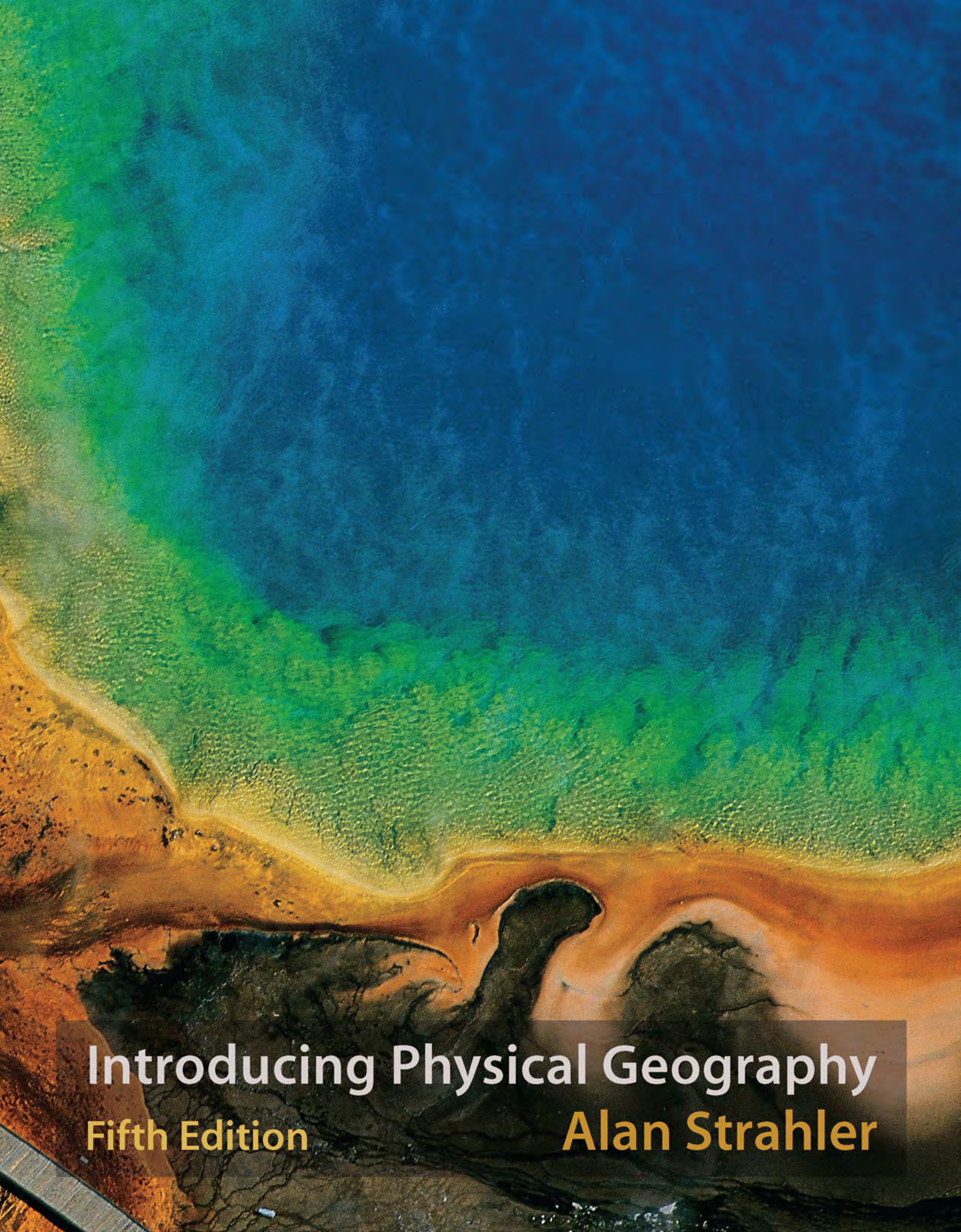


Introducing Physical Geography

Fifth Edition

Alan Strahler

WILEY PLUS

ALL THE HELP, RESOURCES, AND PERSONAL SUPPORT YOU AND YOUR STUDENTS NEED!

1st DAY OF CLASS ... AND BEYOND!

2-Minute Tutorials and all of the resources you & your students need to get started
www.wileyplus.com/firstday

WILEY PLUS Student Partner Program

Student support from an experienced student user
Ask your local representative for details!

WILEY FACULTY NETWORK

Collaborate with your colleagues, find a mentor, attend virtual and live events, and view resources
www.WhereFacultyConnect.com

WILEY PLUS QuickStart

Pre-loaded, ready-to-use assignments and presentations
www.wiley.com/college/quickstart

Technical Support 24/7
FAQs, online chat, and phone support
www.wileyplus.com/support

Your *WileyPLUS* Account Manager
Training and implementation support
www.wileyplus.com/accountmanager

WILEY PLUS
www.wileyplus.com

MAKE IT YOURS!

Fifth Edition

Introducing Physical Geography

Alan Strahler
BOSTON UNIVERSITY

WILEY
John Wiley & Sons, Inc.

VP & Publisher	Jay O' Callaghan
Executive Editor	Ryan Flahive
Assistant Editor	Veronica Armour
Editorial Assistant	Meredith Leo
Marketing Manager	Margaret Barrett
Marketing Assistant	Susan Matulewicz
Production Manager	Dorothy Sinclair
Senior Production Editor	Sandra Dumas
Senior Illustration Editor	Sandra Rigby
Art Director	Jeofrey Vita
Senior Designer	Kevin Murphy
Media Editor	Bridget O'Lavin
Photo Department Manager	Hilary Newman
Senior Photo Editor	Jennifer MacMillan
Interior Design/Cover Design	Laura Ierardi
Production Management Services	Ingrao Associates
Cover Photo	Yann Arthus-Bertand/Altitude

This book was typeset in 10/12 New Baskerville at Integra and printed and bound by WorldColor/DuBuque. The cover was printed by WorldColor/DuBuque.

The paper in this book was manufactured by a mill whose forest management programs include sustained-yield harvesting of its timberlands. Sustained-yield harvesting principles ensure that the number of trees cut each year does not exceed the amount of new growth.

This book is printed on acid-free paper. ♾

ISBN 13 978-0470-13486-3
ISBN 13 978-0470-41811-6

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

Preface

The Fifth Edition of *Introducing Physical Geography* presents a new look and style for students and instructors. Our new edition features:

- A shorter book focusing more directly on the most important concepts.
- A new writing style with more direct wording and simpler sentences.
- A continuing emphasis on visual learning, with improved graphics and photos.
- A revised art program, with graphics restyled and many redrawn for improved comprehension.
- Enhanced connections between physical geography and global change.
- Significant content revisions in many areas.

The New Text

Introducing Physical Geography 5/e is briefer than its predecessor. By refocusing on the most important concepts and ideas within each of the subfields of physical geography, we have significantly shortened the written text. Although we have reduced some detail, we have enhanced the overall flow from topic to topic while still providing the basic support that instructors need in covering the full breadth of our discipline.

We have also reduced the length of the text by merging four chapters into two. Chapter 11 now includes both Earth materials and plate tectonics, and Chapter 12 now expands volcanic and tectonic landform to include work structures. To maintain the direct flow of ideas, we have also reduced boxed features to a single type—*Focus on Remote Sensing*—instead placing essential content appropriately within the chapter narrative.

We have also achieved conciseness by adopting a new and more direct writing style that is less formal and more inviting. By shortening sentences and paragraphs, we have improved the pace and clarified the content. I am pleased to note that this new style was developed with Dr. Zeeya Merali, my collaborator in the first edition of *Visualizing Physical Geography*.

To help draw students into our content, we open each chapter with a striking photo from Yann Arthus-Bertrand, the renowned French photographer, taken from his book, *Earth from Above* (Abrahms, 1999, 2002). These photos, taken from light aircraft at low altitudes, introduce students to the beauty and diversity of the Earth's varied landscapes. Accompanying each photo is a short narrative that relates the photo to the content of the chapter. To continue to stimulate student interest, each chapter now starts with a brief learning preview that asks a series of questions that will be answered in the chapter.

In response to a number of requests from instructors, we have reemphasized the importance of geographers' tools by placing introductions to cartography, remote sensing, geographic information systems, global positioning systems, and global visualization tools in the introductory chapter. By laying these tools out early, we can easily refer to their use throughout the text.

Visual Learning

The Fifth Edition continues and expands our emphasis on visual learning through diagrams and photos. We have increased the number of multipart art pieces that include both photos and diagrams. By combining graphics and photos, we can develop and illustrate facts and concepts synergistically. In many cases, we have also added text explanations with callout lines to particular parts of the photos or graphics. This technique not only makes the graphics clearer, it also helps shorten the main text.

The art program includes many new additions, including both photos and graphics from the National Geographic Image Collection. We are very proud and pleased to offer the superior quality of these visual elements in our new edition. We have also adopted the Winkel Tripel Projection, used in the National Geographic Atlas, for our larger global maps. The Winkel Tripel displays the globe in a more natural way, without the interruptions of the Goode projection.

Geography and Global Change

Physical geography is very relevant to today's concerns about changing global climate and global environments. To help students understand this connection, most chapters begin with a brief section about a global change topic relevant to the chapter. This approach puts the global change material up front, serving as a motivator for the new knowledge to come in the remainder of the chapter. In preparing these sections, we have been especially careful to include the most recent information, drawing on the latest reports of the Intergovernmental Panel on Climate Change and current issues of *Nature* and *Science*, as well as the mainstream scientific literature.

Content Revision

The Fifth Edition also includes some areas of significant content revision. Most important are changes to the weather and climate chapters, which strengthen and improve the presentation of concepts of meteorology. Upper-air dynamics, including jet stream disturbances and their role in the genesis of cyclones, are a particular focus. For these changes, I am particularly grateful to Professor Bruce Anderson, first author of our co-authored work, *Visualizing Weather and Climate*.

Our new edition also continues to emphasize the use of remote sensing in physical geography through the use of Focus on Remote Sensing boxes. These popular features show how geographers study physical processes and map landscapes using airborne and spaceborne imaging instruments and technologies. As always, we have updated our examples of natural phenomena by reference to recent hurricanes, tornados, volcanic eruptions, landslides, earthquakes, floods, and wildfires as a way of maintaining student interest.

Other changes include improved description of the Bergeron process; use of millimeters for precipitation in weather and climate chapters; revised global energy budget values based on new satellite data; new data on global temperatures; new treatments of the Pacific Decadal Oscillation and the North Atlantic Oscillation; specific treatment of arc-continent collisions in plate tectonics; more supercontinent history; updated history of the Aral Sea; and revised treatment of the erosion of glacial valleys.

The Learning Environment

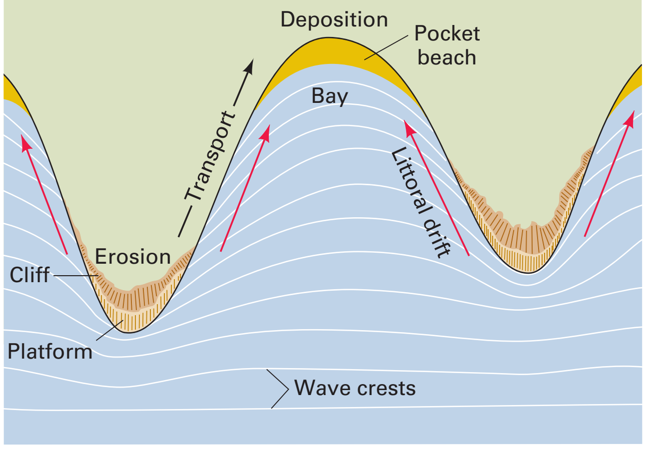
The new Fifth Edition also retains our most popular pedagogical features. Key ideas are highlighted in "windows"—text boxes within the type column that add visual interest and reinforce the importance of key concepts. The *Eye on the Landscape* feature, which points out features in images beyond those of the main caption, helps students learn how to view the landscape in an informed manner. The chapter-closing *In Review* section reads like an abstract, encapsulating the key concepts and terms in short bullets. The review questions, visualizing exercises, and essay questions all provide opportunities for students to reinforce and demonstrate the knowledge they have acquired.

GeoDiscoveries Media Library

This easy-to-use website helps reinforce and illustrate key concepts from the text through the use of animations, videos, and interactive exercises. Students can use the resources for tutorials as well as self-quizzing to complement the textbook and enhance understanding of geography. Easy integration of this content into course management systems and homework assignments gives instructors the opportunity to integrate multimedia with their syllabi and with more traditional reading and writing assignments. Resources include:

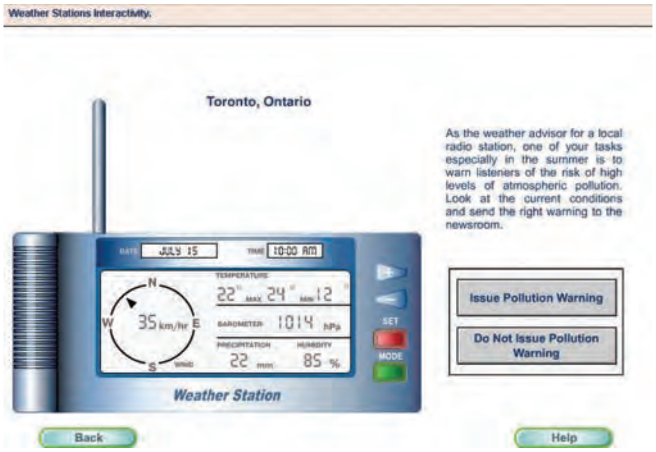
- Animations
- Videos
- Simulations
- Interactive exercises

For Students:
Animations: Key diagrams and drawings from our rich signature art program have been animated to provide a virtual experience of difficult concepts. These animations have proven crucial to the understanding of this content for visual learners.

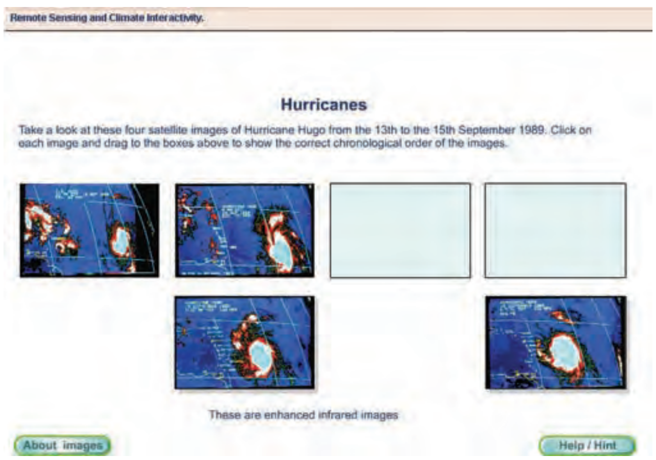


Videos: Brief video clips provide real-world examples of geographic features, and put these examples into context with the concepts covered in the text.

Simulations: Computer-based models of geographic processes allow students to manipulate data and variables to explore and interact with virtual environments.



Interactive Exercises: Learning activities and games build off our presentation material. They give students an opportunity to test their understanding of key concepts and explore additional visual resources.



Book Companion Site – www.wiley.com/college/strahler

In addition to our GeoDiscoveries multimedia content, our book companion site offers a wealth of study and practice materials, including:

Student On-line Resources:

- *Self-quizzes*—chapter-based multiple choice and fill-in-the-blank questions.
- *Annotated Weblinks*—useful weblinks selected to enhance chapter topics and content.
- *Virtual Field Trips*—web sites devoted to the exploration and virtual experience of landscapes and environments around the world.
- *Web Activities*—web-based modules of a series of exercises to introduce topics, and reveal processes and characteristics.
- *Lecture Note Handouts*—key images and slides from the instructor PPTs are made available so that when in class students can focus on the lecture, annotate figures, and add their own notes.
- *GeoDiscoveries Media Library*—link to the media library for students to explore key concepts in greater depth using videos, animations, and interactive exercises.

Instructor Resources include all student resources, plus the following:

- *PowerPoint Lecture Slides*—chapter-oriented slides including lecture notes and text art.
- *Computerized Test Bank*—including multiple-choice, fill-in, and essay questions.
- *Instructor's Manual*—including lecture notes, learning objectives, guides to additional resources, and teaching tips for enhancing the classroom experience.
- *Clicker Questions*—a set of questions for each chapter that can be used during lecture to check understanding using PRS, HITT, or CPS clicker systems.
- *Concept Caching*—an online database of photographs that explores what a physical feature looks like. Photographs and GPS coordinates are "cached" and categorized along core concepts of geography. Professors can access the images or submit their own by visiting www.ConceptCaching.com.
- *Image Gallery*—containing both line art and photos from the text.
- *On-line Essay and In-class Activities*—Materials for in-class projects, with corresponding essay-based homework assignments.

WileyPLUS

WileyPLUS is a course management and educational learning package from John Wiley & Sons. The *Introducing Physical Geography* WileyPLUS interface seamlessly integrates an online version of the textbook with the Geodiscoveries Media Library and book companion site, plus automated grading of questions, and grades that flow automatically into the grade book. It is ideal for both small and large classes and is particularly well suited as a stand-alone platform for online classes. Features include:

1. Map testing: develop students' spatial knowledge with interactive map tests of physical features.
2. Ask the questions you've always wanted to ask by creating questions to add to any assignment. For instance, you could create your own series of questions about the adiabatic process or remote sensing of volcanoes.
3. Set your own policies: give students from one to five (or even unlimited) attempts at each questions, give hints after a missed attempt, set due dates, assign point values, and give individual students extensions. You can set up the assignments so that students lose some percentage of the possible points if they don't give the correct answer by the *n*th attempt.
4. Make announcements or post files for the class.
5. Draw from the instructor resources for in-class Personal Response System/clicker questions or PowerPoint files of graphics.
6. Organize and manage class rosters and grades. You can create rosters or allow students to pay and self-enroll online.
7. The test banks are included among the instructor resources for each chapter, and you can use these to create quizzes and tests for your students to take online. These are automatically graded and will flow into the grade book.

