period the soil should be moistened to a depth of two to three feet (60–90 cm). If the water is applied too slowly, much of it will evaporate and be lost before reaching the roots. If it is applied too quickly on a very permeable soil, such as sand or desert gravel (see the sidebar on page 174), much of it will pass straight through the soil and enter the groundwater. Again it will be lost to the plants.

When the water drains away too quickly the soil dries and the crop wilts for lack of water, and so the farmer increases the rate of irrigation. This is unlikely to help, however, and it may make matters worse if the irrigation system pours water through the soil faster than the groundwater flow can remove it. That is when the water table starts to rise. In parts of Egypt and Morocco the water table is rising at up to 10 feet (3 m) a year, and water tables are also rising, though not so fast, in some places in Ethiopia, India, China, and Australia.

No one may notice that the water table is rising, but if it continues to rise it may reach the roots of crop plants. Soil at the surface will still be dry and crops will grow more slowly or even die, but the problem is not too little water, but too much. Soil around the roots is saturated with water and the roots are unable to take in oxygen. Despite the dry

Porosity and permeability

When soil particles pack together, their irregular shapes mean there are small spaces between them. These spaces are called *soil pores,* and the total percentage of the space they occupy—the *pore space*—in a given volume of soil is known as the *porosity* of that soil.

The size and shape of soil particles determines the size of the soil pores, but without necessarily affecting the total amount of pore space. Sand grains are relatively large and usually very angular in shape. They do not fit together neatly, and consequently sand and sandy soils have large pores. Clay, on the other hand, consists of microscopically small, flat-sided particles that lie in sheets, stacked one on top of another with extremely small pores between them. But the difference in size of the particles means that the total pore space may be similar for both soils. In that case, both soils are equally porous.

They are not equally water permeable, however. *Permeability* is a measure of the speed with which water or air is able to move through a soil. Air does not stick to soil particles, so the air-permeability of a soil depends only on the total pore space. Water does stick to soil particles, however, coating each particle with a film approximately one molecule thick that is tightly bound to the surface. If the soil pores are very small the water adhering to particles may reduce their size even more, slowing the movement of water through the soil and therefore reducing the permeability of the soil.

Permeability is classified by the rate at which water moves through the soil. The usual classification is given in the following table.

Class	**Rate of movement**	
	(inches per hour)	**(millimeters per hour)**
Slow:		
Very slow	less than 0.05	less than 1.25
Slow	0.05–0.20	1.25–5.08
Moderate:		
Moderately slow	0.20–0.80	5.08–20.32
Moderate	0.80–2.50	20.32–63.50
Moderately rapid	2.50–5.00	63.50–127.00
Rapid:		
Rapid	5.00–10.00	127.00–254.00
Very rapid	more than 10.00	more than 254.00

appearance of the soil, the plants are drowning. This is the effect of *waterlogging* and it can be caused by leaks in the channels and pipes carrying irrigation water.

Irrigation water does not need to be fit for people to drink. It contains a variety of mineral salts, including common salt (sodium chloride), and as it drains through the soil more salts present in the soil dissolve into it. As water evaporates from the soil above the water table, more water is drawn upward to replace it, moving through the pores between soil particles. This water also evaporates, and when water evaporates any substances dissolved in it are left behind, because only pure water enters the air as water vapor. Salt water moves upward, evaporates, and the salts it leaves behind accumulate, making the soil progressively saltier. Each time more water passes through the soil, the salts dissolve in it, and consequently the water above the water table also grows steadily saltier. This is called *salination*.

Water and molecules of nutrients can pass through the walls of plant cells by a process called *osmosis*. If the solution—chemical compounds dissolved in water—is stronger on one side of the cell wall than on the other, water will pass through the wall from the weaker to the stronger solution until the two are at the same strength. If the water surrounding the roots of a plant is saltier than the water inside the roots, water will flow out of the roots by osmosis. This will make the plant wilt and eventually it will die. Salination renders the soil infertile. Plants will not grow in it.

The remedy for waterlogging is to drain off the surplus water. Curing salination is more difficult, more costly, and takes much longer. Water must be poured onto the land and removed by good drains to wash out the salts—taking care that the water does not pollute the groundwater or rivers.

Prevention is better than cure. It involves installing good drainage as part of the irrigation system. Because this increases the cost of the installation, it is tempting to cut corners and rely on natural drainage. That is why both waterlogging and salination are now widespread.

What climate change may mean for deserts

Leave a cup of hot coffee standing on a table and before long it will be cold. The coffee will lose some of its heat in the form of radiation—the warmth you feel when you hold out your hands to a fire. A minute or so in a microwave oven will warm the coffee again. The coffee will absorb microwave radiation and convert it to heat. An object that absorbs all of the radiation falling upon it and then radiates away all the energy it absorbed is known as a *blackbody* and the radiation it emits is *blackbody radiation.*

The Earth is a rather inefficient black body. It absorbs about half of the radiation it receives from the Sun. This warms the surface, and the warm surface then radiates the heat back into space. Radiation travels in waves. The distance between one wave crest and the next is the *wavelength* of the radiation, and the shorter the wavelength the more energy the radiation possesses. The wavelength of blackbody radiation is inversely proportional to the temperature of the black body—the hotter the body, the shorter the wavelength of its radiation. The Sun, which is hot, radiates most intensely at short wavelengths. The Earth, which is much cooler, emits long-wave radiation.

During the day, the Earth absorbs shortwave radiation from the Sun and emits long-wave radiation, but it absorbs radiation faster than it loses it. Consequently, the surface grows steadily warmer. By late afternoon the sunshine has become less intense and the Earth starts to lose radiation faster than it absorbs it. This continues through the night, and the Earth cools, but about an hour before dawn the cooling ceases and the surface begins to absorb radiation from the rising Sun.

On the Moon, which is the same distance as Earth from the Sun, nights are extremely cold and days extremely hot. At noon the average temperature is 230°F (110°C) and by the end of the night the temperature has fallen to –274°F (–170°C). It is the Earth's oceans and atmosphere that prevent temperatures from rising and plummeting as they do on the Moon. The oceans absorb heat and release it very slowly, making summers cooler and winters warmer than they would be on a dry planet, and the atmosphere delays the departure of outgoing radiation. This delay occurs because certain gases, especially water vapor but also carbon dioxide, methane, ozone, and some others, absorb long-wave radiation. The gases then radiate the energy they have absorbed, but during the time it remains trapped in the air, the air temperature is held higher than it would be otherwise. If the air contained none of these gases the average temperature over the whole world would be about –0.4°F (–18°C). The actual average temperature is 59°F (15°C). The warming of the air through the absorption of long-wave radiation is known as the *greenhouse effect* and the gases involved are *greenhouse gases.*

Clearly, without the natural greenhouse effect life on Earth would be very uncomfortable. For one thing, outside the Tropics the lakes and seas would be frozen over all year long. We need the greenhouse effect, but for the last few decades we have been increasing it by releasing greenhouse gases, especially carbon dioxide. The enhanced greenhouse effect is making the average temperature rise, and in years to come the resulting global warming may affect deserts.

There are many uncertainties about the extent of global warming and therefore about its consequences, but the most likely estimate is that by the year 2100 the average temperature will have increased by approximately 2.7°F (1.5°C). The warming is not spread evenly. Most of it is taking place to the north of latitude 30°N, and it is most marked during winter in northwestern North America and northeastern Siberia.

A rise in temperature of 2.7°F (1.5°C) will produce an increase in rainfall, but in middle latitudes probably it will also bring longer periods of settled weather, both wet and dry. The continental deserts, such as the Gobi, may become moister, as may the Northern and Western Sahara. If so, the combination of increased rainfall, slightly warmer temperatures, and increased carbon dioxide—which encourages plant growth—may make it possible to farm areas that are presently too dry and cold for growing crops.

The Asian summer monsoon may become more intense. This could bring rain to the Thar Desert, increasing the amount of vegetation growing there.

In North America, the Sonoran Desert may decrease in area due to increased rainfall, but the Mojave Desert, lying in a rain shadow (see “Deserts of continental interiors” on pages 13–16), is less likely to change. The very dry Atacama Desert will continue to receive air that has crossed the South American continent, and air reaching it from the ocean will continue to cross the cold Peru Current. The Atacama climate is likely to remain unchanged. The Namib Desert, in Africa, is also likely to remain dry, for the same reason. The Australian deserts may shrink a little as the southeasterly trade winds bring rather more rain across the northern part of the country.

Many uncertainties surround the entire issue of global warming, but it seems increasingly probable that the effects during the 21st century will be fairly small. Those effects are likely to include a reduction in the total area of the world's deserts. Deserts will become slightly smaller. This will benefit desert peoples and those living along the semiarid desert edges.

Natural climate cycles

Climates change naturally over periods of decades. There were fears in the 1970s that prolonged drought immediately to the south of the Sahara, in the region called the Sahel, meant that

El Niño

At intervals of between two and seven years, the weather changes across much of the Tropics, and especially in southern Asia and western South America. The weather is drier than usual in Indonesia, Papua New Guinea, eastern Australia, northeastern South America, the Horn of Africa, East Africa and Madagascar, and in the northern part of the Indian subcontinent. It is wetter than usual over the central and eastern tropical Pacific, parts of California and the southeastern United States, eastern Argentina, central Africa, southern India, and Sri Lanka. The phenomenon has been occurring for at least 5,000 years, and there is evidence of it happening 350,000 years ago.

The change is greatest at around Christmas—midsummer in the Southern Hemisphere, of course. That is how it earned its name of *El Niño,* "the boy," specifically the Christ child, in Peru, where its effects are most dramatic. Ordinarily, the western coastal regions of South America have one of the driest climates in the world, but El Niño brings heavy rain. Farm crops flourish, so the Christmas gift of rain means there will be a good harvest. Nowadays, however, many communities rely on fishing and during an El Niño the fish disappear.

Most of the time, the prevailing low-level winds on either side of the equator are the trade winds, blowing from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. At high altitudes, the winds flow in the opposite direction, from west to east. Air pressure is usually low over the western side of the Pacific, near the desert was advancing. The seasonal summer rains began to fail in the 1960s, and the drought was at its most severe between 1968 and 1973. By the middle of the 1970s, when the outside world began to take note of events in this remote region, approximately 200,000 people and 4 million livestock had starved to death. The tragedy was on such a huge scale that it was easy to believe the Sahara was advancing southward. The drought came to an end, however, and with the return of the rains in the 1980s the vegetation recovered.

Unusual weather in a single year is sometimes associated with a change in the winds and ocean currents in the equatorial South Pacific. The effects of the change usually become apparent in December, and the event is known as *El Niño,* Spanish for “the (boy) child” (see the sidebar starting on page 178).

Indonesia, and high on the eastern side, near South America. This pressure distribution helps drive the trade winds, and the trade winds drive the Equatorial Current, which flows from east to west, carrying warm surface water toward Indonesia, where it accumulates in a *warm pool.* Cool water flows northward parallel to the South American coast as the Peru Current, with many upwellings that bring nutrients close to the surface where they sustain large shoals of fish.

In some years, however, the pressure distribution changes. Pressure rises over the western Pacific and weakens in the east. The trade winds then slacken. They may cease to blow altogether or even reverse direction, so they blow from west to east instead of east to west. This causes the Equatorial Current to weaken or reverse direction. Water then begins to flow out of the warm pool, moving eastward, and the depth of warm water increases off the South American coast, suppressing the upwelling cold water in the Peru Current. Air moving toward South America is warmed and collects a great deal of moisture as it passes over this warm water, bringing heavy rain to the coastal region. This is an El Niño.

In other years the low pressure deepens in the west and the high pressure in the east rises. This accelerates the trade winds and Equatorial Current, increasing the rainfall over southern Asia and the dry conditions along the South American coast. This is called *La Niña.*

The periodic change in pressure distribution is known as the *Southern Oscillation* and the complete cycle is an *El Niño-Southern Oscillation* (ENSO) event.

During the 1990s, northwestern Europe enjoyed a series of mild winters, but in eastern North America many of the winters were unusually severe. This weather pattern resulted from the *North Atlantic Oscillation* (NAO). A region of low atmospheric pressure is semipermanently centered over Iceland, and there is a region of high pressure centered over the Azores (which lie about 800 miles (1,290 km) west of Portugal), sometimes extending to the Caribbean. These are known respectively as the *Icelandic low* and *Azores* (or *Bermuda*) *high*. Air circulates counterclockwise around areas of low pressure and clockwise around areas of high pressure, so between them the Icelandic low and Azores high produce a flow of air from west to east across the North Atlantic. When the difference in pressure is large—pressure is very low over Iceland and high over the Azores—the NAO is said to be high, and when the difference in pressure is small the NAO is said to be low. A high NAO produces mild winters in western Europe and cold winters in eastern North America.

A similar oscillation affects the North Pacific. It is known as the *Pacific Decadal Oscillation* (PDO) and produces alternating warm and cold weather over periods lasting several decades. Scientists now believe that the NAO and PDO are linked to changes in the distribution of pressure over the North Pole and a circle at about 55°N, known as the *Arctic Oscillation.* All three oscillations together produce the *Northern Hemisphere Annular Mode* (*annular* means "ringlike," referring to the fact that the weather patterns circle the globe).

These changes affect the weather over years or tens of years, but there are also changes that happen over longer periods. Average temperatures in many parts of the world, in both the Northern and Southern Hemispheres, began to increase between 600 C.E. and 800 C.E., reaching a peak between 1100 C.E. and 1300 C.E., when some places were warmer than they are today. This was the Medieval Warm Period. It was followed some centuries later by the Little Ice Age, a time of colder weather that lasted from about 1600 until 1850.