Your investment of time to develop a good course using WileyPLUS can be carried over to subsequent semesters.

For the student, WileyPLUS offers a number of enhanced features—including an affordable price. There are a number of bonus features like map testing, links to related web pages are live and instantaneous. Students can answer questions online and submit electronically to receive immediate feedback. When answering questions, students can click on links to refer to the text or media resources.

Acknowledgments

The preparation of *Introducing Physical Geography,* Fifth Edition, was greatly aided by the following reviewers who read and evaluated the various parts of the manuscript:

William M. Buhay, University of Winnipeg
Christopher Justice, University of Maryland, College Park
Robert M. Hordon, Rutgers University
Francis A. Galgano, United States Military Academy, West Point
Jeffrey P. Schaffer
Thomas A. Terich, Western Washington University

We would also like to thank the reviewers who read and commented on prior editions:

Tanya Allison, Montgomery College
Joseph M. Ashley, Montana State University
Roger Balm, Rutgers State University
David Bixler, Chaffey College
Peter Blanken, University of Colorado, Boulder
Kenneth L. Bowden, Northern Illinois University
David Butler, University of North Carolina, Chapel Hill
Les Dean, Riverside College
Christopher H. Exline, University of Nevada
Jerry Green, Miami University
Clarence Head, University of Central Florida
Peter W. Knightes, Central Texas College
Christopher S. Larsen, State University of New York, Buffalo
Robert E. Lee, Seattle Central Community College
Denyse Lemaire, Rowen University
Eugene J. Palka, U.S. Military Academy, West Point
James F. Petersen, Southwest Texas State University
Clinton Rowe, University of Nebraska-Lincoln
Carol Shears, Ball State University
Carol I. Zinser, State University of New York, Plattsburgh

It is with particular pleasure that I thank the staff at Wiley for their long hours of careful work in the preparation and production of our Fifth Edition. They include our editor Ryan Flahive, editorial assistant Meredith Leo, senior photo editor Jennifer MacMillan, designer Laura Ierardi, illustration editor Sandra Rigby, marketing manager Jeffrey Rucker, new media product manager Tom Kulesa, production coordinator Suzanne Ingrao of Ingrao Associates, and our production editor Sandra Dumas, who made it all come together. Particular

thanks are due to developmental editor Charity Robey, who kept me on the track for many months toward our new vision of a simpler, straighter, stronger text.

Lastly, I would like to acknowledge the debt I owe to my former co-author, Arthur Strahler, who contributed so much to the education of physical geography in the 49 years of his collaboration with John Wiley and Sons and the 29 years of his collaboration with me. I deeply wish he could still be at my side today as the co-author of *Introducing Physical Geography, Fifth Edition*.

Alan Strahler
Boston, Massachusetts
January 1, 2010

About the Author

Alan Strahler earned his Ph.D. degree in Geography from Johns Hopkins in 1969 and is presently Professor of Geography at Boston University. He has published over 250 articles in the refereed scientific literature, largely on the theory of remote sensing of vegetation, and has also contributed to the fields of plant geography, forest ecology, and quantitative methods. In 1993, he was awarded the Association of American Geographers/Remote Sensing Specialty Group Medal for Outstanding Contributions to Remote Sensing. He holds the honorary degree D.S.H.C. from the Université Catholique de Louvain, Belgium, and is a Fellow of the American Association for the Advancement of Science. With the late Arthur Strahler, he is a coauthor of seven textbook titles with eleven revised editions on physical geography and environmental science. He is also the author of *Visualizing Physical Geography* and co-author of *Visualizing Weather and Climate*, in the Wiley Visualizing Series.

Google Earth™ for *Introducing Physical Geography* Fifth Edition

The fifth edition of *Introducing Physical Geography* incorporates the diverse resource of Google Earth™. Through satellite imagery in the text and online tours for each chapter using Google Earth™, instructors and students can view and interact with landforms and landscapes anywhere on the globe to better demonstrate and learn how the processes of physical geography work. Relevant study tools include web quizzes; additional examples with animations; and bonus practice with interactivities to complete the online resources available for use when taking a chapter tour in Google Earth™.

Earth from Above
An aerial portrait of our planet

Since 1990, Yann Arthus-Bertrand has flown over hundreds of countries to shoot a aerial portrait of our planet. His photographs invite all of us to reflect upon the future of Earth and its inhabitants. Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history. Under the assaults of mankind our planet's ecosystem appear everywhere to deteriorate: fresh water, oceans, forests, air, arable land, open spaces, cities.... Whatever the media—books, exhibitions, web sites, films, posters—*Earth from Above* reminds us that each and everyone of us is responsible of the future of the Earth. Because each one of us has a part, we all have the duty to act.

www.yannarthusbertrand.org
www.goodplanet.org

Toward a Sustainable Development

Since 1950, economic growth has been considerable, and world production of goods and services has multiplied by a factor of 8. During this same period, while the world's population has a little more than doubled, the volume of fish caught has multiplied by 5 and the volume of meat produced by 6. The energy demand has multiplied by 5. Oil consumption has multiplied by 7, and carbon dioxide emissions, the main cause of the greenhouse effect and global warming, by 5. Since 1900, fresh water consumption has multiplied by 6, chiefly to provide for agriculture.

And yet, 20 percent of the world's population has no access to sources of drinking water, 25 percent is without electricity, 40 percent has no sanitary installation, 820 million people are underfed, and half of humanity lives on less than $2 a day.

In other words, a fifth of the world's population lives in industrialized countries, consuming and producing in excess and generating massive pollution. The remaining four-fifths live in developing countries and, for the most part, in poverty. Overexploitation of resources leads to the constant degradation of our planet's ecosystem and limited supplies of fresh water, ocean water, forests, air, arable land…

This is not all. By 2050, the Earth will have close to 3 billion additional inhabitants. These people will live, for the most part, in developing countries. As these countries develop, their economic growth will jockey for position with that of industrialized nations – within the limits of ecosystem Earth.

If every person living on the planet consumes as much as a person living in the Western world, we would need three planets to satisfy everybody's needs. However there is a way to meet everyone's needs while preserving natural resources for future generations: we must promote less polluting, less water and energy consuming technologies. Referred to as sustainable development, this new way represents progress for humanity: to consume not less but better.

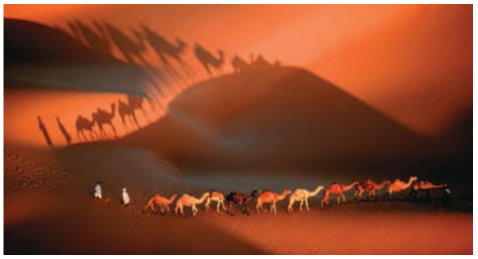
The Earth's situation is not irreversible, but changes need to be made as soon as possible. We have the chance to turn toward a more sustainable development, one that allows us to improve the living conditions of the world's citizens and to satisfy the needs of generations to come. This development would be based on an economic growth respectful both of man and the natural resources of our unique planet.

Such development requires improving production methods and changing our consumption habits. With the active participation of all the world's citizens, each and every person can contribute to the future of the Earth and mankind, starting right now.

The Earth from Above


Introduction
Physical Geography and the Tools Geographers Use


Chapter 1
The Earth as a Rotating Planet


Chapter 2
The Earth's Global Energy Balance

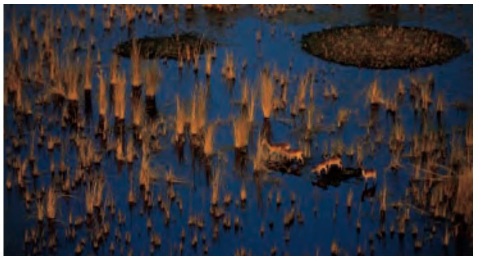

Chapter 3
Air Temperature


Chapter 4
Atmospheric Moisture and Precipitation


Chapter 5
Winds and Global Circulation


Chapter 6
Weather Systems


Chapter 7
Global Climates


Chapter 8
Biogeographic Processes


Chapter 9
Global Biogeography


Chapter 10
Global Soils

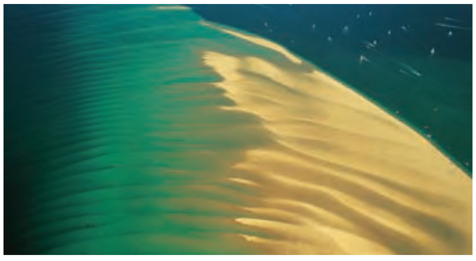

Chapter 11
Earth Materials and Plate Tectonics

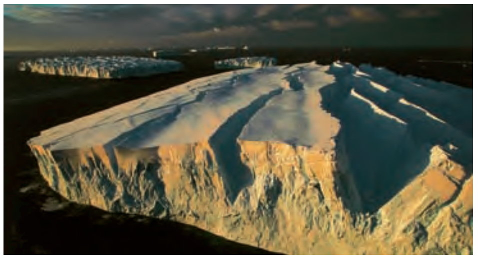

Chapter 12
Volcanic and Tectonic Landforms


Chapter 13
Weathering and Mass Wasting


Chapter 14
Fresh Water of the Continents


Chapter 15
Landforms Made by Running Water


Chapter 16
Landforms Made by Waves and Wind


Chapter 17
Glacial Landforms and the Ice Age

Brief Contents

Contents

Fifth Edition

Introducing Physical Geography

Introduction

Physical Geography and the Tools Geographers Use

The circular plan of this traditional village, north of Antananarivo, Madagascar, with its central walled area and radial paths leading outward, is found early in the development of many civilizations. With its aligned buildings, town square, and areas of gardens and bowers along the periphery, the village center has the basic elements of many modern towns and cities. Surrounding the village are the supporting lands—agricultural plots and pastures on which the village depends. The modern city also has its supporting areas of suburban development and agricultural hinterlands surrounding the city center. The main road at the bottom of the photo is a transportation corridor that connects the village to the outside world. Large cities have many such transportation links, including roads, rivers, and railways.

Human settlements have a physical setting that places bounds on the kinds of human and economic activities that take place in and around the settlement. In this book, we will focus on the natural processes that shape the physical landscape and provide the habitat of the human species.

Traditional village near Antananarivo, Madagascar

Physical Geography and the Tools Geographers Use

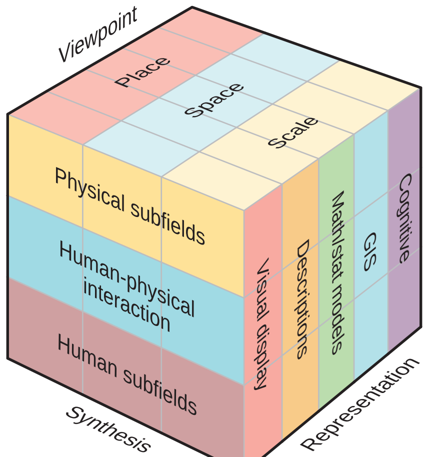
Geography is a modern discipline with ancient roots. But what is geography? What are the big ideas of physical geography? How is physical geography related to global climate change? biodiversity? extreme events? Geographers use special tools to study the Earth. How do maps depict the Earth's curved surface on a flat piece of paper? How does a geographic information system (GIS) work? How do geographers use remote sensing? These are some of the questions we will answer in our Introduction

Introducing Geography

What is geography? Put simply, **geography** is the study of the evolving character and organization of the Earth's surface. It is about how, why, and where human and natural activities occur and how these activities are interconnected.[1]

What makes geography different from other disciplines? Geography adopts a unique set of perspectives to analyze the world and its human and natural phenomena. These perspectives include the spatial viewpoint of geographers, the interest of geographers in the synthesis of ideas across the boundaries of conventional studies, and geographers' usage of tools to represent and manipulate spatial information and spatial phenomena. Figure I.1 shows these perspectives in the form of a cube with each perspective displayed on a different face.

The first unique perspective of geography is its spatial **viewpoint**. Geographers are interested not only in how something happens, but also where it happens and how it is related to other happenings nearby and far away. The spatial viewpoint can focus at three levels. At the *place* level, geographers study how processes are integrated at a single location or within a single region. For example, an urban geographer may study the spatial structure of a particular city—how and where neighborhoods and commercial centers develop and take on their unique characteristics. Or a physical geographer may study the ecology, climate, and soils of a national park. At the *space* level, geographers look at how places are interdependent. An economic geographer may examine how flows of goods, information, or money connect cities and towns that are of different sizes and at different distances apart. Or a physical geographer may map the sources of sediment flowing into a river and chart their downstream effects. Geographers also look at human and natural activities at different



I.1 Perspectives of geography

The three unique perspectives of geography—its spatial viewpoint, its synthesis of related fields, and its representation of spatial processes and information—are diagrammed as three dimensions occupying the sides of a cube.

[1]For descriptions and perspectives of geography, see *Rediscovering Geography: New Relevance for Science and Society* (Washington, DC: National Academy Press, 1997), 234 pp., and *Geography in America at the Dawn of the 21st Century*, G. L. Gaile and C. J. Willmott, eds. (New York: Oxford University Press, 2003), 820 pp., which were used in preparing this introduction.

scales, sometimes zooming in for a close look at something small or pulling back for an overview of something large. Often what looks important at one scale is less important at another.

The second perspective of geography is **synthesis**. Geographers are very interested in putting ideas together from different fields and assembling them in new ways—a process called synthesis. Of particular interest to geographers are studies that link conventional areas of study. In physical geography, for example, a biogeographer may investigate how streamside vegetation affects the flood flow of rivers, thus merging the physical geography subfields of ecology and hydrology. A human geographer may study how economic innovation—developing new kinds of goods and services—varies from region to region according to cultural and legal factors, thus merging the human geography subfields of economics, politics, and sociology. The many connections between environmental processes and human activities are also subjects of geographic synthesis. For example, a classic study area in geography is perception of hazards—why do people build houses next to rivers or beaches when it is only a matter of time before floods or storms will wash their homes away? Here, geographers study the interaction of hydrology with perception and cognitive learning.

The third perspective of geography is geographic **representation**. Here, geographers develop and perfect tools for representing and manipulating information spatially. *Cartography*—the art and science of making and drawing *maps*—is a subfield of geography that focuses on *visual display* of spatial relationships. Visual display also includes remote sensing—acquiring images of the Earth from aircraft or spacecraft and enhancing them to better display spatial information. *Verbal descriptions* use the power of words to explain or evoke geographic phenomena. *Mathematical and statistical models* predict how a phenomenon of interest varies over space and through time. *Geographic information systems* store, manipulate, and display spatial information in very flexible ways. *Cognitive representation* refers to spatial relationships as they are stored in the human brain—mental mapping of real space into the subjective space that people experience.

Taken together, the perspectives of viewpoint, synthesis, and representation define geography as a unique discipline that focuses on how the natural and human patterns of the Earth's physical and cultural landscape change and interact in space and time.

Geography as a discipline has a unique set of perspectives. Geographers look at the world from the viewpoint of geographic space, focus on synthesizing ideas from different disciplines, and develop and use special techniques to represent and manipulate spatial information.

Another way to illustrate geographic perspectives is by an example—Vancouver, British Columbia, illustrated in Figure I.2. The image, a visual display, shows a place, the central city of Vancouver, set in the space of the Strait of Georgia and Pacific and Vancouver Island Ranges and imaged at a local scale. In the geographer's view, Vancouver is a unique landscape shaped by both environmental and human processes and their interactions.

HUMAN AND PHYSICAL GEOGRAPHY

Like many other areas of study, geography can be regarded as having a number of subfields, each with a different focus but often overlapping and interlocking with other subfields. We can organize these subfields into two broad realms—**human geography**, which deals with social, economic and behavioral processes that differentiate places, and **physical geography**, which examines the natural processes occurring at the Earth's surface that provide the physical setting for human activities. Figure I.3 is a diagram showing the principal fields of physical and human geography. Reading downward from the left, we see five fields of physical geography, from climatology to biogeography, which are illustrated in Figure I.4. These topics are the main focus of this text.

Climatology is the science that describes and explains the variability in space and time of the heat and moisture states of the Earth's surface, especially its land surfaces. Since heat and moisture states are part of what we call weather, we can think of climate as a description of average weather and its variation at places around the world. Chapters 1–7 will familiarize you with the essentials of climatology, including the processes that control the weather we experience daily. Climatology is also concerned with climate change, both past and future. One of the most rapidly expanding and challenging areas of climatology is global climate modeling, which we touch on in several chapters. This field attempts to predict how human activities, such as converting land from forest to agriculture or releasing CO_2 from fossil fuel burning, will change global climate.