The coldest part of the Little Ice Age, from 1645 until 1715, coincided with a time when there were very few sunspots or auroras. Sunspots are dark patches on the surface of the Sun caused by intense magnetic fields. They are strongly linked to the intensity of the *solar wind*—a stream of subatomic particles that pours outward from the Sun. Solar-wind particles cause auroras when they reach the Earth, and the intensity of the solar wind affects the formation of clouds. The stronger the solar wind, the fewer clouds form. Edward Walter Maunder (1851–1928), an English solar astronomer, was the first person to identify this period, and it is known as the *Maunder Minimum*. There have been other minima, before and since the Maunder Minimum, and all of them coincide with periods of cool weather. There have also been sunspot maxima, which coincide with warm weather.

The biggest climatic changes of all are those between an ice age and one of the *interglacials* that occur between one ice age and the next. At present we live in an interglacial called the Holocene, which began approximately 10,000 years ago at the end of the most recent ice age, known as the Wisconsinian. The Wisconsinian was the fourth ice age to affect North America in the last 800,000 years. Their dates and names, together with the dates and names of the interglacials, are listed in the table below.

Scientists believe that the onset and ending of ice ages are triggered by changes in the Earth's orbit about the Sun and in its rotation on its own axis. Milutin Milankovitch (1879–1958), a Serbian astrophysicist, calculated when these

Pleistocene glacials and interglacials in North America

Approximate date ('000 years BP)	Name
10–present	*Holocene*
75–10	Wisconsinian
120–75	*Sangamonian*
170–120	Illinoian
230–170	*Yarmouthian*
480–230	Kansan
600–480	*Aftonian*
800–600	Nebraskan

(Names in italic are those of interglacials. BP means "before present," "present" being 1950.)

astronomical changes occurred over several hundred thousand years and compared their timings with climate changes. The fit was precise, and astronomical changes known as the *Milankovitch cycles* (see the sidebar below) were shown to trigger the sequence of events that cause ice ages and interglacials.

Milankovitch cycles

In 1920 Milutin Milankovitch (1879–1958), a Serbian astrophysicist, proposed an astronomical explanation for why ice ages begin and end when they do. Milankovitch had examined regular changes that occur in the Earth's orbit about the Sun and in Earth's rotation on its own axis. He found there were three changes, or cycles, that periodically alter the amount of sunshine falling on the surface. When the three cycles coincide, an ice age either begins or ends. Most climate scientists now accept the Milankovitch theory. The three cycles affect *orbital stretch, axial tilt,* and *axial wobble.*

Earth follows an elliptical path around the Sun, with the Sun occupying one focus of the ellipse. Orbital *eccentricity* changes over a period of 100,000 years. This means that the ellipse grows longer and then shorter again. When the orbit is at its longest, Earth is approximately 30 percent farther from the Sun at both its closest approach (*perihelion*) and its farthest point (*aphelion*) than it is when the ellipse is short—in fact, almost circular. At these times, the sunlight falling on the Earth is less intense.

Instead of being at right angles to the Sun's rays, Earth's axis is tilted, at present by about 23.45°. Over a period of about 42,000 years the angle of tilt varies from 22.1° to 24.5° and back again. The greater the angle of tilt, called the *obliquity,* the more intense the sunshine falling on high latitudes in summer and the less these latitudes receive in winter.

The Earth's axis wobbles like a toy spinning top, so that without changing the angle of tilt, the axis describes a circle, taking 25,800 years to complete one turn. This alters the dates of midsummer day, midwinter day, and the *equinoxes* (days when there are precisely 12 hours of day and 12 hours of night everywhere). At present, Earth is at perihelion (closest to the Sun) on about July 4 and at aphelion on about January 3. In about 10,000 years from now these dates will be reversed due to the axial wobble. The Northern Hemisphere will then receive more solar radiation in summer and less in winter, and the Southern Hemisphere will receive less radiation in summer and more in winter.

When the orbit is at its most eccentric, the axial tilt is at a minimum, and Earth is at aphelion in June or December, summer temperatures in one or the other hemisphere may be low enough to trigger the onset of an ice age.

All of these changes can affect deserts. During cold periods, less water evaporates from the oceans. Consequently, the rainfall decreases. Cold periods are usually dry and are times when deserts expand. Conversely, warm periods are wet, because higher temperatures mean that more water evaporates and then condenses to form clouds. During warm periods, the deserts contract.

Overgrazing and desertification

Desert vegetation is sparse, but it used to be sufficient to support the livestock owned by nomadic tribes. The nomads are *pastoralists*—people who depend on their livestock and grow no crops—and they used the natural resources very efficiently. They owned sheep, goats, camels, horses, and cattle. Each of these feeds differently from the others, so they could graze an area without competing. As they fed they also trampled the ground and urinated and defecated on it. After a time the plants they had not chewed or nibbled were trampled, fouled, and unfit to eat. At this point, members of the tribe

A fence separating overgrazed pasture on the right from protected land on the left shows the effect of allowing livestock an uncontrolled access to pasture. This scene is in the Chihuahuan Desert, Mexico. (Courtesy of Gerry Ellis/Minden Pictures) would ride out to find fresh pasture, and when they had done so, the people would pack up their tents and other belongings and move on. The plants they left behind soon recovered, because the animal droppings fertilized them.

Pastoralists had lived in this way for centuries and there was no reason why their way of life could not continue indefinitely, but it was a hard life. Animals were their only form of wealth and were bartered in exchange for grain and for the goods the people could not make themselves. This meant that the animals were too valuable to be killed for food, except on rare occasions, usually to celebrate some important event. When animals fell sick there was no veterinarian to administer modern drugs. If the traditional herbal remedies failed, the sick animals died. Neither were there doctors or hospitals or schools for the children.

Conditions now are much better. Villages have medical centers and schools that are open to the traveling people, and there are veterinary clinics to tend their animals, so sick animals have a much better chance of recovering. There are also larger markets for their animals among wealthy, meat-eating city dwellers. The traders buy animals for money, with which the pastoralists can buy modern luxuries.

Life for the pastoralists has improved greatly, but the improvement has brought change. Better veterinary care and ready markets mean that livestock herds and flocks are bigger, and their composition is different. Nowadays cars, buses, and trucks carry the people and goods that were once transported by camels and horses. There is less need for these animals, so their numbers have fallen. Sheep and goats provide meat and skins, but the greatest demand, and the best price, is for beef. Many herds consist only of cattle.

A herd of cattle utilizes pasture less efficiently than a mixed herd of four or five species. Combined with the increase in livestock numbers, reduced grazing efficiency damages the pasture. Plants are ripped from the ground or trampled to destruction. This is *overgrazing.*

The situation became especially bad in the southern Sahara and the Sahel region bordering the desert, and the pastoralists were not the only people under pressure. Farmers cultivated the better land. During the droughts that occur from time to time, the pastoralists are able to move in search of pasture, but the farmers can only look on as their crops wither. In desperation, they seek to increase the cultivated area by fencing off land that was formerly used by the nomads. This timeless conflict between farmers and pastoralists underlies the biblical story of Cain and Abel and the fights between cowboys and farmers in the Wild West, and during the second half of the 20th century it was reenacted in Africa.

It has always been a conflict the pastoralists lose. In some places farmers allowed the nomads to graze their stock in the fields after the crop had been harvested, but they charged for this. The nomads could ill afford to pay and, in any case, resented paying for the use of land that was once free to them. When the pastoralists found pasture they could use the farmers often sought to enclose it. The nomads were being forced into smaller areas. At the same time, governments were encouraging them to settle down in villages. There they could have permanent houses, proper medical care, regular schooling for their children, and the possibility of paid jobs. It was an attractive offer and many seized the opportunity. They did not abandon their livestock, however. Animals were their most important possessions and so the herds grazed the land around the villages, and when they had destroyed the plants in the immediate vicinity they moved out a little farther.

Again the composition of the herds changed. As the vegetation deteriorates, there comes a point where cattle can no longer survive. Usually they are sold before they die. Sheep desperately nibble the herbs until those, too, are destroyed and most of the sheep have to go. Goats can climb trees and shrubs in search of leaves, shoots, and twigs, so they survive for longest.

Once the vegetation has gone the bare ground becomes indistinguishable from the surrounding desert. Wind blows away the fine soil, leaving the stones, and the windblown soil buries plants some distance away and kills them. That is how the desert spreads. The process is called *desertification.*

People sometimes blame the pastoralists for the spread of deserts. This is very unfair. They are the victims of this tragedy, not its perpetrators, and their goats, which seem to be destroying what little vegetation remains, are survivors of a catastrophe that was not of their making. Once the rains return, overgrazed land will recover provided it is fenced to keep out livestock until the plants are fully established. It is drought that makes deserts expand, and drought is a natural disaster. In time, the villagers whose parents were nomads whose way of life disappeared will find new ways to prosper in the modern world.

CHAPTER 9

MANAGING THE DESERT

Halting the spread of deserts

Estimates by the United Nations Environment Program (UNEP) suggest that one quarter of the land area of the Earth is either desert or threatened by desertification. This does not mean that deserts are expanding into neighboring territory—in fact they are not. UNEP defines desertification as the deterioration of the quality of land in regions with a dry or semiarid climate.

There are several causes. Poor irrigation leads to waterlogging and salination (see pages 173–175). Overgrazing leaves soil exposed to the wind and vulnerable to erosion (see “Overgrazing and desertification” on pages 183–186). Clearing forest to provide lumber or firewood can also leave land vulnerable to erosion. Growing farm crops year after year without adding fertilizer to replace the nutrients that cropping removes depletes the soil fertility until the land becomes incapable of sustaining crops. The U.S. Bureau of Land Management estimates that 40 percent of the United States is vulnerable to one or other of these types of degradation.

International concern about the extent of the problem and the seriousness of its implications was first expressed in 1973, when nine countries of the Sahel region established a permanent committee to monitor the situation. In August and September 1977 the United Nations Conference on Desertification, held in Nairobi, Kenya, agreed to a plan of action. The issue was raised again at the UN Conference on Environment and Development—the so-called Earth Summit—held in Rio de Janeiro, Brazil, in June 1992. These meetings culminated on June 17, 1994, with the adoption in Paris, France, of the UN Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa (UNCCD). The UNCCD was opened for signature in Paris in October 1994 and it came into force on December 26, 1996.

UNCCD aims to improve the efficiency with which the problem of land degradation is addressed. It does this by coordinating the efforts of the rich industrial nations that provide the finances and by encouraging poorer nations that are suffering from desertification to develop and implement practical measures to halt and reverse the deterioration and to help its victims. Numerous countries are now engaged in relevant projects. Many are in Africa, where the problem is most severe, but land degradation is not confined to Africa. It also affects parts of Latin America and the Caribbean as well as Asia, and nations in these regions are also actively seeking to combat land deterioration.

We cannot prevent droughts, but there are ways to reduce their harm and check the spread of deserts. Desert soils suffer badly from erosion, and erosion is preventable. The first step is to ensure that vegetation covers the ground at all times. Friction with the plants slows the wind, reducing its power to blow away fine-grained material, and plant roots bind soil particles together, making them less susceptible to wind erosion.

Maintaining a permanent vegetation cover is possible only if pressure on the land is reduced. People initially destroyed the plants through overgrazing or overcropping because they had no choice if they were to survive. To take pressure off the land to produce crops or pasturage, these people must be given alternatives. Industries can provide nonagricultural jobs, for example, and credit facilities can be developed to allow farmers to invest in the equipment, seeds of improved crop varieties, and chemicals that will increase crop yields without damaging the land.

Once the pressure on the land is eased, other measures can follow. These include more efficient irrigation, new sources of water for farm use, and better farming methods.

The end of the nomadic way of life

Nomads lead insecure lives. They have a detailed knowledge of the land on which they have lived for generations, but they do not own the land or even rent it. They understand the weather and the seasons, and they know where they are most likely to find pasture for their animals. They know the location of all the water holes and oases. But they have no legally enforceable entitlement to the land they use. Individual nomadic groups traditionally enjoyed access to certain resources at particular times of year, but this was by unspoken and unwritten agreement among the groups, and outsiders were not bound by such agreements. The nomads could be evicted from "their" grazing lands by anyone strong enough to expel them—and they often were. Tribal warfare was common.

The wars and famines of the 20th century displaced vast numbers of people, and this made the plight of the nomads still worse. Waves of refugees swept across the lands bordering the deserts. Sometimes nations unable to feed and accommodate so many desperate people closed their borders to them. Frontier fences and border guards prevented the nomads from moving freely between their traditional grazing lands. With the better pasture enclosed to provide farmland and their migration routes obstructed, the nomads found it increasingly difficult to maintain their way of life. Times had changed and the world no longer had room for pastoralists used to wandering freely. Many nomadic groups settled in permanent villages, where people found jobs and grew crops for their own use.

Life was no more secure for the farmers. They did not own the land they farmed. Indeed, the idea of owning land was quite foreign to most desert peoples, and, in any case, they had no money to buy their plots. They fenced the land they worked to protect their crops from wandering livestock, but their fences did not imply ownership. If someone more powerful claimed the land the farmers could be evicted.

Desert farms could be improved. Crops could be irrigated more efficiently (see "Improving irrigation" on pages 201–205); the land could be managed in ways that reduced erosion; and as the soil became more stable and more fertile, crop yields would increase. Making the necessary improvements requires hard work, however, and it is very difficult to persuade people to invest their time and effort in increasing the value of land from which they can be evicted at any time. If they had security of tenure, farmers would see that improvements continued for several years would make their families more prosperous and that their children would enjoy a much better, richer life.

There are new techniques the farmers could introduce. For example, spraying a mixture of oil and synthetic rubber onto sand dunes stabilizes the sand by binding the grains together. The effect is temporary, but it lasts long enough for the farmer to plant tree seedlings through the surface coating. Eucalyptus and acacia species will grow with only six inches (150 mm) of rain a year, and as they grow the tree roots bind the soil more permanently, while the trees themselves shelter the surface from the erosive wind.