Geomorphology is the science of Earth surface processes and landforms. The Earth's surface is constantly being altered under the combined influence of human and natural factors. The work of gravity in the collapse and movement of Earth materials, as well as the work of flowing water, blowing wind, breaking waves, and moving ice, acts to remove and transport soil and rock and to sculpt a surface that is constantly being renewed through volcanic and tectonic activity. The closing chapters of our book (Chapters 12–17) describe

I.2 Vancouver, British Columbia

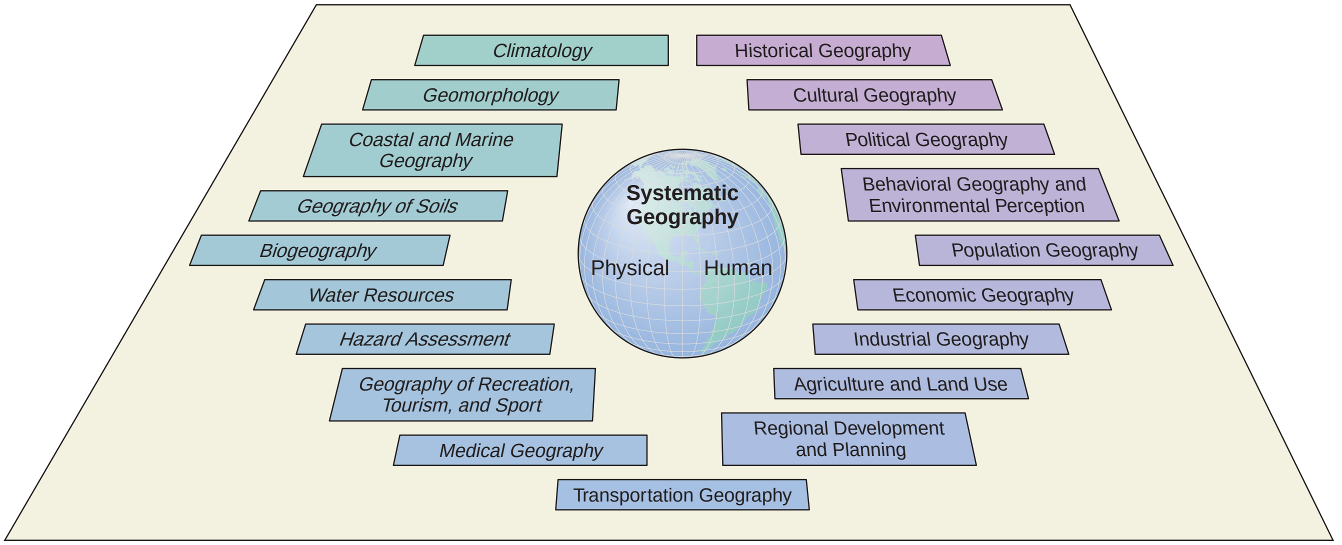
This cosmopolitan city enjoys a spectacular setting on the Strait of Georgia, flanked by the Pacific and Vancouver Island Ranges.

EYE ON THE LANDSCAPE **What else would the geographer see?** (A) For the physical geographer, Vancouver's environment combines snow-capped peaks eroded by glaciers, conifer forests adapted to the cool, maritime climate, and an arm of the ocean that erodes the coast by wave and tidal action. (B) For the human geographer, the image shows a center of economic activity marked by Vancouver's office and residential towers. Areas of low buildings document the differentiation of the city into districts with different characters and history. The road and freeway network demonstrates the city's reliance on cars and trucks to move people and goods within the city. (C) The physical environment interacts with human activity through Vancouver's role as a port city, where land- and water-borne transportation modes meet. Large commercial vessels in the bay mingle with sailboats and powerboats, showing the importance of the city's marine setting to both shipping and recreation.

these geomorphic processes, while the basic geologic processes that provide the raw material are covered in Chapters 11–12. Modern geomorphology also focuses on modeling landform-shaping processes to predict both short-term, rapid changes, such as landslides, floods, or coastal storm erosion, and long-term, slower changes, such as soil erosion in agricultural areas or as a result of strip mining.

The field of **coastal and marine geography** combines the study of geomorphic processes that shape shores and coastlines with their application to coastal development and marine resource utilization. Chapter 16 describes these processes and provides some perspectives on problems of human occupation of the coastal zone.

Geography of soils includes the study of the distribution of soil types and properties and the processes of soil formation. It is related to both geomorphic processes of rock breakup and weathering, and to biological processes of growth, activity, and decay of organisms living in the soil (Chapter 10). Since both geomorphic and biologic processes are influenced by the surface temperature and availability of moisture, broad-scale soil patterns are often related to climate.



I.3 Fields of systematic geography

Biogeography, covered in Chapters 8 and 9, is the study of the distributions of organisms at varying spatial and temporal scales, as well as the processes that produce these distribution patterns. Local distributions of plants and animals typically depend on the suitability of the habitat that supports them. In this application, biogeography is closely aligned with *ecology*, which is the study of the relationship between organisms and environment. Over broader scales and time periods, the migration, evolution, and extinction of plants and animals are key processes that determine their spatial distribution patterns. Thus, biogeographers often seek to reconstruct past patterns of plant and animal communities from fossil evidence of various kinds. *Biodiversity*—the assessment of biological diversity from the perspective of maintaining the diversity of life and life-forms on Earth—is a biogeographic topic of increasing importance as human impact on the environment continues. The present global-scale distribution of life-forms as the great biomes of the Earth provides a basic context for biodiversity.

> **Five major fields of physical geography include climatology (study of climate), geomorphology (study of landforms), coastal and marine geography, geography of soils, and biogeography (study of the distribution patterns of plants and animals).**

In addition to these five main fields of physical geography, two others are strongly involved with applications of physical geography—water resources and hazards assessment. **Water resources** is a broad field that couples basic study of the location, distribution, and movement of water, for example, in river systems or as ground water, with the utilization and quality of water for human use. This field involves many aspects of human geography, including regional development and planning, political geography, and agriculture and land use. We touch on water resources briefly in this book by discussing water wells, dams, and water quality in Chapters 14 and 15.

Hazards assessment is another field that blends physical and human geography. What are the risks of living next to a river, and how do inhabitants perceive those risks? What is the role of government in protecting citizens from floods or assisting them in recovery from flood damages? Answering questions such as these requires not only knowledge of how physical systems work, but also how humans perceive and interact with their physical environment as both individuals and as societies. In this text, we develop an understanding of the physical processes of floods, earthquakes, landslides, and other disaster-causing natural events as a background for appreciating hazards to humans and their activities.

Many of the remaining fields of human geography have linkages with physical geography. For example, climatic and biogeographic factors may determine the spread of disease-carrying mosquitoes (medical geography). Mountain barriers may isolate populations and increase the cost of transporting goods from one place to another (cultural geography, transportation geography). Unique landforms and landscapes may be destinations for tourism (geography of recreation, tourism, and sport). Nearly all human activities take place in a physical environment that varies in space and time, so the physical processes that we examine in this text provide a background useful for further learning in any of geography's fields.

I.4 Fields of physical geography

▲ **Climatology** Climatology studies the transfers of energy and matter between the surface and atmosphere that control weather and climate.

▲ **Geomorphology** Geomorphology is the study of landform-making processes.

▼ **Coastal and marine geography** Coastal and marine geography examines coastal processes, marine resources, and their human interface.

▶ **Biogeography** Biogeography examines the distribution patterns of plants and animals and relates them to environment, migration, evolution, and extinction.

▲ **Geography of soils** Soils are influenced by their parent material, climate, biota, and time.

Spheres, Systems, and Cycles

As a part of your introduction to physical geography, it will be useful to take a look at the big picture and examine some ideas that arch over all of physical geography—that is, spheres, systems, and cycles. The first of these ideas is that of the four great physical realms, or *spheres* of Earth—atmosphere, lithosphere, hydrosphere, and biosphere. These realms are distinctive parts of our planet with unique components and properties. Another big idea is that of *systems*—viewing the processes that shape our landscape as a set of interrelated components that comprise a system. The systems viewpoint stresses linkages and interactions and helps us to understand complex problems, such as global climate change or loss of biodiversity. The last big idea is that of *cycles*—regular changes in systems that reoccur through time.

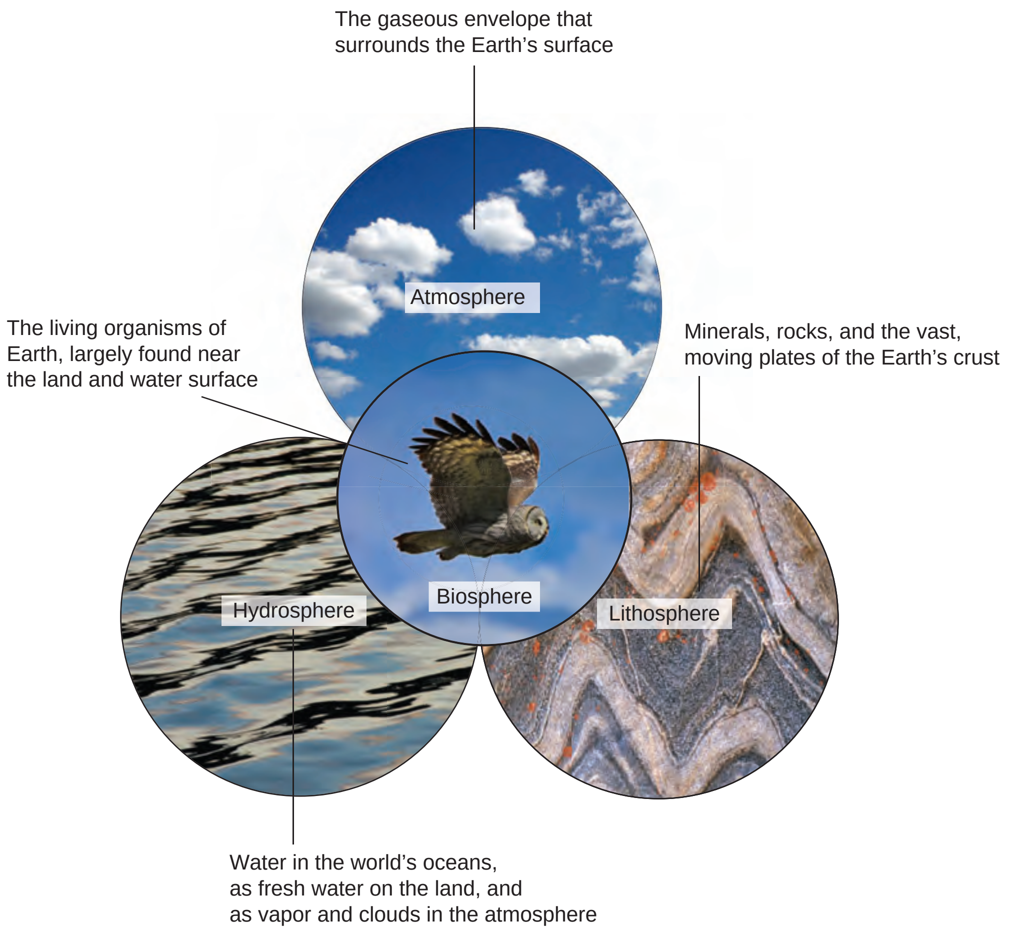
THE SPHERES— FOUR GREAT EARTH REALMS

The natural systems that we will encounter in the study of physical geography operate within the four great realms, or **spheres**, of the Earth. These are the atmosphere, the lithosphere, the hydrosphere, and the biosphere (Figure I.5).

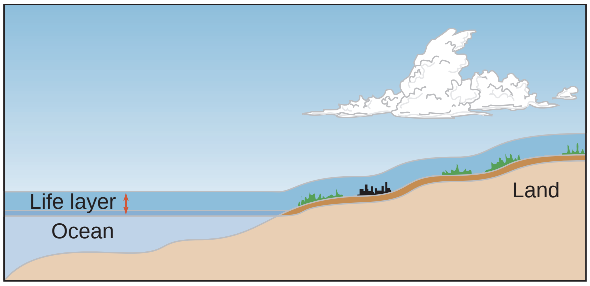
The **atmosphere** is a gaseous layer that surrounds the Earth. It receives heat and moisture from the surface and redistributes them, returning some heat and all the moisture to the surface. The atmosphere also supplies vital elements—carbon, hydrogen, oxygen, and nitrogen—that are needed to sustain life.

The outermost solid layer of the Earth, or **lithosphere**, provides the platform for most Earthly life-forms. The solid rock of the lithosphere bears a shallow layer of soil in which nutrient elements become available to organisms. The surface of the lithosphere is sculpted into landforms. These features—such as mountains, hills, and plains—provide varied habitats for plants, animals, and humans.

The liquid realm of the Earth is the **hydrosphere**, which is principally the mass of water in the world's oceans. It also includes solid ice in mountain and continental glaciers, which, like liquid ocean and fresh water, is subject to flow under the influence of gravity. Within the atmosphere, water occurs as gaseous vapor, liquid droplets, and solid ice crystals. In the lithosphere, water is found in the uppermost layers in soils and in ground water reservoirs.



I.5 The Earth realms



I.6 The life layer

As this sketch shows, the life layer is the layer of the Earth's surface that supports nearly all of the Earth's life. It includes the land and ocean surfaces and the atmosphere in contact with them.

The **biosphere** encompasses all living organisms of the Earth. Life-forms on Earth utilize the gases of the atmosphere, the water of the hydrosphere, and the nutrients of the lithosphere, and so the biosphere is dependent on all three of the other great realms. Figure I.6 diagrams this relationship.

Most of the biosphere is contained in the shallow surface zone called the **life layer**. It includes the surface of the lands and the upper 100 m or so (about 300 ft) of the ocean (Figure I.6). On land, the life layer is the zone of interactions among the biosphere, lithosphere, and atmosphere, with the hydrosphere represented by rain, snow, still water in ponds and lakes, and running water in rivers. In the ocean, the life layer is the zone of interactions among the hydrosphere, biosphere, and atmosphere, with the lithosphere represented by nutrients dissolved in the upper layer of sea water. Throughout our exploration of physical geography, we will often refer to the life layer and the four realms that interact within it.

SCALE, PATTERN, AND PROCESS

As we saw earlier, geographers have unique perspectives that characterize a geographic approach to understanding the physical and human organization of the Earth's surface. Three interrelated themes that often arise in geographic study are scale, pattern, and process. **Scale** refers to the level of structure or organization at which a phenomenon is studied. **Pattern** refers to the variation in a phenomenon that is seen at a particular scale. **Process** describes how the factors that affect a phenomenon act to produce a pattern at a particular scale.

To make these ideas more real, imagine yourself as an astronaut, returning to Earth from a voyage to the Moon. As you approach the Earth and finally touch down on land, your view of our planet takes in scales ranging from global to local. As the scale changes, so do the patterns and processes that you observe (Figure I.7).

At the *global scale*, you see the Earth's major physical features—oceans of blue water, continents of brown Earth, green vegetation, and white snow and ice, and an atmosphere of white clouds and clear air. The pattern of land and ocean is created by the processes of plate tectonics, which shape land masses and ocean basins across the eons of geologic time. The pattern of white clouds, which includes a band of persistent clouds near the Earth's equator and spirals of clouds moving across the globe, is created by atmospheric circulation processes that depend on solar heating coupled with the Earth's slow rotation on its axis. These processes act much more quickly and on a finer spatial scale than those of plate tectonics.

At the *continental scale*, we see the broad differentiation of land masses into regions of dry desert and moister vegetated regions, a pattern caused by atmospheric processes that provide some areas with more precipitation than others. In some regions, air temperatures keep liquid water frozen, producing sea ice and glaciers. Air temperature and precipitation are the basic elements of climate, and so we may regard climate as a major factor affecting the landscape on a continental level.

Scale, pattern, and process are three interrelated geographic themes. Scale refers to the level of structure or organization; pattern refers to the variation seen at a particular scale; and process describes how the pattern at a particular scale is produced.

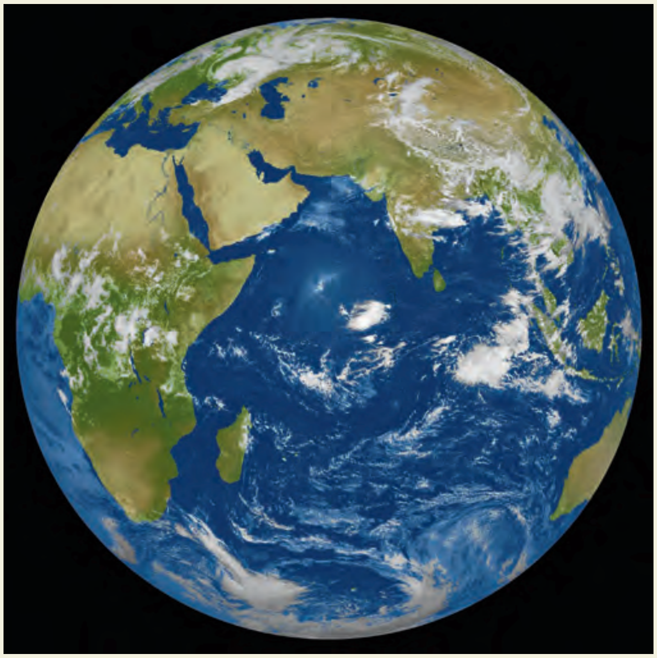
At the *regional scale*, mountain ranges, deserts, lakes, and rivers create a varied pattern caused by interaction between geologic processes that raise mountains and lower valleys with atmospheric processes that provide water to run off the continents while supporting the growth of vegetation. Also evident at the regional scale are broad patterns of human activity, such as the deforestation of the Amazon (Figure 1.7C). Agricultural regions are clearly visible, distinguished by repeating geometric patterns of fields.

At the *local scale*, we zoom in on a landscape showing a distinctive pattern in fine detail. For example, our image of the San Francisco Bay region (Figure I.7D) reveals both the natural processes that carve hillslopes and canyons from mountain masses and the human processes that superimpose city and suburb on the natural landscape. At the finest scale, we see individual-scale landscape features, such as sand dunes, bogs, or freeways, each of which is the result of a different process.

These examples illustrate the themes of scale, pattern, and process as they apply to the landscapes of our planet. Keep in mind, however, that these themes are quite general ones. Throughout this book, we will see many examples of scale, pattern, and process applied to such diverse phenomena as climate, vegetation, soils, and landforms. We will zoom in and out, examining processes at local scales and applying them to regions to create and explain broad patterns observed at continental and global scales.

I.7 Scale, pattern, and process

As the Earth is viewed at increasingly finer scales, different patterns, created by different processes, emerge.



◀ **Global scale** At the global scale, the major surface features of the Earth and atmospheric circulation are readily visible.

▼ **Continental scale** At the continental scale, climate determines the pattern of vegetation. Here, green colors indicate healthy vegetation, with reds and browns showing sparse vegetation cover and desert.

In this way, you will gain a better understanding of how the Earth's surface changes and evolves in response to natural and human activities.

SYSTEMS IN PHYSICAL GEOGRAPHY

The processes that interact within the four realms to shape the life layer and differentiate global environments are varied and complex. A helpful way to understand the relationships among these processes is to study them as **systems**. "System" is a common English word that we use in everyday speech. It typically means a set or collection of things that are somehow related or organized. An example is the solar system—a collection of planets that revolve around the Sun. In the text, we will use the word "system" in this way quite often. Sometimes it refers to a scheme for naming things. For example, we will introduce a climate system in Chapter 7 and a soil classification system in Chapter 10. However, we will also use *system* to mean a group of interrelated processes that operate simultaneously in the physical landscape.

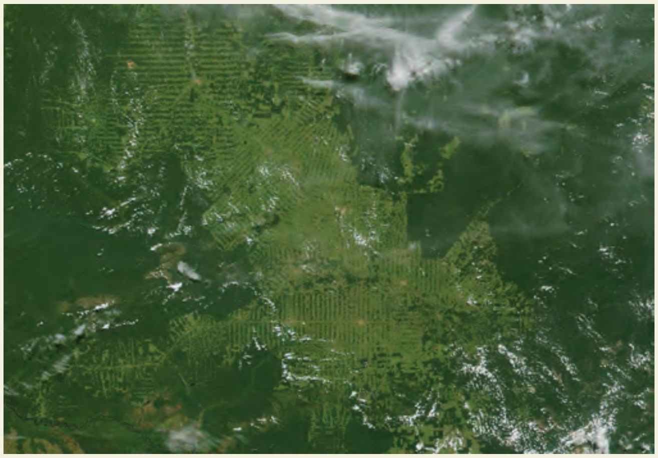
When we study physical geography using a *systems approach,* we look for linkages and interactions among processes. For example, global warming should enhance the process of evaporation of water from oceans and moist land surfaces, generating more clouds. But an increase in clouds also affects the process of solar reflection, in which white, fleecy clouds reflect solar radiation back out to space. This leaves less radiation to be absorbed by the atmosphere and surface and so should tend to cool our planet, reducing global warming. This is actually an example of negative feedback, in which one process counteracts another process to reduce its impact. (We'll present more information about this topic in Chapter 6.) Throughout the text there will be more examples of this systems viewpoint in physical geography.[2]

TIME CYCLES

Many natural systems show **time cycles**—rhythms in which processes change in a regular and repeatable fashion. For example, the annual revolution of the Earth around the Sun generates a time cycle of incoming solar energy flow. We speak of this cycle as the rhythm of the

[2]For a more careful and rigorous treatment of systems as flow systems of energy and matter, see our *Focus on Systems* features in *Physical Geography: Science and Systems of the Human Environment*, 3rd ed., Wiley, 2005.

▶ **Regional scale** At the regional scale, broad patterns of human activity are visible, such as this example of deforestation in Rondonia, in the Brazilian Amazon.



◀ **Local scale** At the local scale, the details of development emerge, as well as the shapes of individual landforms.

seasons. The rotation of the Earth on its axis sets up the night-and-day cycle of darkness and light. The Moon, in its monthly orbit around the Earth, sets up its own time cycle, which we see in ocean tides.

The astronomical time cycles of Earth rotation and solar revolution appear at several places in our early chapters. Other time cycles with durations of tens to hundreds of thousands of years describe the alternate growth and shrinkage of the great continental ice sheets. Still others, with durations of millions of years, describe cycles of the solid Earth in which supercontinents form, break apart, and re-form anew.

Physical Geography, Environment, and Global Change

Physical geography is concerned with the natural world around us—in short, with the human environment. Because natural processes are constantly active, the Earth's environments are constantly changing (Figure I.8). Sometimes the changes are slow and subtle, as when crustal plates move over geologic time to create continents and ocean basins. At other times, the changes are rapid, as when hurricane winds flatten vast areas of forests or even tracts of houses and homes.

Environmental change is now produced not only by the natural processes that have acted on our planet for millions of years but also by human activity. The human race has populated our planet so thoroughly that few places remain free of some form of human impact. Global change, then, involves not only natural processes, but also human processes that interact with them. Physical geography is the key to understanding this interaction.

Environment and global change are sufficiently important that we have set off these topics by placing them in special sections identified with *Eye on Global Change* that open each chapter. What are some of the important topics in global change that lie within physical geography? Let's examine a few.

GLOBAL CLIMATE CHANGE

Are human activities changing global climate? It seems that almost every year we hear that it has been the hottest year, or one of the hottest years, on record. But climate is notoriously variable. Could such a string of hot years be part of the normal variation? This is the key question facing scientists studying global climate

I.8 Dimensions of global change

The dimensions of global change touch on many human activities.

◀ **Global climate change** Is the Earth's climate changing? Nearly all global change scientists have concluded that human activities have resulted in climate warming and that weather patterns, shown here in this satellite image of clouds and weather systems over the Pacific Ocean, are changing.

▶ **Carbon cycle** Clearcutting of timber, shown here on the Olympic Peninsula, Washington, removes carbon from the landscape, while regrowth returns carbon through photosynthesis.

▶ **Biodiversity** Reduction in the area and degradation of the quality of natural habitats is reducing biodiversity. The banks of this stream in the rainforest of Costa Rica are lined with several species of palms.

▼ **Pollution** Human activity can create pollution of air and water, causing change in natural habitats as well as impacts on human health. The discharge from this pulp mill near Port Alice, British Columbia, is largely water vapor, but pulp mill pollutants often include harmful sulfur oxides.

▼ **Extreme events** Hurricanes, severe storms, droughts, and floods may be becoming more frequent as global climate warms. A tornado flattened this neighborhood in Kansas City, Kansas, May 2003.

change. Over the past decade, nearly all scientists have come to the opinion that human activity has, indeed, begun to change our climate. How has this happened?

The answer lies in the greenhouse effect. As human activities continue to release gases that block heat radiation from leaving the Earth, the greenhouse effect intensifies. The most prominent of these gases is CO_2, which is released by fossil fuel burning. Others include methane (CH_4), nitrous oxide (NO), and the chlorofluorocarbons that until recently served as coolants in refrigeration and air conditioning systems and as aerosol spray propellants. Taken with other gases, they act to raise the Earth's surface temperature, with consequences including dislocation of agricultural areas, rise in sea level, and increased frequency of extreme weather events, such as severe storms or record droughts.

Climate change is a recurring theme throughout this book, ranging from the urban heat island effect that tends to raise city temperatures (Chapter 3) to the El Niño phenomenon that alters global atmospheric and ocean circulation (Chapter 5), to the effect of clouds on global warming (Chapter 6), and to rising sea level due to the expansion of sea water with increasing temperature (Chapter 16).

THE CARBON CYCLE

One way to reduce human impact on the greenhouse effect is to slow the release of CO_2 from fossil fuel burning. But since modern civilization depends on the energy of fossil fuels to carry out almost every task, reducing fossil fuel consumption to stabilize the increasing concentration of CO_2 in the atmosphere is not easy. However, some natural processes reduce atmospheric CO_2. Plants withdraw CO_2 from the atmosphere by taking it up in photosynthesis to construct plant tissues, such as cell walls and wood. In addition, CO_2 is soluble in sea water. These two important pathways, by which carbon flows from the atmosphere to lands and oceans, are part of the carbon cycle. Biogeographers and ecologists are now focusing in detail on the global carbon cycle in order to better understand the pathways and magnitudes of carbon flow. They hope that this understanding will suggest alternative actions that can reduce the rate of CO_2 buildup without penalizing economic growth. The processes of the carbon cycle are described in Chapter 8.

Environmental change is produced by both natural and human processes. Human activities are currently changing both the Earth's climate and the global flows of carbon from Earth to ocean to atmosphere.

BIODIVERSITY

Among scientists, environmentalists, and the public, there is a growing awareness that the diversity in the plant and animal forms harbored by our planet—the Earth's biodiversity—is an immensely valuable resource that will be cherished by future generations. One important reason for preserving as many natural species as possible is that, over time, species have evolved natural biochemical defense mechanisms against diseases and predators. These defense mechanisms involve bioactive compounds that can sometimes be very useful, ranging from natural pesticides that increase crop yields to medicines that fight human cancer.

Another important reason for maintaining biodiversity is that complex ecosystems with many species tend to be more stable and to respond better to environmental change. If human activities inadvertently reduce biodiversity significantly, there is a greater risk of unexpected and unintended human effects on natural environments. Biogeographers focus on both the existing biodiversity of the Earth's many natural habitats and the processes that create and maintain biodiversity. These topics are treated in Chapters 8 and 9.

Human activity is reducing the biodiversity of many of the Earth's natural habitats. Environmental pollution degrades habitat quality for humans as well as other species. Extreme weather events, which will become more frequent with human-induced climate change, as well as other rare natural events, are increasingly destructive to our expanding human population.

POLLUTION

As we all know, unchecked human activity can degrade environmental quality. In addition to releasing CO_2, fuel burning can yield gases that are hazardous to health, especially when they react to form such toxic compounds as ozone and nitric acid in photochemical smog. Water pollution from fertilizer runoff, toxic wastes of industrial production, and acid mine drainage can severely degrade water quality. Such degradation impacts not only the ecosystems of streams and rivers, but also the human populations that depend on rivers and streams as sources of water supply. Ground water reservoirs can also be polluted or turn salty in coastal zones when drawn down excessively.

Environmental pollution, its causes, its effects, and the technologies used to reduce pollution, form a subject that is broad in its own right. As a text in physical geography that emphasizes the natural processes of the Earth's land surface, we touch on air and water pollution in several chapters—Chapter 4 for air pollution and Chapter 14 for surface water pollution, irrigation effects, and ground water contamination.

EXTREME EVENTS

Catastrophic events—floods, fires, hurricanes, earthquakes, and the like—can have great and long-lasting impacts on both human and natural systems. Are human activities increasing the frequency of these extreme events? As our planet warms in response to changes in the greenhouse effect, global climate modelers predict that weather extremes will become more severe and more frequent. Droughts and consequent wildfires and crop failures will happen more often, as will spells of rain and flood runoff. In the last decade, we have seen numerous examples of extreme weather events, from Hurricane Katrina in 2005—the most costly storm in U.S. history—to the Southeast drought of 2007, which devastated crops in large parts of the southeastern United States. Is human activity responsible for the increased occurrence of these extreme events? Significant evidence now points in that direction.

Other extreme events, such as earthquakes, volcanic eruptions, and seismic sea waves (wrongly called tidal waves), are produced by forces deep within the Earth that are not affected by human activity. But as the human population continues to expand and comes to rely increasingly on a technological infrastructure ranging from skyscrapers to the Internet, we are becoming more sensitive to damage and disruption of these systems by extreme events.

This text describes many types of extreme events and their causes. In Chapters 4 and 6, we discuss thunderstorms, tornadoes, cyclonic storms, and hurricanes. Droughts in the African Sahel are presented in Chapter 7. Earthquakes, volcanic eruptions, and seismic sea waves are covered in Chapter 12. Floods are described in Chapter 14.

Tools in Physical Geography

Geographers use a number of specialized tools to examine, explore, and interact with spatial data (Figure I.9). One of the oldest tools is the *map*—a paper representation of space showing where things are. While maps will never go out of style, computers have enhanced our ability to store, retrieve, and analyze spatial data through the development of *geographic information systems* (*GIS*). Acquiring geographic information for input to GIS has recently been made much easier through use of the *global positioning system* (GPS), which allows hand-held electronic equipment, linked to signals from orbiting spacecraft, to easily determine the exact latitude, longitude, and elevation of any point on the Earth's surface to within a few meters.

Satellites bearing imaging instruments have provided a wealth of information about the Earth's surface layers, including land, oceans, and atmosphere, that is vital to geographic study. The field of processing, enhancing, and analyzing images and measurements made from aircraft and spacecraft is known as *remote sensing*. Recent developments linking remote sensing, GIS, and GPS with the Internet have produced new Earth visualization tools, such as Google Earth, that are also of great interest to geographers.

Maps, geographic information systems (GISs), and remote sensing are important geographic tools to acquire, display, and manipulate spatial data. Mathematical modeling and statistics are also helpful tools for the geographer.

Tools in geography also include *mathematical modeling* and *statistics*. Using math and computers to model geographic processes is a powerful approach to understanding both natural and human phenomena. Statistics provides methods that can be used to manipulate geographic data so that we can ask and answer questions about differences, trends, and patterns. Because these tools rely heavily on specialized knowledge, they are not included here. Our text does, however, present many examples of geographic information obtained using modeling and statistics.

Maps and Cartography

Cartography is the field of geography concerned with making maps. A **map** is a paper representation of space showing point, line, or area data—that is, locations, connections, and regions. It typically displays a set of characteristics or features of the Earth's surface that are positioned on the map in much the same way that they occur on the surface. The map's scale links the true distance between places with the distance on the map.

Maps play an essential role in the study of physical geography because much of the information content of geography is stored and displayed on maps. Map literacy—the ability to read and understand what a map shows—is a basic requirement for day-to-day functioning in our society. Maps appear in almost every issue of a newspaper and in nearly every TV newscast. Most people routinely use highway maps and street maps. Maps also pop up on web sites. The purpose of this part of our chapter is to provide additional information on the art and science of maps.

MAP PROJECTIONS

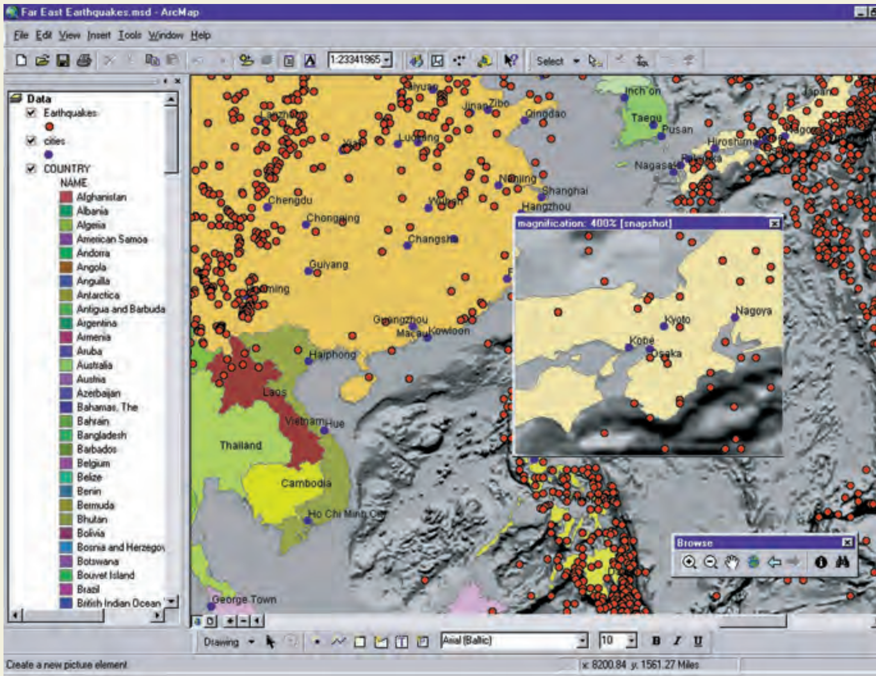
Cartographers record position on the Earth's surface using latitude and longitude. You'll read more about latitude and longitude in Chapter 1, but for now, you probably know that latitude measures position in a north-south direction and that longitude measures position in an east-west direction. Lines of equal latitude are *parallels*, and lines of equal longitude are *meridians*.

I.9 Tools of Physical Geography

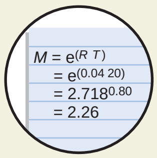
Geographers rely on specialized tools to analyze spatial data.

A

▲ **Cartography** A portion of the U.S. Geological Survey 1:24,000 topographic map of Green Bay, Wisconsin. Using symbols, the map shows creeks and rivers, a bay, swampy regions, urban developed land, streets, roads, and highways.

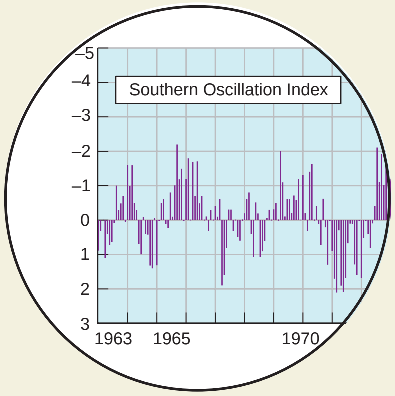


▲ **Geographic information systems (GIS)** Computer programs that store and manipulate geographic data are essential to modern applications of geography. This screen from the ARCInfo GIS program package shows earthquake centers in eastern Asia superimposed on a political map underlain by a shaded relief map of undersea topography.