It seldom rains in the desert, but when it does the rain can be torrential, sending water rushing along gullies and cascading down hillsides, carrying the soil with it. Stones litter the desert surface, and stone walls built across the slope will absorb some of the energy of the flowing water. As the flow slows down and the water loses energy, soil carried by the torrent will settle onto the ground instead of being lost.

Such measures require work and some of them also cost money. Oil and rubber has to be bought and spraying equipment bought or hired. If they are to improve their land, the farmers must be able to borrow money for investment, but banks and other financial institutions are reluctant to lend money to people with no assets. This is another reason why security of tenure is an essential first step to agricultural improvement and reducing erosion. Farmers must have access to credit facilities.

Not everyone can or should work on the land. Alternative employment, in tourism or light industry, for example, helps the farmers in two ways. Members of farming families who have outside jobs bring extra money into the home, money that can be used to improve the standard of living immediately or invested in farm improvements. At the same time, wage earners belonging to nonfarming families will buy food, as will tourists, providing a local market for farm produce.

The nomadic way of life is fast disappearing, but we should not mourn its passing. Although the nomads were romantic figures, with their flowing robes, camels, horses, and tents, theirs was not a glamorous life. It was hard, sometimes violent, and the risk of famine was always present.

Rainmaking

Deserts are dry, but their skies are not cloudless. White clouds appear fairly often, only to drift tantalizingly past without releasing rain. Life on the ground would be so much easier if only the clouds could be induced to release their moisture.

Controlling the weather is an ancient dream. For countless centuries people have sought to achieve it by flattering, appeasing, or bribing the whimsical and usually bad-tempered gods that were thought to manage the wind and rain. Specialist "rainmakers" would perform rituals, often supported by dances or chants performed by other members of the group afflicted by drought.

Old beliefs die hard, but they often change the language in which they are expressed. According to a story circulated during the U.S. Civil War, every major battle was followed by rain. People supposed that rainfall must have been triggered in some way by the explosions of battle, and in 1891 the Congress authorized the expenditure of $9,000 on attempts to reproduce the effect by firing cannons into clouds. When this failed, kites and balloons were used to carry explosives into clouds, where they were detonated. Eventually, the attempts had to be abandoned. Explosions do not cause rain to fall. What the experimenters did not know was that in the space of about an hour an average summer thunderstorm releases as much energy as burning 7,000 tons (6,356 tonnes) of coal. It takes more than a cannon or 19th-century bomb to manipulate the weather by brute force.

Failure proved no deterrent, however, for there was another problem that might be tackled head-on. Hailstorms can devastate crops, and during the 19th century the belief grew in Europe that an explosion inside a storm cloud would prevent hailstones from forming. Large mortars, called *hail cannons,* were built for the purpose. They fired their bombs upward into the threatening cloud. By 1899 thousands of hail cannons were in use throughout Europe. In the year

1900 alone there were approximately 9.5 million firings of hail cannons in Europe. As late as the 1960s their updated descendants were still being used in Russia, where artillery shells and rockets were fired into clouds.

The cannons did not work, but the theory behind them was believable. An explosion produces large numbers of very small particles. Water vapor condenses onto small particles, so adding many more particles might produce a cloud consisting of droplets that were too small to grow into hailstones. The problem may not have been the theory but only the scale. Perhaps the cannons were not big enough.

Hail cannons have not vanished from the world. Instead, they have grown more powerful. On March 2, 2004, the Nissan company demonstrated one it had installed to protect vehicles in the 140-acre (56-ha) parking lot at its factory near Canton, Missouri. This cannon uses acetylene gas to cause an explosion that is repeated every five to six seconds and that sends repeated shock waves to a height of 50,000 feet (15.25 km). The shock waves are believed to disrupt the formation of hailstones. Several firms are manufacturing hail cannons of this type, and the devices are being used in Ontario, Canada, and Queensland, Australia, as well as in the United States.

The Queensland cannons are being blamed for causing a persistent drought downwind of the area where they are used to protect citrus and grape crops. Growers have been using the cannons since the 1980s, and downwind residents claim that approaching storms appear to divide as the cannons are fired into them, pass on either side of their own land, and then rejoin. The Australians are not alone. Some American farmers oppose programs to suppress hailstorms because they believe these reduce rainfall.

It remains to be seen whether or not modern hail cannons can succeed where earlier models failed. There is less uncertainty about the possibility of persuading clouds to release their moisture as rain or snow. The technique for achieving this, known as *cloud seeding,* was discovered accidentally in 1946 (see the sidebar on page 193), and several U.S. states now have cloud-seeding programs. The evidence suggests that seeding can increase the amount of rain or snow that falls by at least 5 percent and sometimes by more.

The discovery of cloud seeding

When an airplane flying in air below freezing temperature passes through a cloud composed of supercooled droplets—droplets that are liquid despite being a few degrees below freezing temperature—water will freeze on contact with the surfaces of the wings and tail. A layer of ice accumulates, altering the shape of the surface and thereby reducing the amount of lift the wings produce. The weight of the ice may also affect the plane's flight characteristics. This is *aircraft icing* and in the 1940s it became a serious problem in military aircraft.

In 1946 Vincent Joseph Schaefer (1906–93) and Bernard Vonnegut (1914–97) were investigating aircraft icing at the General Electric Research Laboratory in Schenectady, New York. They needed to discover what caused icing, and to do this they used a box containing air at a constant –9.4°F (–23°C) to which Schaefer added crystals of different substances in order to identify those that will cause ice crystals to form. During a spell of very hot weather in July, Schaefer found it difficult to maintain the low temperature inside the box. On July 13 he dropped crushed dry ice (solid carbon dioxide) at –109°F (–78°C) into the box to chill the air. Ice crystals formed instantly and there was a miniature snowstorm. A short time later Vonnegut made a similar snowstorm by burning silver iodide and allowing the smoke to enter the box.

On November 13, 1946, Schaefer started a real snowstorm by dropping six pounds (2.7 kg) of dry ice pellets from an airplane into a cloud over Pittsfield, Massachusetts. Later experiments showed that silver iodide also triggers precipitation, and this method is more convenient to use because it does not have to be kept chilled.

Attempting to induce precipitation by injecting material into supersaturated air—air in which the relative humidity is above 100 percent—is called *cloud seeding.* Silver iodide and dry ice are used when the air temperature is between 5°F (–15°C) and 23°F (–5°C). Different substances are sometimes used at other temperatures.

Seeding clouds can bring rain, but it cannot produce clouds with the potential to release precipitation. Only if the clouds have already formed can the technique make them release their moisture in a particular place. Consequently, cloud seeding is likely to be of only limited value in desert climates—and it carries serious risks. A cloud that releases its moisture in one place cannot also release it in another.

Seeding may produce rain for one farming community only by stealing it from another.

Dams

Farming is possible in some desert regions because there is a river to supply irrigation water to the fields on either side. For almost its entire length, the Indus River, carrying water a distance of approximately 1,800 miles (2,896 km) from the Tibetan highlands to the Arabian Sea, crosses land that receives less than 10 inches (250 mm) of rain a year. The name *Indus* is derived from *sindhu,* the Sanskrit word for "ocean," because this vast river, draining an area of 372,000 square miles (963,500 km^2), looked like an ocean to the people who named it. More than 36,000 miles (58,000 km) of canals carry water from the river and its tributaries to irrigate more than 40 million acres (16 million ha) of farmland, and in addition to the canals there are 1 million miles (1.6 million km) of ditches. This is by far the largest irrigation system in the world, and without it the farmlands of Pakistan and northwestern India would be desert.

For centuries, irrigation canals fed by water from the Tigris and Euphrates Rivers sustained farming in the Fertile Crescent of Mesopotamia. Those farms fed the civilizations from which all later Western civilizations developed (see "The Middle East: birthplace of Western civilization" on pages 130–132).

The world's longest river, the Nile, also crosses desert. Rising in the highlands of East Africa, the Nile drains a basin covering 1.1 million square miles (2.85 million km^2) and is 4,157 miles (6,689 km) long. For thousands of years, canals on either side of the river carried Nile water into basins below river level. When the river was in flood with meltwater from the distant mountain snows, dikes that remained closed for most of the year were opened, allowing water to flood the basins. As it did so, the water also deposited a layer of fine silt, rich in plant nutrients. The silt was left behind as the flood subsided and the water drained out of the basins, providing a fertile soil into which the crops were sown.

Unfortunately, rivers like the Nile, Tigris, Euphrates, and Indus are not reliable. If the seasonal rains fail the rivers run dry, and if the rains are unusually heavy the rivers overflow and floods destroy the crops. With too much rain or too little the crops fail and famine is likely. Even when the rivers bring water at the right time, the seasonal nature of the climate means the farmers are able to grow only one crop a year.

The Egyptians knew their river well. They invented a device called a *nilometer* that measured the height of the water very accurately. River water flowed through a tunnel into a cistern, the bottom of which was at the same level as the bed of the river. A graduated obelisk at the center of the cistern, or graduations on the side of the cistern, allowed an official to read the height of the water. When the level began to rise steadily at a nilometer station upstream, word was sent to the authorities downstream, ensuring that the dikes to the fields were opened in time to catch the floodwater.

Water can be stored, however, to be released in a controlled fashion throughout the year. A dam wall built across the river's natural valley will trap water in an artificial lake and floodgates in the wall will then regulate the flow.

The first major damming project on the Nile was completed in 1861. It consisted of a series of dams at the head of the Nile Delta, about 12 miles (19 km) north of Cairo. These dams permanently raised the water level upstream, allowing river water to be released into irrigation channels whenever it was needed. This made it possible for farmers to grow two or even three crops a year. In 1901 another dam was added farther downstream, and in 1902 a dam was built near the town of Asyūt, approximately halfway between Cairo and Aswān. Later, two more dams were built upstream of Asyūt, at Isna in 1909 and at Naj‘ Hammādī in 1930. A much bigger dam was built in 1902 at Aswān, and the largest of all the Nile dams, the Aswān High Dam, was completed in 1970 (see the sidebar on page 196).

The Indus and its tributaries are also dammed. The first dam was the Mangla Dam, on the Jhelum River, an Indus tributary in Pakistan. It was completed in 1967. The Tarbela Dam, also in Pakistan and on the Indus itself, was completed

The Aswān High Dam

Aswān is an Egyptian city located on the eastern bank of the Nile approximately 550 miles (885 km) south of Cairo. The city lies opposite Elephantine Island (also called Jezira Aswān), where there is a restored nilometer. About 3.5 miles (5.6 km) upstream of Aswān an outcrop of granite creates a waterfall known as the *first cataract.* There are an additional five cataracts to the south of the first.

Aswān is an appropriate point at which to dam the Nile. The first Aswān Dam was built in 1902 and subsequently enlarged twice, between 1908 and 1911, and between 1929 and 1934. The dam has four locks to allow ships to pass, and after the second enlargement the granite dam wall was 1.5 miles (2.4 km) long. Behind it a lake extends upstream for 150 miles (240 km). When the river is in flood, surplus water is released through 180 sluices (floodgates) in the wall. A hydroelectric plant inside the dam wall, with an installed capacity of 345 megawatts, came into operation in 1960.

Work on a much bigger dam began at Aswān in 1960. Situated four miles (6.4 km) upstream of the original Aswān Dam, the Aswān High Dam provides year-round irrigation to all the downstream farms bordering the Nile. The High Dam was designed by West German and Soviet engineers. Construction cost $1 billion and was completed in 1970. President Anwar as-Sadat (1918–81) formally inaugurated the dam on January 15, 1971.

When work began the president of Egypt was Gamal Abdel Nasser (1918–70), and the lake behind the Aswān High Dam is known as Lake Nasser. The lake is 310 miles (499 km) long, extending into Sudan for 125 miles (201 km), and an average six miles (9.6 km) wide. Egypt and Sudan share the water in the lake.

The dam wall is rock filled. It is 364 feet (111 m) high, 3,280 feet (1,000 m) thick at the base, and 2.36 miles (3.8 km) long at the crest. The hydroelectric plant inside the wall has an installed capacity of 2.1 gigawatts and supplies almost half of Egypt's electricity.

in the middle 1970s. It is 486 feet (148 m) high and 9,000 feet (2,745 m) long at the crest. The Beas Dam, in India, was completed at about the same time as the Tarbela. It dams the Beas River, an eastern tributary of the Indus, and is 435 feet (133 m) high and 6,400 feet (1,952 m) long.

Dams have also been built across other great rivers. The Karakaya Dam across the Euphrates in Turkey, is 591 feet (180 m) high and 1,293 feet (394 m) long. It was completed in the middle 1980s.

As well as releasing water whenever it is needed, dams also prevent catastrophic flooding, and all large, modern dams contain turbines that use the flow of water to generate electrical power. There are disadvantages, however. Some artificial lakes raise the water table, causing waterlogging and salination (see pages 173–175) in the surrounding land. This has happened with Lake Nasser, behind the Aswān High Dam. Dams trap silt that was formerly deposited on flooded land downstream. Farmers must then buy fertilizer to compensate for the loss of the plant nutrients carried in the silt. Coastal erosion often increases when the silt that once accumulated near the river mouth ceases to arrive. Reducing the flow of water into the sea can allow seawater to penetrate farther inland, as has happened in the Nile Delta. Still, the advantages of controlling these rivers far outweigh the problems. Since 1971 when the Aswān High Dam became operational, Egyptian yields of wheat have increased by 378 percent, of corn by 273 percent, and of rice by 237 percent.