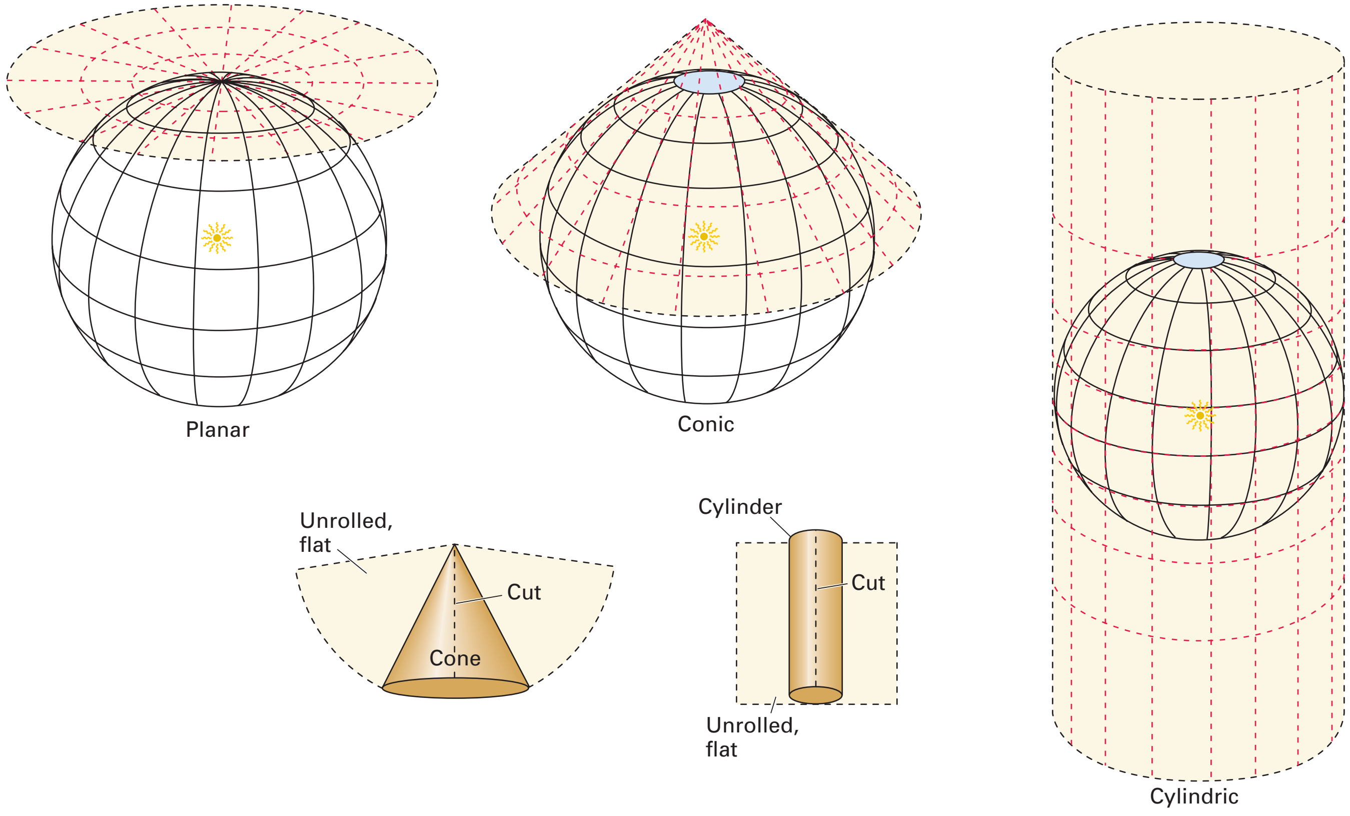


◀ **Mathematical modeling** By describing a phenomenon using a mathematical model, a geographer can predict outcomes and examine "what-if" scenarios. These equations demonstrate the calculation of an exponential growth factor.

▼ **Remote sensing** Remote sensing includes observing the Earth from the perspective of an aircraft or spacecraft. Wildfires on the Greek island of Peloponnesos, seen in a Landsat image from July 2000, are an example.



▲ **Statistics** Statistical tools, such as this graph, allow the exploration of geographic data to determine trends and develop mathematical models. The plot shows the value of the Southern Oscillation Index, an indicator of El Niño conditions.



I.10 Simple ways to generate map projections

Rays from a central light source cast shadows of the spherical geographic grid on target screens. The conical and cylindrical screens can be unrolled to become flat maps.

A **map projection** is an orderly system of lines of latitude and longitude used as a base to draw a map on a flat surface. A projection is needed because the Earth's surface is not flat but, rather, curved in a shape that is very close to the surface of a sphere. All map projections misstate the shape of the Earth in some way. It's simply impossible to transform a spherical surface to a flat (planar) surface without violating the true surface as a result of cutting, stretching, or otherwise distorting the information that lies on the sphere.

Perhaps the simplest of all map projections is a grid of perfect squares. In this simple map, horizontal lines are parallels and vertical lines are meridians. They are equally spaced in degrees, so this projection is sometimes called an *equal-angle grid*. A grid of this kind can show the true spacing (approximately) of the parallels, but it fails to show how the meridians converge toward the two poles. This convergence causes the grid to fail dismally in high latitudes, and the map usually has to be terminated at about 70° to 80° north and south.

Early attempts to find satisfactory map projections made use of a simple concept. Imagine the spherical Earth grid as a cage of wires located on meridians and parallels. A tiny light source is placed at the center of the cage, and the image of the wire grid is cast upon a surface outside the sphere. This situation is like a reading lamp with a lampshade. Basically, three kinds of "lampshades" can be used, as shown in Figure I.10.

Map projections allow the curved surface of the Earth to be displayed on a flat map.

First is a flat paper disk perched on the north pole. The shadow of the wire grid on this plane surface will appear as a combination of concentric circles (parallels) and radial straight lines (meridians). Here we have a polar-centered, or *polar projection*. Second is a cone of paper resting point-up on the wire grid. The cone can be slit down the side, unrolled, and laid flat to produce a map that is some part of a full circle. This is called a *conic projection*. Parallels are arcs of circles, and meridians are radiating straight lines. Third, a cylinder of paper can be wrapped around the wire sphere so as to be touching all around the equator. When slit down the side along a meridian, the cylinder can be unrolled to produce a *cylindrical projection*, which is a true rectangular grid.

None of these three projection methods can show the entire Earth grid, no matter how large a sheet of paper is used to receive the image. Obviously, if the entire Earth grid, or large parts of it, are to be shown, some quite different system must be devised. In Chapter 1, we describe three types of projections used throughout the book—the polar projection; the Mercator projection, which is a cylindrical projection; and the Winkel Tripel projection, which uses special mathematics that provide minimum distortion in a global map.

GEODISCOVERIES **Map Projections**
Watch an animation showing how map projections are constructed.

SCALES OF GLOBES AND MAPS

All globes and maps depict the Earth's features in much smaller size than the true features they represent. Globes are intended in principle to be perfect scale models of the Earth itself, differing from the Earth only in size. The scale of a globe is the ratio between the size of the globe and the size of the Earth, where "size" is some measure of length or distance (but not of area or volume).

Take, for example, a globe 20 cm (about 8 in.) in diameter, representing the Earth, which has a diameter of about 13,000 km. The scale of the globe is the ratio between 20 cm and 13,000 km. Dividing 13,000 by 20, we see that one centimeter on the globe represents 650 kilometers on the Earth. This relationship holds true for distances between any two points on the globe.

Scale is often stated as a simple fraction, termed the **scale fraction**. It can be obtained by reducing both Earth and globe distances to the same unit of measure, which in this case is centimeters. (There are 100,000 centimeters in one kilometer.) The advantage of the scale fraction is that it is entirely free of any specified units of measure, such as the foot, mile, meter, or kilometer. It is usually written as a fraction with a numerator of one using either a colon or with the numerator above the denominator. For the example shown above, the scale fraction is obtained by reducing 20/1300000000 to 1/65000000 or 1:65,000,000.

In contrast to a globe, a flat map cannot have a constant scale. In flattening the curved surface of the sphere to conform to a plane surface, all map projections stretch the Earth's surface in a nonuniform manner, so that the map scale changes from place to place. However, it is usually possible to select a meridian or parallel—the equator, for example—for which a scale fraction can be given, relating the map to the globe it represents.

SMALL-SCALE AND LARGE-SCALE MAPS

When geographers refer to small-scale and large-scale maps, they mean the value of the scale fraction. For example, a global map at a scale of 1:65,000,000 has a scale fraction value of 0.00000001534, which is obtained by dividing 1 by 65,000,000. A hiker's topographic map might have a scale of 1:25,000, for a scale value of 0.000040. Since the global-scale value is smaller, it is a *small-scale map*, while the hiker's map is a *large-scale map*. Note that this contrasts with common use of the terms *large-scale* and *small-scale*. When we refer in conversation to a large-scale phenomenon or effect, we typically refer to something that takes place over a large area and that is usually best presented on a small-scale map.

Maps of large scale show only small sections of the Earth's surface. Because they "zoom in," they are capable of carrying an enormous amount of geographic information in a convenient and an effective manner. Most large-scale maps carry a graphic scale, which is a line marked off into units representing kilometers or miles. Figure I.11 shows a portion of a large-scale map on which sample graphic scales in miles, feet, and kilometers are superimposed. Graphic scales make it easy to measure ground distances.

For practical reasons, maps are printed on sheets of paper usually less than a meter (3 ft) wide, as in the case of the ordinary highway map or navigation chart. Bound books of maps—atlases, that is—usually have pages no larger than 30 by 40 cm (about 12 by 16 in.), whereas maps found in textbooks and scientific journals are even smaller.

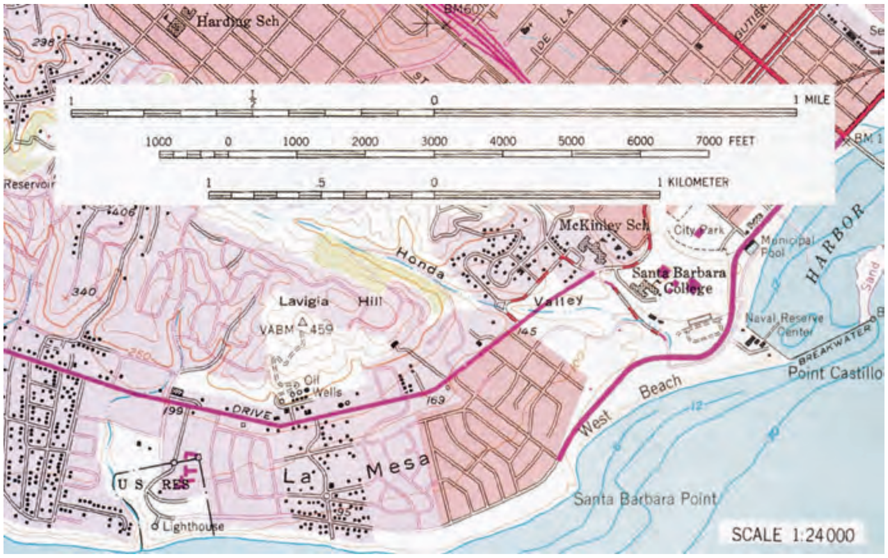
CONFORMAL AND EQUAL-AREA MAPS

With regard to the map projections shown in Figure I.10, it seems obvious that the shape and area of a small feature, like an island or peninsula, will change as the feature is projected from the surface of the globe to a map. With some projections, the area will change, but the shape will be preserved. Such a projection is referred to as *conformal*. The Mercator projection (Figure 1.11) is an example. Here, every small twist and turn of the shoreline of each continent is shown in its proper shape. However, the growth of the continents with increasing latitude shows that the Mercator projection does not depict land areas uniformly. A projection that does show area uniformly is referred to as *equal-area*. Here continents show their relative areas correctly, but their shapes are distorted. No projection can be both conformal and equal-area—only a globe has that property.

Conformal map projections show shapes correctly, whereas equal-area maps show areas correctly.

INFORMATION CONTENT OF MAPS

The information conveyed by a map projection grid system is limited to one category only: absolute location of points on the Earth's surface. To be more useful, maps also carry other types of information. Figure I.11 is a portion of a large-scale *multipurpose map*. Map sheets published by national governments, such as this one, are usually multipurpose maps. Using a great variety of symbols, patterns, and colors, these maps carry a high information content. Appendix 3 shows a larger



I.11 Graphic scales on a topographic map

A portion of a modern, large-scale topographic map for which three graphic scales have been provided.

example of a multipurpose map, a portion of a U.S. Geological Survey topographic quadrangle map for San Rafael, California.

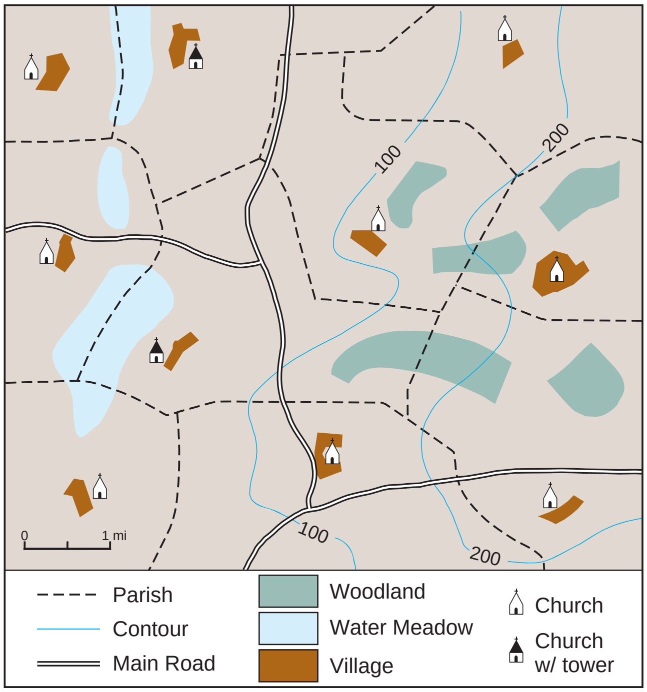
In contrast to the multipurpose map is the *thematic map*, which shows only one type of information, or theme. We use many thematic maps in this text. Some examples include Figure 4.25, mapping the frequency of severe hailstorms in the United States; Figure 5.17, atmospheric surface pressures; Figure 7.7, mean annual precipitation of the world; and Figure 7.10, world climates.

MAP SYMBOLS

Symbols on maps associate information with points, lines, and areas. To show information at a point, we use a *dot*—any small symbol to show point location. It might be a closed circle, an open circle, a letter, a numeral, or a graphic symbol of the object it represents (see "church with tower" in Figure I.12). A *line* can vary in width and can be single or double, colored, dashed, or dotted. A *patch* denotes a particular area, typically using a distinctive pattern or color or a line marking its edge.

Figure I.12 shows symbols applied to a map. There are two kinds of dot symbols (both symbolic of churches), three kinds of line symbols, and three kinds of patch symbols. Altogether, eight types of information are present. Line symbols freely cross patches, and dots can appear within patches. Two different kinds of patches can overlap. For more examples of symbols, consult the display of topographic map symbols facing the map of San Rafael in Appendix 3.

Map symbols can vary with map scale. Maps of very large scale, for example, a plot plan of a house, can show objects in their true outline form. As map scale is decreased, representation becomes more and more generalized. In physical geography, an excellent example is the depiction of a river, such as the lower Mississippi, shown in Figure I.13. The level of depiction of fine detail in a map is described by the term *resolution*. Maps

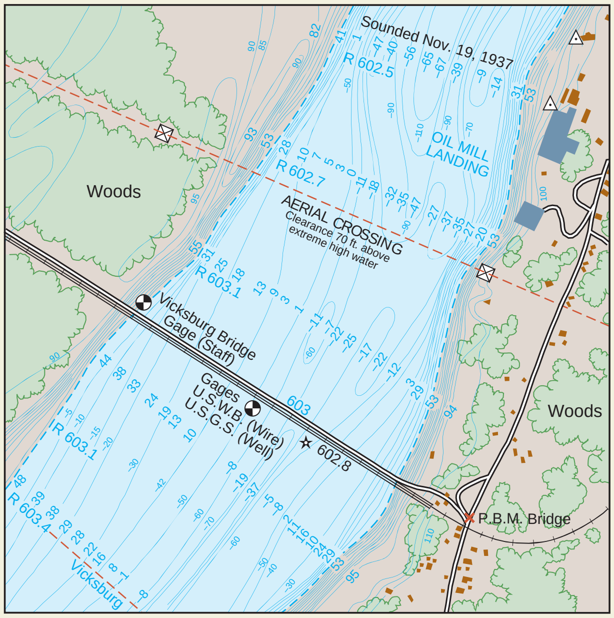


I.12 Map symbols

A multipurpose map of an imaginary area with 10 villages illustrating the use of dots, lines, and patches.

I.13 Map scale and information content

Maps of the Mississippi River on three scales. (Maps slightly enlarged for reproduction.)



▲ **1:20,000 scale** This map shows a detailed plan of the river and even includes contours on the river bed.

▲ **1:250,000 scale** At this scale, the river is depicted by two lines showing its banks and color showing the area of the river.

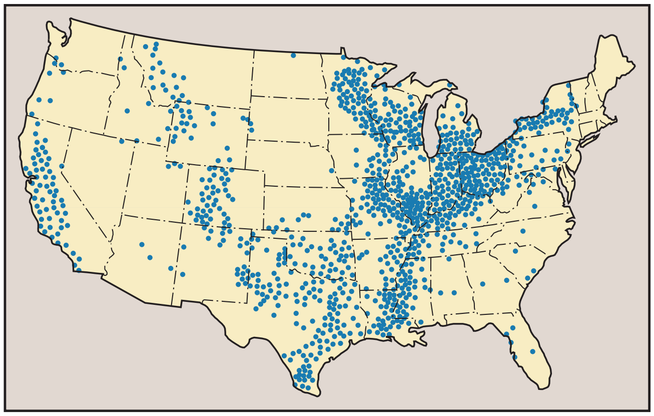
▼ **1:3,000,000 scale** At a very small scale, the river is shown as a solid line.

of large scale have much greater resolving power than maps of small scale.

PRESENTING NUMERICAL DATA ON THEMATIC MAPS

In physical geography, we often need to display numerical information on maps. Weather data provides an example—here we might wish to display air temperature, air pressure, wind speed, or amount of rainfall. Another category of information consists simply of the presence or absence of something. In this case, we can simply place a dot to mean "present," so that when entries are completed, the map shows a field of scattered dots (Figure I.14).