Diverting rivers

Most deserts lie far from a river that could supply water to make them bloom, but in some cases it might be possible to bring water to the desert by diverting the course of a river. It is a hazardous operation, however, and there is much that can go wrong.

In 1905–06 an attempt was made to divert the Colorado River, on the border between California and Arizona, into irrigation channels that would make farming possible in part of the Colorado Desert. Unfortunately, the operation coincided with a spell of very heavy rain and the engineers lost control. The river changed its course and for 16 months water poured into the Salton Trough, a salt-covered basin covering an area of 8,360 square miles (21,652 km^2) that was once the bed of a lake. The river was finally returned to its original course, and in 1907 levees were built to control it. The operation left part of the trough flooded, forming the Salton Sea. The Salton Sea has a surface area of 381 square miles (987 km^2) and its average depth is 31 feet (9.5 m). It is fed by drainage from agricultural land and by a number of small streams but loses water only by evaporation. Consequently, its water is growing steadily saltier—it is now saltier than seawater. The water is also polluted by sewage, suffers from blooms of algae, and contains bacteria and viruses that have caused serious diseases in fish and birds. Scientists at the Salton Sea Authority are taking steps to improve the sea's condition, but it is a difficult task.

In the 1920s Soviet authorities decided that the Soviet Union should become one of the world's leading exporters of cotton, grown on farms on the dry Kirgiz Steppe, in Kazakhstan—now an independent nation but then part of the Soviet Union. The farms expanded and irrigation canals were installed to serve the cotton fields. Irrigation was necessary, because the average annual rainfall in that region amounts to barely five inches (127 mm). Within a few years, the Soviet Union was one of the three major cotton exporters, after the United States and China. By the 1950s the farms needed more water and so more canals were built to bring water from two rivers, the Syr Dar'ya in Kazakhstan and the Amu Dar'ya in Uzbekistan. The canals were unlined and so much of the water soaked away before reaching the cotton fields. Nevertheless, enough arrived at the farms to maintain production. So much water was removed that the rivers were effectively diverted to the farmlands.

Until they were diverted, the Syr Dar'ya and Amu Dar'ya flowed into the Aral Sea. With a surface area of 23,000 square miles (60,000 km^2), the Aral Sea was the fourth largest lake in the world, but diverting the two rivers reduced the amount of water flowing into the sea. Evaporation was high in the desert climate, where winters are cold but average summer temperatures exceed 80°F (27°C), and the Aral Sea steadily began to shrink.

The sea was always shallow. Prior to the river diversion its average depth was 53 feet (16 m), although it was much deeper in some places, and it was dotted with more than a thousand islands. The Aral Sea has now lost 80 percent of the water it once held and become two seas, the Large and Small Aral Seas. If it continues to lose water, by about 2010 it will consist of only three small lakes. Towns that were once sea-ports are now far from the sea, and salt-caked fishing boats lie incongruously in the desert out of sight of the sea.

As the volume of water decreased, the sea became saltier and salt was deposited on land from where the water had evaporated. Most of the fish died, and the wind blew dry salt across the fields. The irrigation system had been wasteful. Water draining from the unlined channels and excessive amounts applied to the crops combined to raise the water table. This caused salination (see "Waterlogging and salination" on pages 173–175) and salt contaminated drinking water. Cotton farming continued, but yields fell.

Scientists and engineers from many countries are collaborating in schemes to restore the Aral Sea, but it will take a long time. Improving the irrigation system to reduce wastage should eventually allow the water table to fall, and it may then be possible to flush the excess salt from the soil.

One method being considered involves bringing water from two rivers, the Ob' and Irtysh, which flow northward and discharge into the Kara Sea, off the northern coast of Siberia. This idea was first proposed in the 1950s as a means of supplying irrigation water to the deserts of Central Asia. It would involve damming both rivers and constructing a canal to carry the water southward. Environmental scientists objected strongly. They feared that diverting so much water might result in winter ice persisting for much longer on the Kara Sea, leading to a deterioration in the climate over a large area, and that diverting freshwater would result in the Kara Sea becoming saltier. The scheme was eventually abandoned, but in May 2003 it was revived and is now being actively studied.

The experience of the Salton Sea and the Aral Sea suggests that although diverting rivers to irrigate deserts seems a straightforward proposition, the consequences can be disastrous.

Farming oases and making artificial oases

The farmers of the Nile Valley have sustained Egyptian civilization for thousands of years, and most visitors to Egypt explore the Nile and its cities but stray no farther. But most of the land of Egypt lies to the west of the Nile, and despite being in the Sahara parts of it are inhabited—and farmed. The Egyptian government is encouraging development in a western region called the New Valley, which occupies 145,331 square miles (376,505 km^2), more than one-third of the total area of Egypt. At present, 150,000 people live there, but numbers are certain to increase in the coming years as the New Valley develops, eventually to rival the Nile Valley in importance.

Oases are often depicted as being small—a pool of water surrounded by grass and palm trees providing an island of tranquillity in the midst of the hostile desert. Oases are cultivated with great care, almost as gardens, and they gave many people their image of paradise. Some oases are like that, but others are much larger and contain large villages, farms, and even factories, as well as gardens. The Al-Hasa oasis in Saudi Arabia, for example, covers 30,000 acres (12,000 ha) and the New Valley, 200–300 miles (322–483 km) to the west of the Nile River, contains even more extensive oases.

The New Valley comprises three large oases, Khārga, Dakhla, and Farafra, as well as several smaller ones. The regional capital is the city of El Khârga, with an industrial quarter, airport, and road and rail links to the cities of the Nile Valley. At the center of El Khârga there is a statue of a woman holding her children. The woman represents Egypt and her children are the oases.

The valley has abundant mineral resources, including marble, limestone, granite, sand suitable for glass making, and phosphate rock, which is the raw material for phosphate fertilizer. It is also a fertile agricultural area. The oases have been inhabited for thousands of years and there are many historical sites and monuments. The farms, covering approximately 520,000 acres (21,000 ha), are watered from more than 1,170 wells that deliver a total of 94.41 million cubic feet (2.6 million m^3) of water every day.

The New Valley Project aims to expand the cultivated area by reclaiming 2.18 million acres (882,000 ha) of desert using water carried by a canal from behind the Aswān High Dam on the Nile. The first phase of the project has already begun.

There are oases in most deserts, but some are partly or entirely artificial. Kattakurgan, for example, is a city of almost 60,000 people in Uzbekistan that grew up in the 18th century as a trade and handicraft center built around a natural oasis. Today a modern reservoir holding water from the Zeravshan River supplies the farms and provides recreational facilities. In effect, the oasis has been enlarged using imported water. Most of Uzbekistan is desert, but its rivers provide water for the cities and surrounding farms.

There is often water deep below ground and desert people learned long ago that there are ways to reach it. They built underground watercourses, called *qanats, foggara,* or *qarez,* among other names depending on the language, that guided water into depressions where it surfaced to irrigate fields and supply drinking water (see the sidebar on page 202). No one knows just when the first qanats were constructed, but it may have been thousands of years ago. They were probably invented in Iran, where new ones are still being made. The idea spread both east and west—qanats provided water for some of the oases on caravan routes across the Gobi.

Of course, it would have been easier and safer to dig canals to carry water. That is the way the Roman engineers did it, with *aqueducts,* but the ancient Iranians knew that a canal crossing the hot, windy desert and exposed to the air would lose much of its water by evaporation. An underground canal, on the other hand, would deliver all of its water to the fields that needed it.

Oases have always allowed people to live in the otherwise uninhabitable desert. If ways can be found to bring water into the desert it will most likely be used to create new oases.

Improving irrigation

Southern Israel is shaped like an inverted triangle, bordered on the western side by the Sinai Peninsula and by the Jordan Valley in the east. This region is called the Negev. Nowadays, the name simply means “southland,” but it is derived from a Hebrew verb root that means “to dry.” The Negev is a dry place, although not all of it is desert. In the north, around Beersheba, the annual rainfall of eight to 12 inches (203–305

Qanats

Qanat is the Arabic and Turkish name for an artificial underground river system that supplies village communities with water for drinking and irrigation. In North Africa the Berbers call them *foggara;* in Pashto (Iranian) they are *qarez.* Similar watercourses are found across the arid regions of Asia as far as western China, and there are the remains of qanats in Spain, built by the Moors. They are most common in central Iran. The technology is very ancient.

Constructing and maintaining a qanat system is labor intensive and very strenuous. Centuries ago slaves performed the work, and when slavery died out many of the watercourses collapsed and were lost. Today local people build and maintain the qanats.

There is often water flowing through an aquifer below the desert surface, and the first step in planning a qanat is to locate the underground water. The aquifer must be at a higher level than the land it will supply, because the water will flow downhill. There must be sufficient water to fill a well to a depth of 6.5 feet (2 m) within about 10 hours, and the flow must be reliable, continuing throughout the year.

Once the aquifer has been located, either by sinking a well into a hillside until it finds water or by noting patches of damp earth at the base of a slope, the next stage is to dig ventilation shafts at intervals along the route of the qanat. The shafts are just wide enough to allow a man to work and are usually 50–70 feet (15–21 m) deep, although some descend more than 150 feet (45 m). Workers then dig out the underground channel. The material they excavate is removed in leather buckets through the ventilation shafts and used to build a mound around the mouth of each shaft to prevent occasional floods from washing earth down into the channel. In places where there is a danger of cave-ins, stonework supports the roofs of channels and the sides of shafts.

A wealthy individual who finances the surveying and construction of a qanat owns the water that flows through it and charges the villagers for its use. If the villagers build the qanat themselves, they own the water.

Once a year the qanat must be cleared of debris that has fallen into it. A contractor may undertake this work, but often the villagers do it themselves. Boys are often used, because they have more room to move about than grown men, but the men go down if there is a risk of a channel or ventilation shaft collapsing.

mm) allows farms to grow cereals without irrigation. Farther south, however, the rainfall averages only three to four inches (76–102 mm) and Eilat, at the southern tip of the triangle, receives only one inch (25 mm) a year. These are averages, however, and the rainfall varies greatly from year to year throughout the Negev. When there is rain it often arrives during intense storms that cause flash flooding but are of little use to farmers, because the rain drains away too rapidly.

During Roman times the Negev was a different place. The climate was probably almost as dry then as it is now, but the southern Negev was covered with prosperous farms supplying grain to the Roman Empire. Farming was possible because a people called the Nabataeans had found a way to conserve water.

The Nabataeans built terraces of fields, each surrounded by a low wall built of stone, in tiers descending the hillsides. Each time it rained, water ran down the upper part of the hillside and soaked into the top tier of terraces until they were thoroughly saturated and water lay on the surface. When the water rose high enough it overflowed the boundary walls onto the terraces below, then onto those below that, until it reached the bottom terraces. Any remaining water then drained into an underground storage tank, for use later. The Nabataeans truly made the desert bloom, but when Arabs invaded the region in the seventh century the system was abandoned and the southern Negev reverted to desert.

Along the dry border between India and Pakistan, not far from the Thar Desert, the monsoon climate (see “Monsoons” on pages 58–62) brings all the year’s rain during a short summer period. Bikaner, for example, in Rajasthan State, India, receives an average 11.6 inches (294 mm) of rain a year, but more than half of it falls in July and August. Farmers in this part of the world have developed a technique for conserving water that is similar to the one invented all those years ago by the Nabataeans.

Villagers have built dams of earth across the valleys. During the rainy season, water rushing down the steep hillsides accumulates behind the dams and for a time there is an artificial lake behind each dam. After the rains have ended, the water soaks into the ground, and when there is no more water lying on the surface the farmers plant their crops of wheat and chickpeas. The water that soaks downward joins the groundwater and continues moving slowly downhill to fill wells sunk on the lower ground that provide water for irrigation at other times of the year.

Both the Nabataean and Indian-Pakistani systems do more than conserve water. They also conserve soil and its fertility. Water that roars and tumbles in torrents down the hillsides washes away the soil it crosses. When a stone wall or earth dam checks its progress, the soil it carries settles to the surface as a layer of rich silt.

Terracing can conserve water only in hilly country where the rainfall occurs mainly in short, heavy storms. Elsewhere, farmers must use a different way to improve the efficiency of their irrigation. Many have installed drip or trickle irrigation, a system that works well in hot, dry climates. It is widely used in Israel.

Water is carried along plastic pipes 0.5–1.0 inch (13–25 mm) in diameter with small holes, called *emitters,* at intervals along them. No more than one gallon (3.7 l) of water drips or trickles from each emitter every hour, and it is delivered directly to the soil beside the crop plant. The spacing of the emitters can be varied to suit the crop. A grapevine might need one or two emitters and a fruit tree might have eight, with the delivery pipe laid in a circle around it. Where the climate is very hot and the evaporation rate is high, the pipe is often buried below ground.

Fertilizer is often added to the irrigation water. Drip irrigation allows the amount of fertilizer to be rigorously controlled and the fertilizer is delivered slowly, at a measured rate, directly to the soil around the plant roots. This is a highly efficient way to apply fertilizer.

The disadvantage of drip irrigation is the ease with which the emitters become clogged. Water must be filtered before entering the pipes to minimize the risk, and if a pipe breaks or an emitter clogs, a plant will show signs of distress and may be lost unless the damage is repaired quickly.

This irrigation system can also deposit salts in the soil around the edge of the wetted area. It happens because there is no need to incur the expense of purifying irrigation water to a standard high enough for domestic use. The water contains salts—indeed, it may be fairly salty—and the salts are deposited in the soil as the water evaporates. The soil around the crop plants is kept permanently moist, so salts do not accumulate to harm them, and consequently the problem is not serious.