In some scientific programs, measurements are taken uniformly, for example, at the centers of grid squares laid over a map. For many classes of data, however, the locations of the observation points are predetermined by a fixed and nonuniform set of observing stations. For example, weather and climate data are often collected at stations typically located at airports. Whatever the



I.14 Dot map

A dot map showing the distribution of soils of the order Alfisols in the United States.

Table I.1 Examples of Isopleths

Name of Isopleth	Greek Root	Property Described	Examples in Figures
Isobar	*barros*, weight	Barometric pressure	5.17
Isotherm	*therme*, heat	Temperature of air, water, or soil	3.20
Isotach	*tachos*, swift	Fluid velocity	5.26
Isohyet	*hyetos*, rain	Precipitation	4.17
Isohypse (topographic contour)	*hypso*, height	Elevation	19.9 19.10

sampling method used, we end up with an array of numbers and dots indicating their location on the base map.

Although the numbers and locations may be accurate, it may be difficult to see the spatial pattern present in the data being displayed. For this reason, cartographers often simplify arrays of point values into isopleth maps. An **isopleth** is a line of equal value (from the Greek *isos,* "equal," and *plethos,* "fullness" or "quantity"). Figure 3.21 shows how an isopleth map is constructed for temperature data. In this case, the isopleth is an *isotherm,* or line of constant temperature. In drawing an isopleth, the line is routed among the points in a way that best indicates a uniform value, given the observations at hand.

Isopleth maps are important in various branches of physical geography. Table I.1 gives a partial list of isopleths of various kinds used in the Earth sciences, together with their names and the kinds of information they display. A special kind of isopleth, the *topographic contour* (or isohypse), is shown on the maps in Figures I.11, I.13A, and in the portion of the San Rafael topographic map in Appendix 3. Topographic contours show the configuration of land surface features, such as hills, valleys, and basins.

In contrast to the isopleth map is the *choropleth* map, which identifies information in categories. Our global maps of vegetation (Figure 9.6) and soils (Figure 10.16) are examples of thematic choropleth maps.

Isopleth maps show lines of equal value. Choropleth maps show categorical information associated with particular areas.

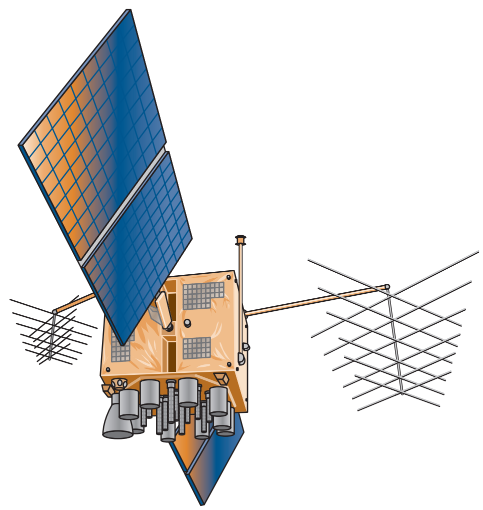
Cartography is a rich and varied field of geography with a long history of conveying geographic information accurately and efficiently. If you are interested in maps and mapmaking, you might want to investigate cartography further.

The Global Positioning System

The latitude and longitude coordinates of a point on the Earth's surface describe its position exactly. But how are those coordinates determined? For the last few hundred years, we have known how to use the position of the stars in the sky coupled with an accurate clock to determine the latitude and longitude of any point. Linked with advances in mapping and surveying, these techniques became highly accurate, but they were impractical for precisely determining locations in a short period of time.

Thanks to new technology originally developed by the U.S. Naval Observatory for military applications, there is now in place a **global positioning system** (GPS) that can provide location information to an accuracy of about 20 meters within a minute or two. The system uses 24 satellites that orbit the Earth every 12 hours, continuously broadcasting their position and a highly accurate time signal (Fig. I.15).

To determine location, a receiver listens simultaneously to signals from four or more satellites. The receiver compares the time readings transmitted by each satellite with the receiver's own clock to determine how long it took for each signal to reach the receiver. Since the radio signal travels at a known rate of speed, the receiver can convert the travel time into the distance between the receiver and the satellite. Coupling the distance to



I.15 GPS satellite

A GPS satellite as it might look in orbit high above the Earth. The U.S. Navy NAVSTAR GPS satellite system consists of 24 orbiting satellites.

each satellite with the position of the satellite in its orbit at the time of the transmission, the receiver calculates its position on the ground to within about 20 m (66 ft) horizontally and 30 m (98 ft) vertically.

The accuracy of the location is affected by several types of errors. One of the larger sources is the effect of the atmosphere on the radio waves of the satellite signal as they pass from the satellite to the receiver. Charged particles at the outer edge of the atmosphere (ionosphere) and water vapor in the lowest atmospheric layer (troposphere) act to slow the radio waves. Since the conditions in these layers can change within a matter of minutes, the speed of the radio waves varies in an unpredictable way. Another transmission problem is that the radio waves may bounce off local obstructions and then reach the receiver, causing two slightly different signals to arrive at the receiver at the same time. This "multipath error" creates noise that confuses the receiver.

There is a way, however, to determine location within about 1 m (3.3 ft) horizontally and 2 m (6.6 ft) vertically. The method uses two GPS units, one at a base station and one that is mobile and used to determine the desired locations. The base station unit is placed at a position that is known with very high accuracy. By comparing its exact position with that calculated from each satellite signal, it determines the small deviations from orbit of each satellite, any small variations in each satellite's clock, and the exact speed of that satellite's radio signal through the atmosphere at that moment. It then broadcasts that information to the GPS field unit, where it is used to calculate the position more accurately. Because this method compares two sets of signals, it is known as *differential GPS*.

The global Geographic Positioning System uses signals from a constellation of orbiting satellites to locate points on the Earth with high accuracy.

In North America, differential GPS information is now available everywhere using the *Wide Area Augmentation System (WAAS)*, which is provided by the U.S. Federal Aviation Administration and the Department of Transportation. The system includes about 25 ground receiving stations that monitor the signals of GPS satellites and provide a stream of differential correction information. This information is uploaded to a geostationary satellite, where it is rebroadcast to receivers on the ground. A GPS unit with a built-in WAAS receiver can determine position to within a few meters.

The enhanced accuracy of differential GPS is required for coastal navigation, where a few meters in position can make the difference between a shipping channel and a shoal. It is also required for the new generation of aircraft landing systems that will allow much safer instrument landings with equipment that is much lower in cost than existing systems.

As GPS technology has developed, costs have fallen exponentially. It is now possible to buy a small, handheld GPS receiver for less than $100. Besides plotting your progress on a computer-generated map as you drive your car or sail your boat, GPS technology can even help parents keep track of children at a theme park. And with the coupling of wireless telephones and GPS, you can even get driving directions over your phone.

GEODISCOVERIES **Global Positioning Systems**
Watch an animation on the Navistar Global Positioning System to learn more about how the system works.

Geographic Information Systems

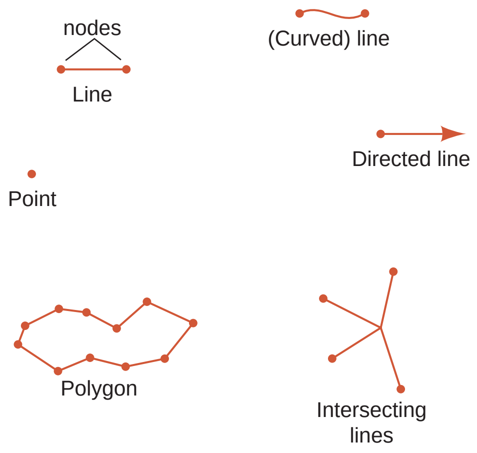
Maps, like books, are very useful devices for storing information, but they have limitations. Recent advances in computing capability have enabled geographers to develop a powerful new tool to work with spatial data—the **geographic information system (GIS)**. A GIS is a computer-based system for acquiring, processing, storing, querying, creating, analyzing, and displaying spatial data. Geographic information systems have allowed geographers, geologists, geophysicists, ecologists, planners, landscape architects, and others to develop applications of spatial data processing ranging from planning land subdivisions on the fringes of suburbia to monitoring the deforestation of the Amazon Basin.

GEODISCOVERIES **Geographic Information Systems**
Watch a narrated animation to explore the key ideas behind geographic information systems and see some examples.

SPATIAL OBJECTS IN GEOGRAPHIC INFORMATION SYSTEMS

Geographic information systems are designed to manipulate spatial objects. A **spatial object** is a geographic point, line, or area to which some information is attached. This information may be as simple as a place name or as complicated as a large data table with many types of information. Some spatial objects are illustrated in Figure I.16.

A *point* is a spatial object without an area, only a location. A *line* is also a spatial object with no area, but it has two points associated with it, one for each end of the line. These special points are often referred to as *nodes*. Normally a line is straight, but it can also be defined as a smooth curve having a certain shape. If the two nodes marking the ends of the line are



I.16 Spatial objects

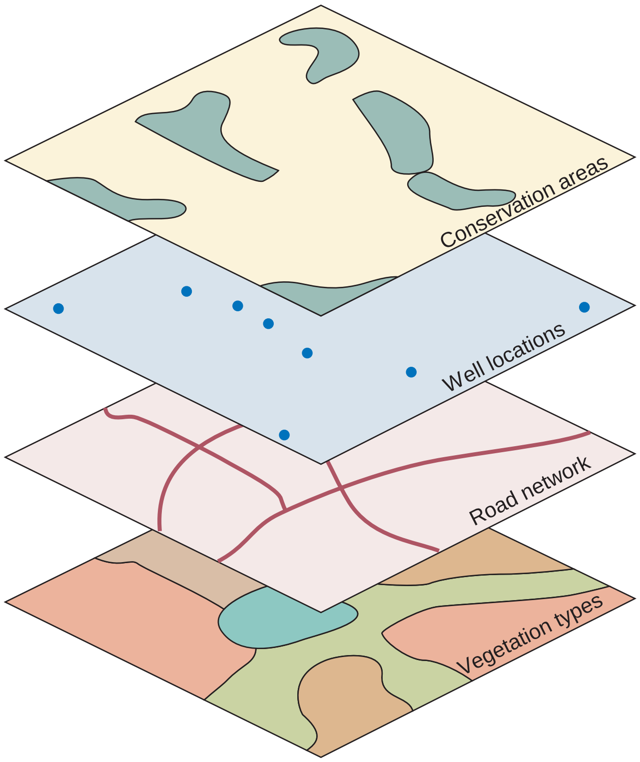
Spatial objects in a GIS can include points, lines of various types, intersecting lines, and polygons.

differentiated as starting and ending, then the line has a direction. If the line has a direction, then its two sides can be distinguished. This allows information to be attached to each side—for example, labels for land on one side and water on the other. Lines connect to other lines when they share a common node. A series of connected lines that form a closed chain is a *polygon*. A polygon identifies an *area*, the last type of spatial object.

By defining spatial objects in this way, computer-based geographic information systems allow easy manipulation of the objects and permit many different types of operations to compare objects and generate new objects. As an example, suppose we have a GIS data layer composed of conservation land in a region represented as polygons and another layer containing the location of preexisting water wells as points within the region (Figure I.17). It is very simple to use the GIS to identify the wells that are on conservation land. Or the conservation polygons containing wells may also be identified and even output as a new data layer. By comparing the conservation layer with a road network layer portrayed as a series of lines, we could identify the conservation polygons containing roads.

Geographic information systems use computers to store, process, analyze, and display spatial data.

We could also compare the conservation layer to a layer of polygons showing vegetation type, and tabulate the amount of conservation land in forest, grassland, brush, and so forth. We could even calculate distance zones around a spatial object, for example, to create a map of buffer zones that are located within, say, 100 meters of conservation land. Many other possible manipulations exist.



I.17 Data layers in a GIS

A GIS allows easy overlay of spatial data layers for such queries as "Identify all wells on conservation land."

KEY ELEMENTS OF A GIS

A geographic information system consists of five elements: data acquisition, preprocessing, data management, data manipulation and analysis, and product generation. Each is a component or process needed to ensure the functioning of the system as a whole.

In the *data acquisition* process, data are gathered together for the particular application. These may include maps, air photos, tabular data, and other forms as well. In *preprocessing*, the assembled spatial data are converted to forms that can be ingested by the GIS to produce data layers of spatial objects and their associated information.

The *data management* component creates, stores, retrieves, and modifies data layers and spatial objects. It is essential to proper functioning of all parts of the GIS. The *manipulation and analysis* component is the real workhorse of the GIS. Utilizing this component, the user asks and answers questions about spatial data and creates new data layers of derived information.

The last component of the GIS, *product generation*, produces output products in the form of maps, graphics, tabulations, or statistical reports that are the end products desired by the users. Taken together, these components provide a system that can serve many geographic applications at many scales.

Many new and exciting areas of geographic research are associated with geographic information systems, ranging from development of new ways to manipulate spatial data to the modeling of spatial processes using a GIS. An especially interesting area is understanding how outputs are affected by errors and uncertainty in spatial data inputs, and how to communicate this information effectively to users.

Geographic information systems is a rapidly growing field of geographic research and application. Given the rate at which computers become ever more powerful as technology improves, we can expect great strides in this field in future years.

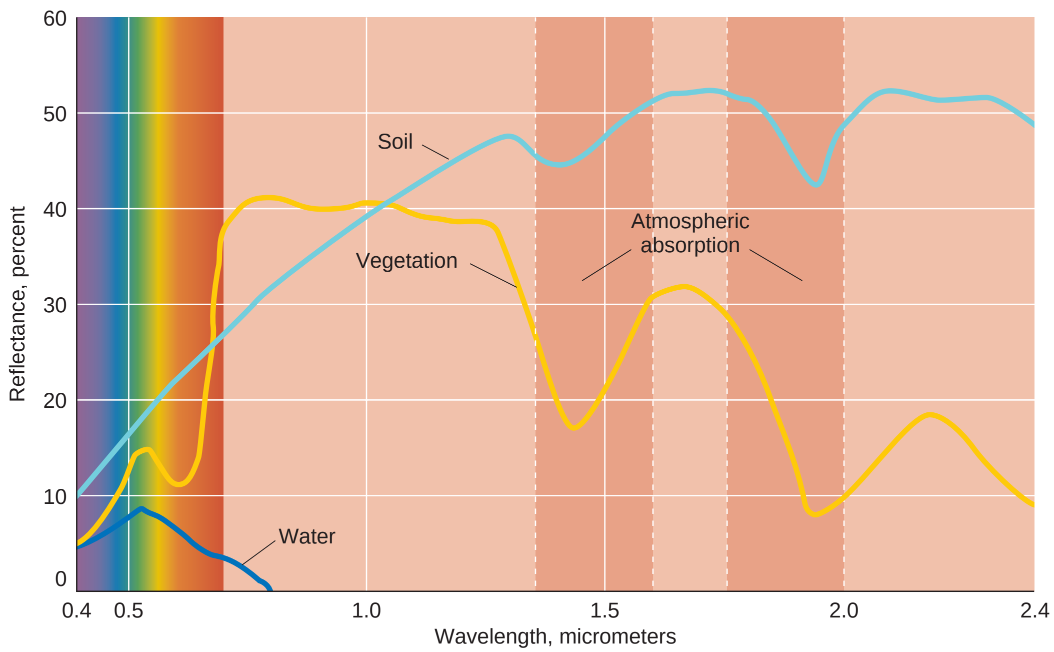
Remote Sensing for Physical Geography

Another important geographic technique for acquiring spatial information is **remote sensing**. This term refers to gathering information from great distances and over broad areas, usually through instruments mounted on aircraft or orbiting spacecraft. These instruments, or *remote sensors*, measure electromagnetic radiation coming from the Earth's surface and atmosphere as received at the aircraft or spacecraft platform. The data acquired by remote sensors are typically displayed as images—photographs or similar depictions on a computer screen or color printer—but are often processed further to provide other types of outputs, such as maps of vegetation condition or extent, or of land-cover class. Information obtained can range from fine local detail—such as the arrangement of cars in a parking lot—to a global-scale picture—for example, the "greenness" of vegetation for an entire continent. As you read this textbook, you will see many examples of remote sensing, especially images from orbiting satellites.

All substances, whether naturally occurring or synthetic, are capable of reflecting, transmitting, absorbing, and emitting *electromagnetic radiation*. For remote sensing, however, we are only concerned with energy that is reflected or emitted by an object and that reaches the remote sensor. For remote sensing of reflected energy, the Sun is the source of radiation in many applications. As we will see in Chapter 2, solar radiation reaching the Earth's surface is largely in the form of light energy that includes visible, near-infrared, and shortwave infrared light. Remote sensors are commonly constructed to measure radiation reflected from the Earth in all or part of this range of light energy. For remote sensing of emitted energy, the object or substance itself is the source of the radiation, which is related largely to its temperature.

COLORS AND SPECTRAL SIGNATURES

Most objects or substances at the Earth's surface possess color to the human eye. This means that they reflect radiation differently in different parts of the visible spectrum. Figure I.18 shows how the reflectance of water,



I.18 Reflectance spectra of vegetation, soil, and water

The amount of energy reflected by surfaces of vegetation, soil, and water depends on the wavelength of the light. Note that water vapor in the atmosphere absorbs radiation strongly at wavelengths from about 1.2 to 1.4 μm and 1.75 to 1.9 μm, so it is not possible for a space-borne remote sensor to "see" the surface at those wavelengths.

vegetation, and soil varies with light ranging in wavelength from visible to shortwave infrared. Water surfaces are always dark but are slightly more reflective in the blue and green regions of the visible spectrum. Thus, clear water appears blue or blue-green to our eyes. Beyond the visible region, water absorbs nearly all radiation it receives and so looks black in images acquired in the near-infrared and shortwave infrared regions.

Vegetation appears dark green to the human eye, which means that it reflects more energy in the green portion of the visible spectrum while reflecting somewhat less in the blue and red portions. But vegetation also reflects very strongly in near-infrared wavelengths, which the human eye cannot see. Because of this property, vegetation is very bright in near-infrared images. This distinctive behavior of vegetation—appearing dark in visible bands and bright in the near-infrared—is the basis for much of vegetation remote sensing, as we will see in many examples of remotely sensed images throughout this book.

Different types of remotely-sensed objects or surfaces often reflect the electromagnetic spectrum differently, providing characteristic spectral signatures.

The soil spectrum shows a slow increase of reflectance across the visible and near-infrared spectral regions and a slow decrease through the shortwave infrared. Looking at the visible part of the spectrum, we see that soil is brighter overall than vegetation and is somewhat more reflective in the orange and red portions. Thus, it appears brown. (Note that this is just a "typical" spectrum—soil color can actually range from black to bright yellow or red.)

We refer to the pattern of relative brightness within the spectrum as the spectral signature of an object or type of surface. Spectral signatures can be used to recognize objects or surfaces in remotely sensed images in much the same way that we recognize objects by their colors. In computer processing of remotely sensed images, **spectral signatures** can be used to make classification maps, showing, for example, water, vegetation, and soil.

THERMAL INFRARED SENSING

While objects reflect some of the solar energy they receive, they also emit internal energy as heat that can be remotely sensed. Warm objects emit more *thermal radiation* than cold ones, so warmer objects appear brighter in thermal infrared images. Besides temperature, the intensity of infrared emission depends on the *emissivity* of an object or a substance. Objects with higher emissivity appear brighter at a given temperature than objects with lower emissivities. Differences in emissivity affect thermal images. For example, two different surfaces might be at the same temperature, but the one with the higher emissivity will look brighter because it emits more energy.

Some substances, such as crystalline minerals, show different emissivities at different locations in the thermal infrared spectrum. In a way, this is like having a particular color, or spectral signature, in the thermal infrared spectral region. In Chapter 11 we will see examples of how some rock types can be distinguished and mapped using thermal infrared images.

RADAR

There are two classes of remote sensor systems: passive and active. *Passive systems* acquire images without providing a source of wave energy. The most familiar passive system is the camera, which uses electronic detectors or photographic film to sense solar energy reflected from the scene. *Active systems* use a beam of wave energy as a source, sending the beam toward an object or surface. Part of the energy is reflected back to the source, where it is recorded by a detector.

Radar is an example of an active sensing system that is often deployed on aircraft or spacecraft. Radar systems in remote sensing use the *microwave* portion of the electromagnetic spectrum, so named because the waves have a short wavelength compared to other types of radio waves. Radar systems emit short pulses of microwave radiation and then "listen" for a returning microwave echo. By analyzing the strength of each return pulse and the exact time it is received, an image is created showing the surface as it is illuminated by the radar beam.

Radar systems used for land imaging emit microwave energy that is not significantly absorbed by water. This means that radar systems can penetrate clouds to provide images of the Earth's surface in any weather. In contrast, ground-based weather radars use microwaves that are scattered by water droplets or ice crystals and produce an image of precipitation over a region. They detect rain, snow, and hail and are used in local weather forecasting.

Radar is a passive remote sensing system that emits a pulse of microwaves toward the ground and then measures the time and strength of the response scattered back to the radar instrument.

Figure I.19 shows a radar image of the folded Appalachian Mountains in south-central Pennsylvania. It is produced by an air-borne radar instrument that sends pulses of radio waves downward and sideward as the airplane flies forward. Surfaces oriented most nearly at right angles to the slanting radar beam will return the strongest echo and therefore appear lightest in tone. In contrast, those surfaces facing away from the beam

I.19 Side-looking radar image from south-central Pennsylvania

The image shows a portion of the folded Appalachians with zigzag ridges and intervening valleys. The area shown is about 40 km (25 mi) wide.

will appear darkest. The effect is to produce an image resembling a three-dimensional model of the landscape illuminated at a strong angle. The image shows long mountain ridges running from upper right to lower left and casting strong radar shadows to emphasize their three-dimensional form. The ridges curve and turn sharply, revealing the geologic structure of the region. Between the ridges are valleys of agricultural land, which are distinguished by their rougher texture in the image. In the upper left is a forested plateau that has a smoother appearance.

DIGITAL IMAGING

Modern remote sensing relies heavily on computer processing to extract and enhance information from remotely sensed data. This requires that the data be in the form of a **digital image**. In a digital image, large numbers of individual observations, termed *pixels*, are arranged in a systematic way related to the Earth position from which the observations were acquired.

The great advantage of digital images over photographic images is that they can be processed by computer, for example, to increase contrast or sharpen edges (Figure I.20). *Image processing* refers to the manipulation of digital images to extract, enhance, and display the information that they contain. In remote sensing, image processing is a very broad field that includes many methods and techniques for processing remotely sensed data.

Many remotely sensed digital images are acquired by scanning systems, which may be mounted in aircraft or on orbiting space vehicles. Scanning is the process of receiving information instantaneously from only a very small portion of the area being imaged (Figure I.21). The scanning instrument senses a very small field of view that runs rapidly across the ground scene. Light from the field of view is focused on a detector that responds very quickly to small changes in light intensity. Electronic circuits read out the detector at very short time intervals and record the intensities. Later, the computer reconstructs a digital image of the ground scene from the measurements acquired by the scanning system.

Most scanning systems in common use are **multispectral scanners**. These devices have multiple detectors and measure brightness in several wavelength regions simultaneously. An example is the Thematic Mapper instrument used aboard the Landsat series of Earth-observing satellites. This instrument simultaneously collects reflectance data in seven spectral bands. Six wavebands sample the visible, near-infrared and shortwave infrared regions, while a seventh records thermal infrared emissions. Figure I.22 shows a color composite of the Boston region acquired by the Landsat Thematic Mapper. The image uses red, near-infrared, and shortwave infrared wavebands to show vegetation in green, beaches and bare soils in pink, and urban surfaces in shades of blue.

An alternative to scanning is *direct digital imaging* using large numbers of detectors arranged in a two-dimensional array (Figure I.23). This technology is in common use in digital cameras and is also used in some imagers on spacecraft. The array has millions of tiny detectors arranged in rows and columns that individually measure the amount of light they receive during an exposure. Electronic circuitry reads out the measurement made by each detector, composing the entire image rapidly. Advanced digital cameras now record detail as finely as film cameras.

ORBITING EARTH SATELLITES

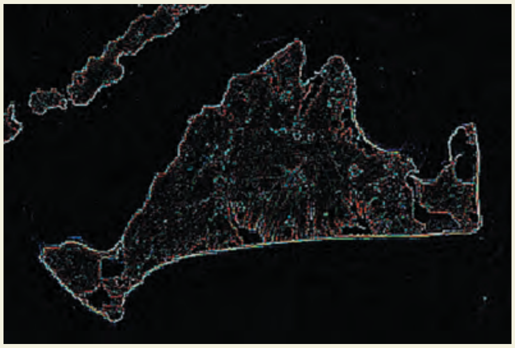
With the development of orbiting Earth satellites carrying remote sensing systems, remote sensing has expanded into a major branch of geographic research. Because orbiting satellites can image and monitor large geographic areas or even the entire Earth, we can now

I.20 Image processing

These four panels show an image of the island of Martha's Vineyard, Massachusetts, acquired by the Landsat Enhanced Thematic Mapper instrument on August 26, 2000.

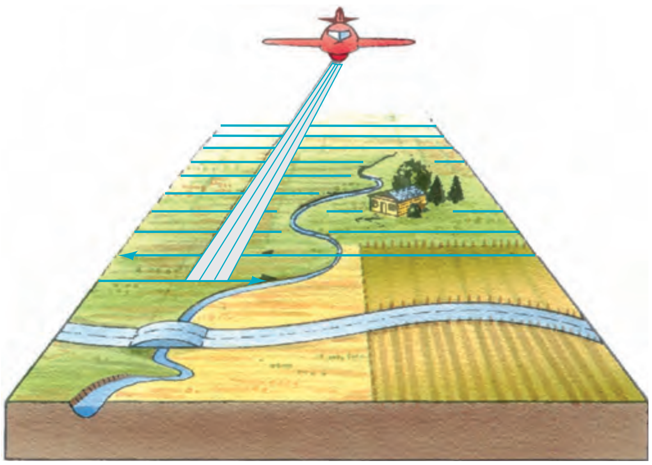
▲ As originally acquired, the image lacks contrast.

▲ The color scales are adjusted to show a wider range of colors.



▲ An edge enhancement computation shows edges within the image as bright pixels.

▲ When the edge image is added to contrast-enhanced image, the result is an image that appears clearer and sharper than the original.



I.21 Multispectral scanning from aircraft

As the aircraft flies forward, the scanner sweeps from side to side. The result is a digital image covering the overflight area.

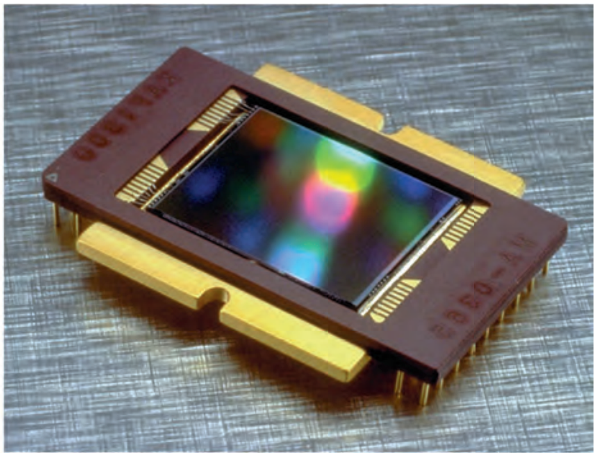
carry out global and regional studies that cannot be done in any other way.

Most satellites designed for remote sensing use a **Sun-synchronous orbit** (Figure I.24a). As the satellite circles the Earth, passing near each pole, the Earth rotates underneath it, allowing all of the Earth to be imaged after repeated passes. The orbit is designed so that the images of a location acquired on different days are taken at the same hour of the day. In this way, the solar lighting conditions remain about

A Sun-synchronous orbit allows a remote imager to cover nearly all the Earth's surface with only slowly varying illumination conditions. A geostationary orbit places the imager above a single point on the equator, watching an area of about half the Earth.

I.22 Landsat image of Boston

An image of Boston, acquired by Landsat Thematic Mapper on September 27, 1991. In this false-color composite, the red color is from the shortwave infrared band (1.55 to 1.75 μm), the green from the near-infrared (0.79 to 0.91 μm), and the blue from the red band (0.60 to 0.72 μm).



I.23 An area array of detectors

The center part of this computer chip is covered by an array of tiny light detectors arranged in rows and columns.

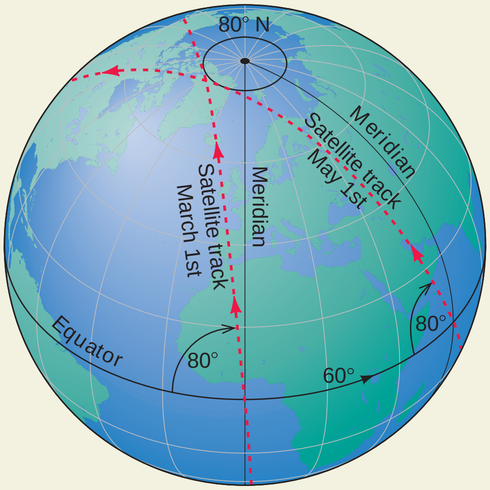
the same from one image to the next. Typical Sun-synchronous orbits take 90 to 100 minutes to circle the Earth and are located at heights of about 700 to 800 km (430 to 500 mi) above the Earth's surface.

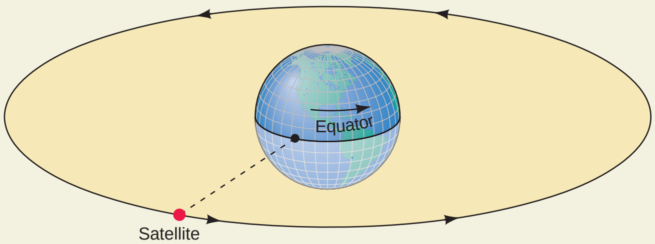
Another orbit used in remote sensing is the **geostationary orbit** (Figure I.24B). Instead of orbiting above the poles, a satellite in geostationary orbit constantly revolves above the equator. The orbit height, about 35,800 km (22,200 mi), is set so that the satellite makes one revolution in exactly 24 hours in the same direction that the Earth turns. Thus, the satellite always remains above the same point on the Equator. From its high vantage point, the geostationary orbiter provides a view of nearly half of the Earth at any moment.

Geostationary orbits are ideal for observing weather, and the weather satellite images readily available on

I.24 Satellite orbits

▼ **Earth track of a Sun-synchronous orbit** With the Earth track inclined at 80° to the Equator, the orbit slowly swings eastward at about 30° longitude per month, maintaining its relative position with respect to the Sun. This keeps the solar lighting conditions similar from one image of a location to the next. Between March 1 and May 1 (shown) the orbit moves about 60°.





▲ **Motion of a geostationary satellite** Because the satellite revolves around the Earth above the Equator at the same rate as the Earth's rotation, it appears fixed in the sky above a single point on the Equator.

television and the Internet are obtained from geostationary remote sensors. Geostationary orbits are used by communications satellites. Since a geostationary orbiter remains at a fixed position in the sky for an Earthbound observer, a high-gain antenna can be pointed at the satellite and fixed in place permanently, providing high-quality, continuous communications. Satellite television systems also use geostationary orbits.

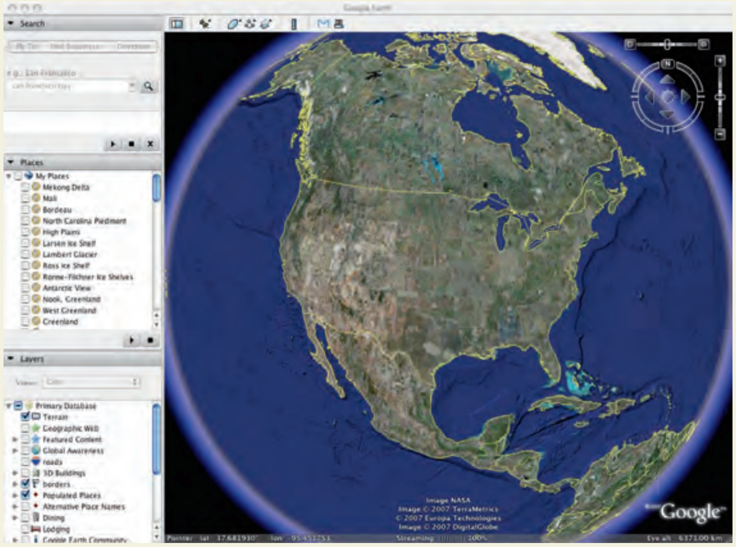
Remote sensing is an exciting, expanding field within physical geography and the geosciences in general. As you read the rest of this text, you will see many examples of remotely sensed images.

Earth Visualization Tools

Within the last few years, remote sensing, geographic information systems, and GPS technology have been integrated into new and exciting Internet tools for visualizing the Earth. Google Earth and World Wind are outstanding examples of these **Earth visualization tools**.

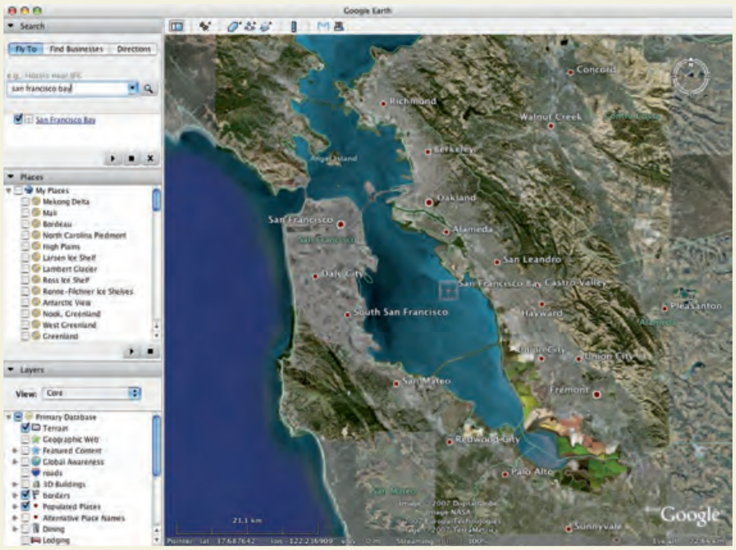
I.25 Google Earth images

These four images show screens for Google Earth.



◀ The opening screen shows a view of the globe centered on the United States. At the left are saved locations, called placemarks, and a list of GIS features that can be enabled.

▶ Zooming in to the San Francisco Bay region, we can see many physical and cultural features identified by name.