Desalination

When water evaporates it is only water molecules that enter the air. Substances dissolved in the water are left behind. That is what causes salination (see "Waterlogging and salination" on pages 173–175), but it also suggests that if water is allowed to evaporate and the vapor made to condense into liquid, the condensed water will be pure, its dissolved salts having been removed. The process is called *distillation* and it has been known for thousands of years. Aristotle (384–322 B.C.E.) mentioned it as a way to obtain pure water from seawater, and distillation has been used for centuries to separate chemicals that vaporize at different temperatures. Removing dissolved salts to obtain water that is fit to drink is called *desalination,* and distillation is the most widely used desalination technique, although it is not the only one.

In 1869 the British built a distillation plant at Aden, in Yemen, to provide drinking water for ships calling at the port. Today approximately 75 percent of all desalinated water is produced and used in the Middle East—the distillation plant at Al Jubayl, Saudi Arabia, produces 1.2 billion gallons (4.7 billion l) a year. The United States produces about 10 percent of the world total.

Most desalination plants, including the one at Al Jubayl, use the *multistage flash evaporation* process. Seawater enters along a pipe that passes through a series of chambers, where the pipe is coiled. Water in the pipe is cold, and water vapor inside the chambers condenses onto it and drips into a receptacle to be piped away as freshwater. After it has passed through the final chamber, the seawater pipe passes through a heater where its temperature is increased to about 195°F (90°C). The heated water is then sprayed into the first chamber. The pressure inside the chamber is lower than the pressure inside the pipe and the pressure difference causes the water drops to vaporize instantly. This is *flash evaporation* and it supplies the vapor that condenses onto the cold pipe. The remaining seawater is now a little saltier because of the freshwater that has been removed from it. It passes into the second chamber where the pressure is lower than it was in the first. Again some of the water vaporizes and is collected. The process is repeated—it is *multistage*—until the residue is concentrated brine. Some desalination plants use the *long-tube vertical distillation process*. The principle is similar, but the chambers are vertical tubes and steam is used to heat and vaporize the salt water.

Freezing also separates water from substances dissolved in it and some desalination plants use this principle. In one version seawater is chilled almost to freezing and sprayed into a chamber where the pressure is low. Some of the water vaporizes instantly, absorbing the latent heat to do so from the water around it (see the sidebar "Lapse rates and stability" on pages 60–61 for an explanation of latent heat). Some of the water freezes, and a mixture of ice and salt water falls to the bottom of the chamber and is piped to a second chamber where the salt water is separated from the ice. The water vapor in the first chamber is then compressed, forcing it to condense as freshwater that is used to wash the remaining brine from the ice and to melt it. The melted ice is collected as freshwater.

Alternatively, in the first chamber, seawater is mixed with a refrigerant substance such as propane or butane that vaporizes at a temperature above 32°F (0°C). The refrigerant vaporizes, absorbing latent heat from the water, some of which freezes. The ice and brine are separated, and the ice is taken to a second chamber where it is washed and from there to a third chamber. The refrigerant is piped out of the top of the chamber and compressed. This makes it condense and raises its temperature. Still in its pipe, the warm refrigerant melts the ice in the third chamber and then returns to the first chamber to be mixed with a new batch of seawater.

Reverse osmosis is an entirely different way to separate salt and water. If a membrane that allows water molecules to pass but not others separates two solutions at different concentrations, water will pass through the membrane from the weaker to the stronger solution until both are at the same concentration. This process is called *osmosis* and it happens because an *osmotic pressure* draws water molecules across the membrane. If sufficient pressure is applied to the stronger solution, however, water will cross the membrane in the opposite direction, from the stronger to the weaker solution. This is reverse osmosis. The process is used to obtain freshwater, but only from water that is less salty than seawater.

Desalination plants require regular maintenance to keep the pipes and surfaces free from the scale that collects on them as water evaporates and minerals are left behind. Removing the freshwater also leaves a residue of brine that is very salty indeed and must be disposed of carefully to avoid causing pollution.

All desalination processes use energy, and consequently desalinated water is expensive. Scientists and engineers are working on ways to use energy more efficiently and reduce the cost of desalination. This is already feasible in small plants. In hot desert countries solar power is sufficient to run simple distillation plants suitable for providing drinking water to households or small communities.

Icebergs to water desert crops?

Freezing separates pure water from any substances dissolved in it. Consequently, icebergs that drift across the oceans in high latitudes consist of freshwater, and they represent a very large amount of water. Each year icebergs entering arctic waters—almost all of them from glaciers along the coast of Greenland—contain about 67 cubic miles (280 km^3) of water. Those entering Antarctic waters contain about 300 cubic miles (1,250 km^3) of water. It is very pure water. So pure, in fact, that a company in St. John's, Newfoundland, sells melted iceberg water in bottles.

With so much solid, pure freshwater available in high latitudes and so many desert communities desperately short of water, it is hardly surprising that the idea of using icebergs has been debated for many years. A single Antarctic iceberg, and by no means a giant, contains in the region of 35 million tons (32 million tonnes) of water. This is enough to supply a city of half a million people for a year.

The obvious way to transport this water would be to attach cables to the iceberg and tow it into a harbor, where it could be broken into pieces, melted, and piped to reservoirs. Unfortunately, there is a problem, because once an iceberg enters warm water it melts rapidly. In the time it would take to tow an iceberg from south of the Antarctic Circle to Australia, 50–80 percent of it would have melted. That means only large icebergs would be of use. In fact, they would need to weigh approximately 350 million tons (318 million tonnes). Towing a block of ice that big would require several very powerful seagoing tugs. The ships would burn a great deal of fuel and, consequently, the water would be very expensive. It would probably be too costly for the poor farmers who need it along the edges of deserts.

There is an alternative. Communities living on densely populated small islands are often short of water because even if the rainfall is plentiful they lack the space to build storage reservoirs. Some of these communities are now supplied with water that is transported from the mainland in huge plastic pouches towed by ships. Icebergs might be transported in much the same way.

Plastic sheeting paid out from a ship would sink under its own weight and would move beneath the chosen iceberg either through the natural movement of sea currents or by being pulled by cables. Tubes along the edges of the sheet would then be inflated, causing the edges to surface and thereby wrapping the underside of the iceberg. More sheeting would then be laid over the top of the iceberg and welded to the lower sheet to make a watertight seal. The iceberg would then be completely enclosed inside a plastic bag and the bag could be towed to wherever the water was needed. There would be no need to hurry, because it would not matter if the ice melted, since it was contained inside a watertight bag. This also means no allowance need be made for losses due to melting and therefore smaller icebergs could be captured. The bag would also prevent contamination of the ice or water by seawater.

The operation would use fuel, so the water would be fairly expensive, but in other respects it would not harm the environment. The plastic could be reused or recycled, and unless all the glaciers and ice sheets melt, which is unlikely in the near future, the supply of icebergs is inexhaustible—icebergs break naturally from the edges of ice sheets and the ends of glaciers. It would be impossible to use icebergs faster than they are produced naturally, because they cannot be removed until they have broken free.

Like the water produced from seawater in desalination plants (see pages 205–207), water from melted icebergs would need to travel from the coast to the regions where it is needed. Transport by pipeline, railroad, or highway would add considerably to the cost, and it might be considered uneconomical to use this source of water to supply people living thousands of miles inland. For those within a few hundred miles, however, icebergs may one day prove a reliable source of clean water for domestic use and for irrigation.

Dry farming

At intervals of about 22 years, the Great Plains of North America suffer drought. Droughts occurred there in the 1950s, 1970s, and 1990s, but the worst droughts of modern times happened in the 1930s. Crops failed, the soil dried to dust, and the wind blew away the soil together with the seeds the farmers had sowed. In the summer of 1934 a cloud of dust three miles (4.8 km) high covered an area of 1.35 million square miles (3.5 million km^2). Dust fell on ships 300 miles (480 km) from shore and birds, choked by the dust, fell dead to the ground. The area of the Great Plains affected by this disaster came to be known as the *Dust Bowl*.

Farmers and agricultural scientists learned the lessons of the Dust Bowl years, and when the rains returned farming methods changed. Some areas were left unplowed to allow the natural prairie grasses to return. Droughts are a natural event and the prairie grasses and herbs are able to survive them, their roots binding the soil together and preventing it from blowing away.

The climate of the Great Plains is dry even outside the drought years. Nevertheless, early European explorers found several Native American tribes farming the land successfully without relying on irrigation. When European settlers began farming the land they used the techniques they had learned farther east, where the climate was wetter, and dug irrigation channels to provide the water their crops needed. In the early years they had to work so hard simply to feed themselves that they had no time to experiment with alternative farming methods. Now and then, however, a reservoir would lose its water or channels would break and an irrigation system would fail. Farmers noticed that when this happened the crop was greatly reduced, but it was not lost entirely.

A breakthrough came early in the 1860s when a group of Scandinavian settlers plowed the land close to what is now Bear River City, Utah. The water they used to irrigate their crops was alkaline and the crops failed. With only poisonous water available to them, the farmers did the only thing they could think of. Sagebrush was growing on the land around their farms. They plowed this land, mixing the sagebrush plants into the soil as they did so, sowed their seeds, and hoped for the best. The experiment succeeded and they harvested a good crop. They had devised their own version of what is now known as *dry farming*.

During the subsequent decades of the 19th century, the possibilities of dry farming were explored more deeply at the agricultural colleges that were being established across America. Dry-farming techniques were developed independently in Utah, California, Washington, and Colorado. Following the Dust Bowl years, dry-farming techniques were adopted over an even wider area. Today dry farming is practiced widely in regions where rainfall is sparse and unreliable. It cannot succeed in a true desert, where even a light shower of rain is a rare event, but it does make farming without irrigation possible in climates with less than about 12 inches (305 mm) of rain a year.

Dry farming begins by selecting a crop that tolerates dry conditions—wheat, for example, rather than potatoes. There are several versions of dry farming, but all of them conserve moisture by tilling the soil thoroughly and including a period during which the land lies fallow. Where possible, the land is plowed in the fall and the seed is sown as soon as the soil has been prepared. Once the crop has been harvested the land is left fallow, commonly for three years. An entire field may be left uncultivated, or crops may be grown in widely spaced strips separated by uncultivated strips, with the cropped strips being moved each year. Wild plants grow on the fallow land, and from time to time these are plowed into the soil. The plants gather moisture, and plowing buries their moist tissues before they have time to lose water by transpiration (see "Why plants need water" on pages 85–86). By the end of the fallow period the partly decomposed wild plants will have released sufficient moisture into the soil to sustain the next crop.

Dry farming is not unique to North America, of course. Farmers in many parts of the world have found ways to grow crops in dry climates without irrigation. Using modern crops, adapted to the climatic conditions, traditional methods of dry farming might be developed further to increase food production and the prosperity of agricultural communities living along the edges of the world's deserts.

Corridor farming

Acacia trees belong to the family Fabaceae, the same plant family as peas, beans, peanuts, soybeans, and lentils. They are all legumes. This means their roots exude chemicals that attract *Rhizobium* bacteria. These bacteria penetrate the fine root hairs and exude another chemical that makes the root grow longer and curl around the bacteria. As the bacterial colony and root both continue to grow, a *nodule* develops on the root. Root nodules are clearly visible among the roots. They look like white or gray "lumps" about the size of the head of a map pin. *Rhizobium* bacteria convert atmospheric nitrogen into soluble nitrogen compounds the plant is able to absorb. Nitrogen is a principal component of all proteins, so it is an essential nutrient. If the soil conditions suit them, the bacteria "fix" much more nitrogen than either the bacteria or their host plant can use, and they excrete the surplus into the soil, where it is available to other plants. In this way, legumes improve the fertility of the soil, reducing substantially the amount of fertilizer farmers need to apply in order to grow other crops on the same or adjacent ground.

Trees of any species also shelter the soil and crop plants from the wind. Farmers often plant trees for this purpose, to make shelterbelts. Wind erosion is a serious problem in dry climates, and belts of trees help reduce erosion. If the trees improve soil fertility at the same time they are doubly useful.

The use of trees to shelter and feed the soil forms the basis of a farming system known as *corridor farming* or *alley cropping.* The trees are grown in rows and the farm crop grown in rows between them. The crop is therefore grown in a tree-lined corridor or alley, hence the name. The crop is sown at the start of the rainy season and harvested as soon as it is ready, but the trees are left to continue growing through the dry season. At the end of the dry season the trees are cut down almost to ground level. This technique, known as *coppicing,* encourages many shoots to grow from the stumps. The system simultaneously produces a conventional farm crop, tree leaves that are fed to livestock when the trees are cut down, and also wood that can be used to make small articles or burned as fuel. Far from injuring the tree, coppicing prolongs its life and makes the tree shorter and bushier, thus increasing the number of shoots and leaves it produces and making it a more effective windbreak.

Several combinations of trees and crops are used. In eastern Rajasthan, India, close to the Thar Desert, farmers grow millet in corridors of *Prosopis cineraria* trees, known locally as *khejri* or *jandi.* In the Sahel region and the dry areas of East Africa the apple-ring acacia, also known as winter thorn and camel thorn (*Alhagi maurorum*), grows beside other cereal crops. In some parts of the Middle East mung beans (*Vigna radiata*) are grown beside the umbrella thorn or Israeli babool (*Acacia tortilis*)—this is the tree historians believe may have supplied the wood to make the biblical Ark of the Covenant. *Prosopis* and *Faidherbia* are small leguminous trees closely related to *Acacia.*

Apple-ring acacia is especially useful, because it has the unusual habit of bearing leaves throughout the dry season and shedding them at the start of the rainy season. Animals are able to feed on its leaves and shoots through the dry season when food is scarce. The cut branches of this tree can also be stored without losing their nutritional value for livestock.

Corridor farming was first developed for the humid tropics, where it prevents soil erosion, especially on steep hillsides, but it has also proved highly successful in dry climates. It is a technique that allows farmers to raise plant crops and livestock together. It improves the land, reduces erosion, and increases agricultural output—and therefore contributes to the prosperity of farming communities.

New crops for dry climates

Biologists believe there are approximately 270,000 species of plants. We cultivate only a tiny proportion of all those species. Members of the grass family (Poaceae) provide most of our staple foods. There are about 9,000 grass species, but we use only about two dozen of them—wheat (four species), oats, rye, barley (two species), rice (two species), corn (maize), sugarcane, millet (about 10 species), and sorghum. The bean family (Fabaceae) is even larger, with about 16,400 members. Beans are rich in proteins, making them highly nutritious, but we grow only about two dozen species—beans (about nine species), broad beans, jack beans, peas, asparagus peas, cowpeas, lablab, soybeans, lentils, peanuts, pigeon peas, chickpeas, bambarra groundnut, and alfalfa and clover, which are grown to feed livestock.

Most of these crop plants are difficult to grow in dry climates because they require abundant water, and scientists are exploring alternatives—crops for the desert. So far they have found several. Some are already cultivated locally but could be grown more widely. Others are wild plants that might be domesticated.

Love-lies-bleeding (*Amaranthus caudatus*) is a popular garden plant that is also known as cattail, tumbleweed, and Inca wheat. Its edible seeds are rich in protein, and amaranths are among the few plants (soybean is another) that contain the amino acid lysine, an essential nutrient for humans. Amaranths grow naturally in Central and South America and were cultivated for their seeds until imported cereals displaced them. Prince's feather (*A. hypochondriacus*), native to Mexico, has edible leaves as well as seeds.

Echinochloa species resemble rice and millet and have names like jungle rice, Shama millet, Japanese millet, and paddy-rice mimic weed. As the last name suggests, some are troublesome weeds. Channel millet (*E. turnerana*) is different. It produces highly nutritious seeds and grows well with just one watering, making it potentially valuable as a crop for dry climates. Channel millet grows wild in Australia.

An Andean plant called quinoa, or quinua (*Chenopodium quinoa*), is one of the richest sources of plant protein. Like the amaranths, quinoa was grown for its seeds until imported

Genetic modification

Most physical characteristics of living organisms are determined by the *genes* that are contained in the *chromosomes* present in the nucleus of almost all cells. Genes consist of strings of deoxyribonucleic acid (DNA) arranged in two complementary strands that are wound together in a spiral. When cells divide, the two strands of DNA separate, molecules present in the cell attach themselves to the unpaired strands to reconstitute the spiral pair, and both daughter cells receive a full set of the chromosomes carrying the genes. A chromosome contains many genes joined end to end and interspersed with sections of DNA that carry no genetic information. When plants or animals reproduce, each parent contributes a set of single DNA strands, which combine to produce a paired set in the offspring.

Traditionally, plant breeders develop new varieties by choosing individual plants that possess desirable characteristics and breeding them with members of an existing variety, in the hope of transferring the desirable traits into the resulting offspring. The breeders then cross the offspring with one another or with one of their parents. This process must be repeated many times before the new variety is ready to be grown commercially. Since it involves breeding, obviously it works only among members of the same species.

Breeders also induce *mutations*—genetic changes—to produce entirely new characteristics. They do this by exposing plants to chemicals known to induce mutations or by bombarding them with radiation. It is a hit-or-miss process, but if a useful characteristic appears it can be transferred to other varieties by conventional breeding.

In the 1970s scientists learned how to identify the genes or sets of genes responsible for particular traits, to remove those genes from the cells of one organism, and to insert cereals displaced it, and it is still grown locally in the mountains of Bolivia, Chile, Ecuador, and Peru. Its seeds are enclosed in an outer layer that is extremely bitter. Probably a defense against insects and birds, this feature might make the plant easy to grow with little need for insecticide, and washing removes the bitter flavor.

Buffalo gourds, also known as mock orange and chilicote (*Cucurbita foetidissima*), are rich in oils as well as protein (and their roots have laxative properties). They grow in the dry wastelands of the southwestern United States and Mexico and are highly tolerant of drought. They are also productive. A single plant can produce an average of 60 fruits containing

them into the DNA of another organism. This is called *genetic modification,* or *genetic engineering.*

For example, modern varieties of wheat and rice are much shorter than older varieties. This allows them to support heavier heads of grain without falling over, or *lodging,* when they are battered by wind and rain. These varieties were bred by traditional methods in breeding programs that lasted for many years. The same result could be achieved much more quickly today by identifying the gene that makes particular plants short stemmed, extracting it, and inserting it into plants that produce heavy heads of grain.

As well as being quicker than traditional breeding, genetic modification is much more precise. Traditional breeding transfers thousands of genes from one organism to another. If some of those genes confer undesirable characteristics, further breeding is needed to remove them. Genetic modification manipulates just one or a few genes with known properties.

Genetic modification takes several forms. It may increase or decrease the activity of certain genes without transferring genes from one organism to another. If it does involve transferring genes, the transfer may be between members of the same species or between members of similar but distinct species. It may also involve transferring genes between wholly unrelated organisms. Some crop varieties have been genetically modified by inserting into their DNA a gene from a bacterium, *Bacillus thuringiensis.* This gene causes the cell to produce a substance that is poisonous to insect pests. *Bt plants,* as these are known, produce their own insecticide, rendering them resistant to pest attack. The insecticide has been used for many years, by spraying crops with a *Bt* bacterial culture, but genetic modification does away with the need for spraying and greatly reduces the amount of insecticide entering the environment.

2.5 pounds (1.15 kg) of seeds. In addition to its fruits, the buffalo gourd grows a starchy underground tuber in which it stores water. After two growing seasons the tuber weighs approximately 70 pounds (32 kg) and contains as much starch as 20 potato plants grown in moist, well-drained soil.

Clearly there are many little-known plants that have great potential as crop plants in dry regions. Not all of these are food plants. Vetiver, also known as khus and cuscus (*Vetiveria zizanoides*), is a tropical grass, looking much like pampas grass, which grows in India. Its dried roots give off a pleasant perfume when watered. They are woven into items such as mats and baskets and used in scent making. An immensely tough plant that can survive sunshine, shade, snow, and even immersion in water, vetiver also grows in deserts. Rows of it, planted on hillsides parallel to the contours, would quickly merge to make a screen strong enough to check the movement of soil, thus preventing erosion.

Searching for plants that might thrive in a desert environment is a slow, labor-intensive business with no guarantee of success. An alternative is to modify existing plants to help them tolerate harsh conditions. Many desert soils are salty, some because they are the beds of seas that dried up long ago and others because faulty irrigation systems have led to salination (see “Waterlogging and salination” on pages 173–175). Plants known botanically as *halophytes*—“salt lovers”—flourish in salt soils. If their ability to tolerate salt can be bred into useful crop plants, farming could expand into those saline soils. Some plants survive drought better than others, and if crop plants could acquire those drought-resistant characteristics there would be less need for irrigation on desert farms. That would reduce the cost of crop production.

Plant breeders have been working for many years to produce such crop varieties. Conventional plant breeding is slow, however. The plants must be grown and crossed with one another for many generations in order to establish the desired features securely—so they will not disappear in subsequent generations—in a commercial plant variety. Today techniques of genetic modification (see the sidebar on pages 214–215) greatly reduce the time this takes. At the same time, genetic modification offers still wider opportunities to transfer desirable and heritable traits between plants of different species and even to insert into cultivated plants traits taken from organisms that are not plants at all.

So far, genetic modification has been used principally to develop crops that are more resistant to insect pests and that can be grown with less use of herbicides. In years to come there will be crops that are modified to produce nutritious food on land that today cannot be farmed at all.

Food from the polar regions

Along the northern fringes of North America and Eurasia there is an environment equivalent to the semiarid borders of low-latitude deserts such as the Sahara. The climate is dry and strongly seasonal. The dry season is the long winter, when all of the water is frozen. In summer the ground surface thaws and water is available, but the summer is brief. The vegetation consists of scattered shrubs, just a foot or two (up to 60 cm) tall, growing in hollows where they are sheltered from the drying effect of the incessant wind. There are grasses, sedges, and lichens, but also large expanses of bare rock and gravel. This is the *tundra,* a name derived from *tundara,* the Sami word for a treeless plain where below the surface the ground remains frozen throughout the year. (Sami, or Lapp, is a language spoken in northern Finland, Sweden, and Norway, and on the Kola Peninsula in Russia.) The permanently frozen layer is called *permafrost.*

Traditionally, the people of the tundra lived a seminomadic life very similar to that of the Bedouin and other desert tribes. They owned herds of caribou, known in Europe as reindeer (*Rangifer tarandus*). In summer the herds grazed in the tundra and in winter they migrated southward, to the edges of the *taiga*—the belt of coniferous forest that stretches across northern Canada and Eurasia. Their owners lived in conical tents made from reindeer hides. In southern Greenland there are sheep farmers who live a settled life similar to that of farmers tilling the land around the oases found in deserts far to the south.

The nomadic way of life is slowly breaking down in the far north, just as it is in other parts of the world. The change is due not to droughts and political troubles, as it is along the border of the Sahara, but to the gradual spread of industry and the rapid expansion of modern communications. Mining companies provide employment and attract local people to the settled way of life that it brings. Governments provide schools, hospitals, and other services that encourage people to settle in villages, and modern communications—TV and the Internet—bring people into contact with the wider world and show them alternative ways of life. When young people grow up they leave to seek their fortunes elsewhere.

In the high Arctic, to the north of the tundra, no plants grow on the bare rock and ice, but food is plentiful in the sea. There are fish, seals, walruses, birds, and whales. It is very unlikely that these resources can be exploited more intensively than they are now or that they can be enhanced. The traditional demand for local use is limited, but there is also a much wider demand for fish. Iceland and Greenland are heavily dependent on their fisheries. These were formerly based on cod (*Gadus morhua*) and capelin (*Mallotus villosus*), but like all the other North Atlantic species these have been overexploited, and catches are now restricted to conserve the stocks.

Fishing fleets also visit Antarctic waters. Antarctic cod (*Notothenia coriiceps*), not closely related to the true cod species found only in the Northern Hemisphere, was once abundant but was fished almost to extinction. Icefish (*Chaenocephalus aceratus*), related to the cods, has also been fished very heavily. It is unlikely that the Southern Ocean will yield more food than it does now.

Krill (see “Animals of the Antarctic” on pages 124–125) are extremely abundant around the shores of Antarctica. There are believed to be 66 million–170 million tons (60–155 million tonnes) of *Euphausia superba,* the most numerous species, and in 1972 fishing fleets began hunting them in earnest. By the middle 1970s the fleets, mainly from the Soviet Union and Japan, were catching approximately 550,000 tons (500,000 tonnes) a year. Then the catch began to decrease. Today the annual catch is about 110,000 tons (100,000 tonnes) a year, caught mainly by ships from Japan and Poland.

Catching krill was easy. The animals feed on the algae growing on the underside of the sea ice. Consequently, they are found close to the edge of the ice. The problem was utilizing them. Their shells contain high concentrations of fluorine, making them dangerous to eat unless the shells are removed before the meat is used, and the meat does not keep. Enzymes in the gut of the krill degrade the meat, rendering it unfit to eat. These problems have been overcome in recent years, raising the possibility of expanding the krill fishery, and new uses have been found for the enzymes that degrade the meat. They can now be made into medicines used to treat a number of illnesses, including cancer and gangrene. Krill are also fed to fish raised in fish farms and suitably processed krill is an ingredient in some prepared fish dishes.

Apart from krill, however, it is unlikely that the polar deserts or the seas around them will become a major source of food in years to come.

Conflicts over water resources

Water is a precious commodity to people who live in or near a desert. Without water life cannot continue. Farmers need it to produce food, manufacturing industries need it, and people need it in their homes. It is not surprising that competition for scarce water resources has led to conflict many times in the past or that water and access to it has been used as a weapon of war.

Lebanon, Syria, Israel, and Jordan all depend on water drawn from the Jordan River and its tributaries. In 1951 Jordan announced plans to use water from the Yarmūk River, one of the principal tributaries entering the Jordan from the east, to provide irrigation in the Jordan Valley. This would reduce the amount of water entering the Jordan. Israel responded by draining marshes close to the Israeli-Syrian border, leading to border clashes between Israeli and Syrian troops. In the following years Israel planned a scheme to divert water from the Jordan to irrigate farms in the Negev; Jordan and Syria planned to dam the Jordan near its source, and Israeli forces destroyed the construction site; and in 1969

Israel destroyed a Jordanian canal carrying Jordan water. Access to water resources has since been agreed between Israel, Syria, and Jordan, but it remains one of the most contentious issues standing in the way of a settlement of the conflict between Israel and Palestine.

Egypt depends upon water from the Nile (see "Egypt" on pages 132–134). The Nile has two branches, the Blue Nile and the White Nile, which join at Khartoum, Sudan. The Blue Nile rises in Ethiopia, and in 1978 the Ethiopians proposed to dam the river to provide water for irrigation. This almost led to war, and Egypt continues to threaten Ethiopia with retaliation if that country diverts water from the Blue Nile without discussing the matter first.

Turkey is constructing a series of dams, hydroelectric plants, canals, and irrigation systems as part of its Southeast Anatolia Project. The first stages in the project became operational in 1992. When completed it will divert approximately half of the water flowing through the Euphrates, reducing the amount of water entering Iraq and Syria to less than half its present flow. This also provides Turkey with a powerful weapon. The Turkish government has threatened to cut off the water supply to Syria unless it ends its support for Kurdish rebels operating in southern Turkey.

There have also been fights within countries. In September and October 2002 riots broke out in the states of Karnataka and Tamil Nadu, India, over allocation of water from the Kāveri River which crosses the border between them.

Such disputes are far from new. In about 2500 B.C.E. Urlama, king of the city of Lagash (in Sumer, the land lying between the Euphrates and Tigris), deprived the city of Umma of its water supply by diverting water into ditches. Urlama's son, Il, later cut off the supply to Girsu, another city.

Sometime around 1700 B.C.E., rebels led by Iluma-Ilum declared the independence of Babylon from Sumerian rule. In the resulting fighting the Sumerian king, called Abish or Abi-Eshuh, dammed the Tigris River to block the retreat of the rebels. Babylon was destroyed in 695 B.C.E. The city was then part of the Assyrian Empire and had rebelled. Having razed the city, the Assyrian king, Sennacherib, diverted one of its principal irrigation canals to allow water to wash over the ruins. Babylon recovered and established its own empire, and between 605 B.C.E. and 562 B.C.E. the Babylonian king Nebuchadrezzar used the Euphrates and canals taking water from it to make defensive moats around the huge ramparts of the city.

Water has been a weapon of war and a source of conflict between neighbors for thousands of years, but it has also been the subject of many international treaties. Approximately 3,600 such agreements have been reached between rulers or governments since 805 C.E. Most of those negotiated prior to the early 19th century related to rights of navigation, fishing rights, or boundaries. Some of those agreed since then have dealt with water itself and the right of access to it.

Today the United Nations provides a forum where disputes over water resources can be resolved. Agreements are usually made under the auspices of the UN Environment Program (UNEP), the Food and Agriculture Organization (FAO), or the World Bank. In May 1997 the UN General Assembly adopted the UN Convention on the Law of the Non-navigational Uses of International Watercourses. This is now the principal statement of international law regarding the management of water resources.

The need for agreement has never been more urgent. More than 1.7 billion people, living in more than 80 countries, experience water shortages some or all of the time. Although the size of the global population is stabilizing, the number of people living in many desert lands is likely to continue increasing for some time to come. This will increase the pressure on water supplies. At the same time the fact that 150 of 200 major river systems in the world are shared by two nations and that 50 are shared by 10 shows there is a very real risk of war over water resources.

We must hope that sense and good will prevail and that plans are implemented to use scarce water more efficiently. The world's arid lands may then enjoy peace and prosperity.

CONCLUSION

What future for deserts?

Deserts are barren, inhospitable places. The very word conjures an image of featureless sand dunes stretching beautiful but terrible for as far as the eye can see. Elsewhere the desert surface is made of bare rock and gravel. The wind is incessant, blowing dust that stings as it strikes the skin and sometimes generating dust storms that turn day into night and drive the dust through clothing, through doors and windows, and into every corner. Temperatures range from the scorching heat of midday to the bitter cold of the hours before dawn. And water is the most precious of all commodities. Other deserts are icy wildernesses, no less windy and arid—despite the snow and ice that covers the ground and the screaming blizzards of blown snow that reduce the world to a uniform whiteness.

Yet there is a surprising amount of life in these harshest of environments. No plants grow on the shifting sand of the dunes because their roots can find no anchorage, but there are plants in most other parts of the desert. Some survive as seeds that germinate when it rains, blanketing the desert with green leaves and brilliant flowers and completing their life cycle from seed to seed before the ground dries once more. Other plants store water in their tissues or become dormant during the driest part of the year. There are animals that avoid the excesses of heat and cold and use water so economically that some of them never need to drink. Even in the cold deserts of the Arctic and Antarctica the seas teem with living organisms. Deserts, both hot and cold, are also home to peoples who have found ways to thrive in them.

There is much we can learn from the ways in which plants, animals, and people have adapted to desert life, and the information we acquire will be very useful. If the characteristics that enable desert plants to survive heat, drought, and salt-laden soils could be transferred to crop plants, for example, large expanses of land on the edges of deserts might be cultivated sustainably. That would reduce the risk of soil erosion due to overgrazing and overcultivation. The adaptations developed by desert peoples might help many more people learn to use water more sparingly in those parts of the world where freshwater is in short supply. The physiological adaptations that allow desert animals to remain healthy in extreme conditions might provide medical scientists with information that could be used in treating human patients.

Traditional ways of desert life are disappearing, however, and the day may soon come when the last of the nomadic pastoralists have settled in villages. In the north the Inuit peoples now have permanent homes, although some continue to hunt and fish for food. Villages provide medical centers, schools, shops, and other amenities, and they often attract companies offering jobs. These represent improved living standards and wider opportunities for young people. There may be little time left for us to learn about the old ways from individuals who have lived them.

Desert plants and animals are not threatened, however. If the world is growing warmer, it is possible that some of the low-latitude deserts, such as the Sahara, will shrink in size. This will happen (if it does) because a warmer climate will allow the ITCZ (see “Monsoons” on pages 58–62) to move farther from the equator, bringing the equatorial rains to what are now the margins of deserts. The deserts are unlikely to disappear, however.

Continental and west coast deserts exist because of their locations. No matter what happens to the climate, air will still cross a continent before reaching them, losing its moisture as it does so. Those regions will remain arid.

All predictions of climate change agree that warming will affect the polar regions first and most strongly. Temperatures have already risen in Alaska, Yukon, and northeastern Siberia, and the Antarctic Peninsula is markedly warmer than it was decades ago (although much of the interior of Antarctica is colder). If this trend continues it may reduce the area of polar desert by allowing more species to establish themselves in places that at present are too cold and dry for them.

Deserts are part of our world. Harsh and unforgiving, they nevertheless harbor highly adapted species of plants and animals; desert species have evolved strategies and physiological modifications that enable them to meet the challenges of extreme temperatures and absence of water. At the same time, the deserts remind us of our own dependence on the rain that waters the crops that feed us.

SI UNITS AND CONVERSIONS

UNIT	QUANTITY	SYMBOL	CONVERSION
Base units			
meter	length	m	1 m = 3.2808 feet
kilogram	mass	kg	1 kg = 2.205 pounds
second	time	s	
ampere	electric current	A	
kelvin	thermodynamic temperature	K	1 K = 1°C = 1.8°F
candela	luminous intensity		
mole	amount of substance	cd	mol
Supplementary units			
radian	plane angle	rad	$\pi/2$ rad = 90°
steradian	solid angle	sr	
Derived units			
coulomb	quantity of electricity	C	
cubic meter	volume	m^3	1 m^3 = 1.308 $yards^3$
farad	capacitance	F	
henry	inductance	H	
hertz	frequency	Hz	
joule	energy	J	1 J = 0.2389 calories
kilogram per cubic meter	density	kg m^{-3}	1 kg m^{-3} = 0.0624 lb. $ft.^{-3}$
lumen	luminous flux	lm	
lux	illuminance	lx	

(continues)

(continued)

UNIT	QUANTITY	SYMBOL	CONVERSION
meter per second	speed	m s^{-1}	1 m s^{-1} = 3.281 ft s^{-1}
meter per second squared	acceleration	m s^{-2}	
mole per cubic meter	concentration	mol m^{-3}	
newton	force	N	1 N = 7.218 lb. force
ohm	electric resistance	Ω	
pascal	pressure	Pa	1 Pa = 0.145 lb. in^{-2}
radian per second	angular velocity	rad s^{-1}	
radian per second squared	angular acceleration	rad s^{-2}	
square meter	area	m^2	1 m^2 = 1.196 $yards^2$
tesla	magnetic flux density	T	
volt	electromotive force	V	
watt	power	W	1W = 3.412 Btu h^{-1}
weber	magnetic flux	Wb	

Prefixes used with SI units

PREFIX	SYMBOL	VALUE
atto	a	$\times 10^{-18}$
femto	f	$\times 10^{-15}$
pico	p	$\times 10^{-12}$
nano	n	$\times 10^{-9}$
micro	μ	$\times 10^{-6}$
milli	m	$\times 10^{-3}$
centi	c	$\times 10^{-2}$
deci	d	$\times 10^{-1}$
deca	da	$\times 10$
hecto	h	$\times 10^{2}$
kilo	k	$\times 10^{3}$
mega	M	$\times 10^{6}$

PREFIX	SYMBOL	VALUE
giga	G	$\times 10^{9}$
tera	T	$\times 10^{12}$

Prefixes attached to SI units alter their value.

GLOSSARY

ablation the removal of snow and ice by melting and by SUBLIMATION

adiabatic a change in temperature that involves no exchange of heat with an outside source

adobe clay found in deserts that is used as a building material

aklé dune a sand dune in the form of a long, wavy ridge at right angles to the wind; the crescent-shaped sections alternately face into the wind (linguoid) and away from the wind (barchanoid)

albedo the reflectiveness of a surface to light, measured as the percentage of light reflected

alluvial pertaining to rivers

anabatic describes a wind that blows up the side of a hill

andhis *see* SIMOOM

angle of repose the maximum degree of slope at which a pile of dry, loose grains remains stable; it is typically between 32° and 36°

anticyclone a region in which the atmospheric pressure is higher than it is in the surrounding air

aphelion the point in its orbit at which the Earth is farthest from the Sun

aquifer an underground body of permeable material (such as sand or gravel) lying above a layer of impermeable material (such as rock or clay) that is capable of storing water and through which the GROUNDWATER flows

arroyo (donga, wadi, ouadi) a dry river valley with steep sides and a flat floor

artesian well a well that flows without pumping because it taps into water held under pressure in an AQUIFER that is contained by layers of impermeable material above and below

asthenosphere the upper part of the MANTLE, in which the rocks are slightly plastic and deform under pressure

barchan a crescent-shaped sand dune that forms where the wind blows mainly from one direction; the crescent faces into the wind with the tails pointing downwind

barchanoid pertaining to a BARCHAN dune. *See* AKLÉ DUNE.

blackbody a body that absorbs all of the radiation falling upon it and emits all of its absorbed radiation at a wavelength inversely proportional to its temperature

blubber a thick layer of fatty tissue lying beneath the skin of whales and seals; it provides thermal insulation

boundary current an ocean current that flows northward or southward close to the coast of a continent and parallel to it. In the Northern Hemisphere, eastern boundary currents carry cold water southward on the eastern side of ocean basins (not along the eastern coasts of continents), while western boundary currents carry warm water northward on the western side of ocean basins

butte an isolated, flat-topped hill, made by the erosion of horizontal layers of sedimentary rock

caravan a group of camels or vehicles crossing a desert together

caravansary a facility providing secure overnight accommodation for CARAVANS and those traveling with them

carboxylation a chemical reaction in which a molecule gains a carbon atom

chelicera (pl. chelicerae) one of the appendages resembling claws possessed by spiders and scorpions

chlorophyll the pigment present in the leaves and sometimes stems of green plants that gives them their green color. Chlorophyll molecules trap light, thus supplying the energy for PHOTOSYNTHESIS

chloroplast the structure in plant cells that contains CHLOROPHYLL and in which PHOTOSYNTHESIS takes place

clay mineral material consisting of particles smaller than 0.00008 inch (0.002 mm) that stack together. A clay soil contains at least 20 percent of clay particles by weight

climatic optimum a period during which average temperatures are higher than in the preceding and succeeding periods

cloud seeding dropping particles of solid carbon dioxide, silver iodide, or some other substance into a cloud in order to make rain or snow fall

continental drift the movement of the continents in relation to one another across the Earth's surface

convection the transfer of heat by vertical movement within a fluid

core temperature the temperature inside an animal's body, deep below the surface

countercurrent exchange the exchange of heat between blood traveling in opposite directions through arteries and veins that lie side by side. This chills blood flowing away from the center of the body and warms blood returning to the heart

crop milk *see* PIGEON MILK

cutaneous respiration the exchange of respiratory gases through the skin. Amphibians (such as frogs, toads, salamanders) have skins that allow gas molecules to pass through, and a significant proportion of their RESPIRATION takes place through the skin

cyclone *see* depression

deflation the removal of surface material (such as dry soil or sand) by the wind

deposition the changing of water vapor directly to ice, without passing through a liquid phase

depression (cyclone) a region along a weather front where the atmospheric pressure is lower than it is in the surrounding air

desalination the purification of salt water by the removal of salt to render it fit for use in irrigation or to drink

desertification the deterioration of land until its quality is similar to that of desert

desert pavement (rock pavement) a thin layer of gravel or small stones that covers the surface of an area of desert

desert rose a petal-shaped rock, sometimes resembling a rose, that results from chemical reactions in calcite (calcium carbonate) and gypsum (calcium sulfate) minerals

desert varnish a thin, dark-colored layer of iron and manganese oxides that forms on exposed rock surfaces in hot deserts

dew-point temperature the temperature at which water vapor condenses to form dew or cloud droplets

diurnation a period of dormancy into which an animal enters for part of the day

donga *see* ARROYO

draa a ridge of sand or chain of sand dunes, more than 1,000 feet (300 m) high, lying some distance from its nearest neighbor, that is found in the Sahara

dry adiabatic lapse rate *see* LAPSE RATE

eccentricity the extent to which the orbit of a planet, satellite, or other body departs from a circle

ecliptic the plane of the Earth's orbit about the Sun

ectotherm an animal that maintains a constant body CORE TEMPERATURE by behavioral means, such as by basking in warm sunshine to warm up and seeking shade to cool down

El Niño a weakening or reversal of the prevailing easterly winds over the tropical South Pacific Ocean that happens at intervals of two to seven years. This weakens the wind-driven surface ocean current, allowing warm water to accumulate off the South American coast and producing weather changes over a large area

endotherm an animal that maintains a constant body CORE TEMPERATURE by physiological means, such as by dilating or contracting blood vessels in the skin, shivering, and sweating

ENSO the full cycle of EL NIÑO and its opposite, La Niña, associated with the SOUTHERN OSCILLATION

equinox March 20–21 and September 22–23, when the noonday Sun is directly overhead at the equator and day and night are of equal length everywhere in the world

estivation a period of dormancy into which an animal enters to escape a period of hot or dry weather

exotherm *see* POIKILOTHERM

false color unnatural color used in some satellite images to enhance the difference between types of surface, such as between vegetation types or between seawater and ice. Vegetation often appears red in false color images

GDP *see* GROSS DOMESTIC PRODUCT

greenhouse effect the absorption and reradiation of longwave radiation emitted by the Earth's surface by molecules of water vapor, carbon dioxide, ozone, and several other "greenhouse gases," warming the air

gross domestic product (GDP) the value of all the goods and services produced within a country during a specified time (usually one year)

groundwater underground water that flows through an AQUIFER

gyre the approximately circular path followed by the surface currents in all the oceans

halophyte a plant that tolerates salt

harmattan a moderate or strong, hot, dry, dusty wind that blows during the day across West Africa south of the Sahara

heliostat a mirror, driven by a motor so it tracks the Sun, that reflects solar radiation and focuses it onto a small area in order to generate high temperatures

hibernation a state of dormancy into which an animal enters to avoid a period of winter cold

homeotherm an animal that maintains a constant body CORE TEMPERATURE either by behavioral (an ECTOTHERM) or physiological (an ENDOTHERM) means

humidity the amount of water vapor present in the air

humus decomposed plant and animal material in the soil

hydrogen bond a chemical bond between hydrogen and nitrogen, oxygen, and fluorine. Hydrogen bonds link water molecules in the liquid and solid phases and also occur in a range of other compounds

igneous describes a rock formed when molten MAGMA cools and solidifies

infrared radiation electromagnetic radiation with a wavelength from 0.7 μm to 1 mm (1 μm is equal to one millionth of one meter)

inselberg a steep-sided, isolated hill standing on a plain (the name is German for "island hill")

isostasy the theory that there is a constant mass of rocks above a certain level below the Earth's surface. If the volume of rock is greater in one place than in another, such as where rocks form a mountain, then that rock and the mountain's roots will be less dense than the thinner, denser crust beneath

jet stream a winding ribbon of strong wind about 5–10 miles (8–16 km) above Earth's surface. Jet streams are typically thousands of miles long, hundreds of miles wide, and several miles deep

katabatic describes a cold wind that blows downhill

khamsin a hot, dry wind that blows in Egypt and Sudan

La Niña *see* ENSO

lapse rate the rate at which the air temperature decreases (lapses) with increasing altitude. In unsaturated air the dry *adiabatic* lapse rate is 5.38°F per thousand feet (9.8°C per km); in saturated air the saturated adiabatic lapse rate varies, but it averages 2.75°F per thousand feet (5°C per km)

latent heat the heat energy that is absorbed or released when a substance changes phase between solid and liquid, liquid and gas, and solid and gas. For water at 32°F (0°C) the latent heat of melting and freezing is 80 cal. per gram (334 joules per gram); of vaporization and condensation 600 cal. per gram (2,501 J per gram); and for SUBLIMATION and DEPOSITION 680 cal. per gram (2,835 J per gram)

leads areas of open water in a sea otherwise covered with ice

lifting condensation level the altitude at which the air is at the DEW-POINT TEMPERATURE and water vapor begins to condense to form cloud; the lifting condensation level marks the cloud base

linguoid *see* AKLÉ DUNE

lithosphere the uppermost part of the solid Earth, comprising the crust and upper MANTLE

Little Ice Age a period lasting from the 16th century until the early 20th century during which temperatures throughout the world were lower than they were before or have been since

magma hot, molten rock from the base of the Earth's crust and the upper part of the MANTLE

mandible in vertebrate animals, the lower jaw; in birds, strictly the lower jaw and bill but often applied to both upper and lower parts of the bill. In arthropods (such as insects, spiders, scorpions, crustaceans), part of the mouthparts used to seize and cut food items

mantle that part of the Earth's interior lying between the outer edge of the inner core and the underside of the crust

mesa a wide, flat-topped hill

mesophyll the tissue lying just below the surface of a leaf, where PHOTOSYNTHESIS takes place

monsoon a reversal in wind direction that occurs twice a year over much of the Tropics, producing two seasons with markedly different weather

mushroom rock *see* PEDESTAL ROCK

nilometer a device invented in ancient Egypt that monitors the level of water in the Nile River, allowing the seasonal flood to be predicted accurately

oasis a region in a desert where the WATER TABLE lies close enough to the surface for plant roots to obtain moisture

obliquity the extent to which the Earth's rotational axis is tilted with respect to the plane of the ECLIPTIC

occlusion the stage in the life cycle of a frontal weather system at which advancing cold air has pushed beneath warmer air and begun to lift the warm air clear of the surface

orogeny mountain building

osmosis the movement of water or some other solvent through a partially permeable membrane from a region of low SOLUTE concentration to a region of high solute concentration until the solutions are at equal concentration on both sides of the membrane

ouadi *see* ARROYO

parabolic dune a crescent-shaped sand dune in which the wind blows into the hollow part of the crescent and the tails of the crescent point in the direction from which the wind blows

partial pressure in a mixture of gases such as air, that part of the total pressure that can be attributed to one of the constituent gases. For example, air consists of approximately 79 percent nitrogen and 21 percent oxygen; if the air pressure is 1,000 millibars (mb) then the partial pressure of oxygen is 210 mb

pastoralist an individual who leads a seminomadic life herding livestock from one area of seasonal pasture to another, deriving a living from the products of the livestock

pedestal rock (mushroom rock) an unstable, mushroom-shaped rock most often found in deserts or semiarid regions; it forms through chemical reactions that dissolve minerals from regions in the rock where moisture is retained

pedipalps in arachnids (such as spiders, scorpions, mites, etc.), appendages at the front of the body used to kill and manipulate prey, and also for defense and digging. Pedipalps are sensitive to touch and chemicals (equivalent to the senses of taste and smell). In arachnids with large CHELICERAE (such as spiders) the pedipalps are also used as walking legs; in those with small chelicerae (such as scorpions) the pedipalps are large and used in hunting

perihelion the point in the Earth's orbit when it is closest to the Sun

permafrost permanently frozen ground. To become permafrost the ground must remain frozen throughout a minimum of two winters and the summer between

permeability the ability of a material to allow water to flow through it

phloem tissue through which the products of photosynthesis and hormones are transported from the leaves to all parts of a vascular plant

phosphorylation a chemical reaction in which phosphate (PO_4) is added

photorespiration a reaction in which rubisco, the enzyme responsible for capturing carbon dioxide during PHOTOSYNTHESIS, instead captures oxygen, triggering a chain of reactions that release carbon dioxide but without releasing any energy

photosynthesis the sequence of chemical reactions in which green plants and cyanobacteria use sunlight as a source of energy for the manufacture (synthesis) of sugars from hydrogen and carbon, obtained from water and carbon dioxide, respectively. The reactions can be summarized as:

$$6CO_2 + 6H_2O + \textit{light} \rightarrow C_6H_{12}O_6 + 6O_2\uparrow$$

The upward arrow indicates that oxygen is released into the air; $C_6H_{12}O_6$ is glucose, a simple sugar

pigeon milk (crop milk) a highly nutritious liquid produced from the lining of the crop in all pigeons (males as well as females) and fed to the chicks

plasmodesmata passageways in the MESOPHYLL of plants through which the initial four-carbon compound moves in the C4 pathway of PHOTOSYNTHESIS

plate tectonics the theory holding that the Earth's crust comprises a number of rigid sections, or plates, that move in relation to one another

playa (salina, sabkha) a low-lying plain with a surface covered by salt formed by the evaporation of a lake

poikilotherm (exotherm) an animal that is unable to control its body CORE TEMPERATURE, which is therefore equal to the temperature of its surroundings

polar front the boundary between tropical and polar air

porosity the percentage of the total volume of a material that consists of spaces between particles

postabdomen the hind part of the abdomen that a scorpion carries raised over its back; its "sting"

process water water used during an industrial process that becomes incorporated in the product

purchasing power parity GROSS DOMESTIC PRODUCT per person, corrected for overvaluation or undervaluation of the local currency by pricing a basket of goods and services first in the local currency and then in U.S. dollars. This yields a fairly true valuation of the local currency against which the GDP is adjusted

qanat an artificial underground watercourse, built in a desert to collect and transport water for irrigation

rain shadow the drier climate on the lee (downwind) side of a mountain range caused by the loss of moisture as air approaching the mountains is forced to rise, whereupon its water vapor condenses and falls as rain or snow on the windward slopes. Once past the mountains, the air subsides and contracts, and this compression raises the temperature of the subsiding air, further reducing its RELATIVE HUMIDITY

reg a stone-covered desert surface, often consisting of rounded pebbles

relative humidity the amount of water vapor present in air at a particular temperature expressed as the percentage of the water vapor needed to saturate the air at that temperature

respiration the sequence of chemical reactions in which living cells oxidize carbon in sugar to release energy; the opposite of PHOTOSYNTHESIS. The reactions can be summarized as:

$$C_6H_{12}O_6 + 6CO_2 \rightarrow 6CO_2 + 6H_2O + \textit{energy}$$

$C_6H_{12}O_6$ is glucose, a simple sugar

reverse osmosis a method for removing salt from water by applying sufficient pressure to drive water molecules through a partially permeable membrane from the stronger to the weaker solution, the opposite direction to that in OSMOSIS

rock pavement *see* DESERT PAVEMENT

sabkha *see* PLAYA

salina *see* PLAYA

salination the accumulation of salts in the upper soil, eventually rendering the soil infertile

sand mineral particles, commonly of quartz (silicon oxide) from 0.002 to 0.079 inches (0.05–2 mm) in size

saturated adiabatic lapse rate *see* LAPSE RATE

saturation the condition in which the moisture held by a substance is at a maximum. Saturated air holds as much water vapor as is possible at that temperature; if more water vapor is added an equivalent amount will condense into liquid

saturation vapor pressure the VAPOR PRESSURE at which water vapor saturates a layer of air at a given temperature lying immediately above an open water surface

seafloor spreading the theory that the ocean floor is created at ridges where MANTLE material rises to the surface and the crustal rocks move away from the ridges on either side, causing the ocean basin to widen as the seafloor spreads

seif dune a long sand dune with a wavy crest and an equal angle of slope on both sides; it can extend for hundreds of miles. Seif dunes typically form by the extension of the arms of BARCHAN dunes

silt mineral particles 0.000000079–0.000002 inch (0.002–0.05 μm) in size

simoom (andhis) a hot, dry, usually dusty wind that blows in spring and summer across the southeastern Sahara and the Arabian Peninsula

soil horizon a horizontal layer in a SOIL PROFILE that differs in its mineral or organic composition from the layers above and below it, and from which it can be clearly distinguished visually

soil profile a vertical section cut through a soil from the surface to the underlying rock

solar cell a device that converts light energy into electric current

solar chimney a device for generating electrical power from the upward flow of air heated by sunlight beneath an extensive, transparent canopy and funneled through a tall cylindrical structure (the chimney) containing generating turbines

solar panel a device that uses solar heat to raise the temperature of water

solar pond a device for heating water that consists of a pool of salt water with freshwater floating above it. Sunshine passes through the freshwater and heats the black material lining the base and sides of the pond; this heats the salt water

solstice one of the two dates each year when the noonday Sun is directly overhead at one or other of the Tropics and the difference in length between the hours of daylight and darkness is at its most extreme. The solstices occur on June 21–22 and December 22–23

solute a substance that is dissolved in another substance (the solvent) to form a solution

solvent *see* SOLUTE

southern oscillation a change that occurs periodically in the distribution of surface atmospheric pressure over the equatorial South Pacific Ocean

specific heat capacity the amount of heat that must be applied to a substance in order to raise its temperature by one degree. It is measured in calories per gram per degree Celsius (cal/g/°C) or in the scientific units of joules per gram per kelvin (J/g/K; 1K = 1°C = 1.8°F)

star dune a sand dune consisting of a number of ridges that radiate from a central point. It forms where the wind direction is highly variable

stomata (sing. stoma) small openings, or pores, on the surface of a plant leaf through which the plant cells exchange gases with the outside air. Stomata can be opened or closed by the expansion or contraction of two guard cells surrounding each stoma

subduction the movement of one crustal plate beneath another, returning the crustal rock to the Earth's MANTLE

sublimation the direct change of phase from solid to gas without passing through the liquid phase

supercooling the chilling of water to below freezing temperature without triggering the formation of ice

supersaturation the condition in which the RELATIVE HUMIDITY of air is greater than 100 percent

tail dune a sand dune that forms as a “tail” pointing downwind on the lee side of a rock or boulder in an area where the wind blows predominantly from one direction

transform fault a boundary between two crustal plates that are moving past each other in opposite directions

transpiration the evaporation of water through leaf STOMATA when these are open for the exchange of gases

turgor rigidity of plant tissues due to water held under pressure in the cells

vapor pressure the PARTIAL PRESSURE exerted on a surface by water vapor present in the air

virga precipitation that falls from the base of a cloud but evaporates before reaching the ground; it is visible as a gray, veil-like extension below the cloud

wadi *see* ARROYO

waterlogging the accumulation of water in a soil until it fills most of the spaces between soil particles

water table the upper margin of the GROUNDWATER; soil is fully saturated below the water table but unsaturated above it

weathering the breaking down of rocks by physical and chemical processes

wetting front in dry climates, the limit to which rainwater penetrates the ground and where substances washed from the upper soil tend to accumulate

xerophyte a plant that tolerates dry conditions

xylem plant tissue through which water entering at the roots is transported to all parts of the plant

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INDEX

Note: *Italic* page numbers refer to illustrations.