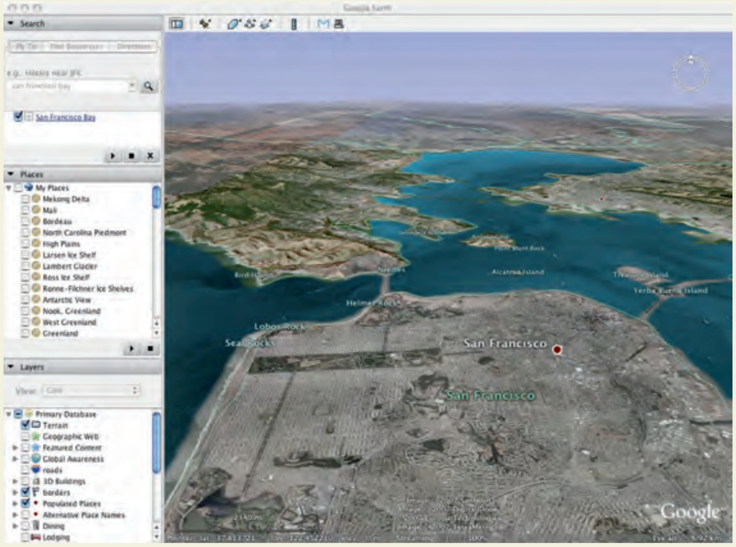


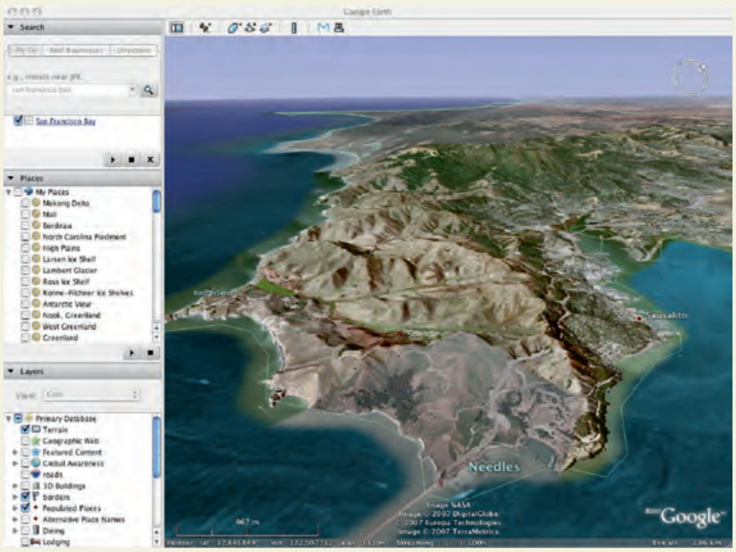
GOOGLE EARTH

Google Earth is a program for personal computers that allows users to roam the Earth's surface at will and zoom in on images showing the surface in detail. The program uses the Internet to access a large database of images maintained by Google (Figure I.25). The spatial resolution of the images varies from location to location, depending on the Earth imagery available. Basic coverage is provided largely by Landsat satellite data, with pixels 15 or 30 m (50 or 100 ft) on a side. But many areas of much higher spatial detail are present, using other satellite sources as well as air photos. Some states and a number of European countries are covered by images at 1-m spatial resolution. A few locations are covered at resolutions as fine as 15 cm (6 in.). Most of the images are less than three years old.

The images in Google Earth are linked to an elevation database that was also provided by an application of remote sensing using radar mapping technology. As a result, the elevation of each pixel is known to an accuracy

▶ By changing the viewpoint, the program provides an oblique image of the city of San Francisco looking northward.





◀ Moving the field of view and choosing a new viewpoint, the town of Sausalito with Mount Tamalpais in the background comes into view.

of 5–10 m, depending on the location. This allows computation of synthetic three-dimensional views of the landscape, including simulated fly-overs. By placing the viewer in motion over the landscape, the fly-over gives a strong visual impression of three-dimensional terrain, even though it is viewed on a flat computer screen.

Earth visualization tools merge remote sensing, GIS, and GPS technology to provide interactive viewing of the Earth's surface and its physical and cultural features.

Also linked to the image database are layers of GIS information. These include natural features, such as rivers and peaks, as well as political land boundaries and place names. A road network can also be superimposed. A search capability allows the user to type in a location (for example, the name of a city or town) and have the program zoom in to a close view. You can even ask to see restaurants, lodgings, parks, and recreation areas through the GIS linkages.

Because Google Earth provides a view of nearly every point on land, it is a very useful tool for studying physical geography. Our web site provides fly-over tours for each chapter. These are files of placemarks locating views of interest that can be downloaded and opened with the Google Earth application.

OTHER EARTH VISUALIZATION TOOLS

Although Google Earth is at present the most technologically advanced of web-based Earth visualization tools, several other tools are readily available. NASA's World Wind is a similar window on the Earth that starts with a global view and allows zooming in for fine detail. It also uses an elevation database, so it can provide three-dimensional renderings of the surface as well as realistic fly-overs.

TerraServer.com provides overhead high-resolution photos, with spatial resolutions as fine as 30 cm (11.8 in.) per pixel over many urbanized areas of the United States. Outside of the United States, most of the coverage is at 15 m (50 ft) per pixel with some inset areas in higher resolution. The service requires a subscription and payment for downloading images.

TerraServer-USA, a service of the U.S. Geological Survey, provides on-line topographic maps for the United States. Many of these are orthophoto maps that use high-resolution air photos as a base. The Geological Survey also hosts the National Map on the web, an extensive database with a large number of map layers, including administrative boundaries, geographic names, geology, land use and cover, natural hazards, topography, and transportation.

A Look Ahead

Our chapter has presented an introduction to geography, to physical geography, and to some of the big ideas that arch over physical geography. We have introduced some of the key environmental and global change topics that will appear in our text. We have also described some of the special tools that geographers use, including maps, Geographic Information Systems, and remote sensing. Armed with these tools and ideas, we are ready to proceed to the subject itself. We will start with weather and climate, where we will see how solar energy drives a vast circulation of atmosphere and oceans that changes our physical environment from day to day, week to week, and year to year.

Humans are now the dominant species on the planet. Nearly every part of the Earth has felt human impact in some way. As the human population continues to grow and rely more heavily on natural resources, our impact on natural systems will continue to increase. Each of us is charged with the responsibility to treat the Earth well and respect its finite nature. Understanding the processes that shape our habitat as they are described by physical geography helps us all to become better citizens of our home planet.

IN REVIEW INTRODUCING PHYSICAL GEOGRAPHY

- **Geography** is the study of the evolving character and organization of the Earth's surface. Geography has a unique set of perspectives. Geographers look at the world from the **viewpoint** of geographic space, focus on the **synthesis** of ideas from different disciplines, and develop and use special techniques for the **representation** and manipulation of spatial information.
- **Human geography** deals with social, economic, and behavioral processes that differentiate places, and **physical geography** examines the natural processes occurring at the Earth's surface that provide the physical setting for human activities.
- **Climatology** is the science that describes and explains the variability in space and time of the heat and moisture states of the Earth's surface, especially its land surfaces. **Geomorphology** is the science of Earth surface processes and landforms. **Coastal and marine geography** is a field that combines the study of geomorphic processes that shape shores and coastlines with their application to coastal development and marine resource utilization. **Geography of soils**

includes the study of the distribution of soil types and properties and the processes of soil formation. **Biogeography** is the study of the distributions of organisms at varying spatial and temporal scales, as well as the processes that produce these distribution patterns. Water resources and hazards assessment are applied fields that blend both physical and human geography.

- Scale, pattern, and process are three interrelated geographic themes. **Scale** refers to the level of structure or organization at which a phenomenon is studied, **pattern** refers to the variation in a phenomenon seen at a particular scale, and **process** describes how the factors that affect a phenomenon act to produce a pattern at a particular scale. The processes of physical geography operate at multiple scales, including *global, continental, regional,* and *local.*
- **Spheres**, **systems**, and **cycles** are three overarching themes that appear in physical geography. The four great Earth realms are **atmosphere**, **hydrosphere**, **lithosphere**, and **biosphere**. The life layer is the shallow surface layer where lands and oceans meet the atmosphere and where most forms of life are found.
- Physical processes often act together in an organized way that we can view as a **system**. A *systems approach* to physical geography looks for linkages and interactions between processes.
- Natural systems may undergo periodic, repeating changes that constitute **time cycles**. Important time cycles in physical geography range in length from hours to millions of years.
- Physical geography is concerned with the natural world around us—the human environment. Natural and human processes are constantly changing that environment.
- Global climate is changing in response to human impacts on the greenhouse effect. Global pathways of carbon flow can influence the greenhouse effect and are the subject of intense research interest.
- Maintaining global biodiversity is important both for maintaining the stability of ecosystems and guarding a potential resource of bioactive compounds for human benefit. Unchecked human activity can degrade environmental quality and create pollution.
- Extreme events take ever-higher tolls on life and property as populations expand. Extreme weather—storms and droughts, for example—will be more frequent with global warming caused by human activity.
- Important tools for studying the fields of physical geography include **maps**, **geographic information systems**, **remote sensing**, *mathematical modeling,* and *statistics.*
- **Cartography** is the art and science of making **maps**, which depict objects, properties, or activities as they are located on the Earth's surface.
- A **map projection** is an orderly system for displaying the curved surface of the Earth on a flat map. Common map projections include *polar, conic*, and *cylindrical.*
- The scale of a map relates distance on the Earth to distance on a globe or flat map. It is expressed by the **scale fraction**. *Large-scale maps* show small areas, while *small-scale maps* show large areas.
- *Conformal* maps preserve the shapes of geographic features, but not their areas. *Equal-area* maps show the areas of geographic features correctly, but distort their shape. Only a globe is both conformal and equal-area.
- *Multipurpose maps* use symbols, patterns, and colors to convey different types of information on the same map. *Thematic maps* display a single class of information, or theme.
- Map symbols include *dots, lines*, and *patches. Resolution* describes the level of detail shown on a map.
- **Isopleth** maps show lines of equal value for a continuously varying property. They are constructed from individual observations at points. A temperature map of isotherms is an example. A *choropleth* map shows categories of information, such as soil type or rock type, as areas on a map.
- The **global positioning system (GPS)** locates the position of an observer on the Earth using signals from Earth satellites. The fine accuracy of location is affected by the atmosphere, which is constantly changing.
- *Differential GPS* significantly improves location accuracy. It uses two GPS receivers, one at a base station and one at nearby locations to be plotted. In North America, the *Wide Area Augmentation System* provides differential GPS information by geostationary satellite broadcast.
- A **geographic information system (GIS)** is a computer-based tool for working with spatial data. It works with **spatial objects**, which include *points, lines*, and *polygons*, and manipulates information associated with spatial objects.
- A geographic information system has five elements: *data acquisition, preprocessing, data management, data manipulation and analysis*, and *product generation.*
- ***Remote sensing*** refers to acquiring information from a distance, usually of large areas, by instruments called *remote sensors* flown on aircraft or spacecraft. The information is obtained by measuring *electromagnetic radiation* reflected or emitted by an object or type of Earth surface.
- Most objects or surfaces reflect the colors of the spectrum differently, creating distinctive **spectral signatures**. Vegetation is dark green in the visible spectrum, but bright in the near-infrared.
- Objects or surfaces emit *thermal radiation* in proportion to their temperature. *Emissivity*, which affects the amount of radiation emitted at a given temperature, varies with the object or surface type.

- *Passive* sensing systems rely on environmental illumination or internal emission, while *active* systems provide their own source of energy. **Radar** is an active sensing system that uses microwave radiation.
- Remote sensing uses **digital images** that are processed by computer. *Image processing* is used to extract and enhance the information content of digital images. Digital images are typically acquired by a **multispectral scanner** or by a *direct digital imager* that uses an array of detectors.
- Satellite orbits used for remote sensing include Sun-synchronous and geostationary. The **Sun-synchronous orbit** covers most of the Earth while maintaining similar illumination conditions for repeat images. The **geostationary orbit** keeps the imager always above the same point on the Equator.
- **Earth visualization tools** integrate remote sensing, GIS, and GPS technology to create a visual simulation of the Earth's surface viewable on a networked computer. Google Earth is a prominent example.

KEY TERMS

geography, p. 4
viewpoint, p. 4
synthesis, p. 5
representation, p. 5
human geography, p. 5
physical geography, p. 5
climatology, p. 5
geomorphology, p. 5
coastal and marine geography, p. 6
geography of soils, p. 6
biogeography, p. 7
water resources, p. 7
hazards assessment, p. 7
spheres, p. 10
atmosphere, p. 10
lithosphere, p. 10
hydrosphere, p. 10
biosphere, p. 11
life layer, p. 11
scale, p. 11
pattern, p. 11
process, p. 11
systems, p. 12
time cycles, p. 12
cartography, p. 16
map, p. 16
map projection, p. 18
scale fraction, p. 19
isopleth, p. 22
global positioning system (GPS), p. 22
geographic information system (GIS), p. 23
spatial object, p. 23
remote sensing, p. 25
spectral signature, p. 26
radar, p. 26
digital image, p. 27
multispectral scanner, p. 27
Sun-synchronous orbit, p. 28
geostationary orbit, p. 29
Earth visualization tool, p. 30

REVIEW QUESTIONS

1. What is geography? Identify three perspectives used by geographers in studying the physical and human characteristics of the Earth's surface.
2. How does human geography differ from physical geography?
3. Identify and define five important subfields of science within physical geography.
4. Identify and define three interrelated themes that often arise in geographic study.
5. Name and describe each of the four great physical realms of Earth. What is the life layer?
6. Provide two examples of processes or systems that operate at each of the following scales: global, continental, regional, and local.
7. How is the word "system" used in physical geography? What is a systems approach?
8. What is a time cycle as applied to a system? Give an example of a time cycle evident in natural systems.
9. Identify and describe two interacting components of global change.
10. How is global climate change influenced by human activity?
11. Why are current research efforts focused on the carbon cycle?
12. Why is loss of biodiversity a concern of biogeographers and ecologists?
13. How does human activity degrade environmental quality? Provide a few examples.
14. How do extreme events affect human activity? Is human activity influencing the size or reoccurrence rate of extreme events?
15. Describe three types of map projections as they might occur by projecting a wire globe onto a flat sheet of paper.
16. What is the scale fraction of a map or globe? Can the scale of a flat map be uniform everywhere on the map? Do large-scale maps show large areas or small areas?
17. How do conformal and equal-area maps differ?
18. What types of symbols are found on maps, and what types of information do they carry?
19. How are numerical data represented on maps? Identify three types of isopleths. What is a choropleth map?
20. What is the global positioning system? How does it work? What factors cause errors in determining ground locations?
21. What is differential GPS, and why is it important?
22. What is a geographic information system?

23. Identify and describe three types of spatial objects.
24. What are the key elements of a GIS?
25. What is remote sensing? What is a remote sensor?
26. Compare the reflectance spectra of water, vegetation, and a typical soil. How do they differ in the visible spectrum? in near-infrared and shortwave infrared wavelengths?
27. What is emissivity, and how does it affect the amount of energy emitted by an object?
28. Is radar an example of an active or a passive remote sensing system? Why?
29. What is a digital image? What advantage does a digital image have over a photographic image?
30. Describe two ways of acquiring a digital image.
31. How does a Sun-synchronous orbit differ from a geostationary orbit? What are the advantages of each type?
32. What technologies are involved in earth visualization tools? How do these tools make use of the Internet?

Chapter 1
The Earth as a Rotating Planet

Here in Finland at 60° north latitude, the days provide as few as six hours of sunlight in winter and as many as eighteen hours in summer. To extend the winter growing day, many greenhouses are illuminated well before dawn and long after dusk. Greenhouses in Finland grow vegetables and flowers year around. Over 35,000 tons of tomatoes are raised in Finnish greenhouses each year to meet the demand for fresh, local produce.

Although winter days are short, summer brings many hours of daylight, and north of the Arctic Circle, residents of Scandinavia enjoy the "midnight Sun" of days when the Sun doesn't set. The Midsummer Festival, celebrated at about the time of the summer solstice, is a traditional holiday. Homes are decorated with birch leaves and garlands of flowers. Swedes celebrate with maypole dances using special songs, while Norwegians, Finns, and Danes mark the holiday with beach bonfires. Pickled herring with schnapps, and beer, is a traditional dish of the festival.

Day length is just one aspect of climate that is determined by the rotation of the Earth on its axis and its revolution around the Sun. These are the subjects of this chapter.

An illuminated greenhouse in Sauvo, Finland.

The Earth as a Rotating Planet

This chapter is concerned with the motion of the Earth as a planet—both its rotation around its polar axis and its revolution around the Sun. What are the environmental effects of the Earth's rotation? How does the rotation naturally lead to the geographic grid of parallels and meridians? How is the curved geographic grid projected to construct flat maps? How does our global system of timekeeping work? What is the cause of the seasons, in which the length of the daylight period varies with latitude through the year? These are some of the questions we will answer in this chapter.

The Shape of the Earth

As we all learn early in school, the Earth's shape is very close to a sphere (Figure 1.1). Pictures taken from space by astronauts and by orbiting satellites also show us that the Earth is a ball rotating in space.

Today it seems almost nonsensical that many of our ancestors thought the world was flat. But to ancient sailors voyaging across the Mediterranean Sea, the shape and breadth of the Earth's oceans and lands were hidden. Imagine standing on one of their ships, looking out at the vast ocean, with no land in sight. The surface of the sea would seem perfectly flat, stretching out and meeting the sky along a circular horizon. Given this view, perhaps it is not so surprising that many sailors believed the Earth was a flat disk and feared their ships would fall off its edge if they ventured too far.

We also see information about the shape of the Earth when we watch the Sun set with clouds in the sky. The clouds still receive the direct light of the Sun, although it is gone from the sky as seen at ground level. The movement of solar illumination across the clouds is easily explained by a rotating spherical Earth.

Actually, the Earth is not perfectly spherical. The Earth's equatorial diameter, at about 12,756 km (7926 mi), is very slightly larger than the polar diameter, which is about 12,714 km (7900 mi). As the Earth spins, the outward force of rotation causes it to bulge slightly at the equator and flatten at the poles. The difference is very small—about three-tenths of 1 percent—but strictly speaking the Earth's squashed shape is closer to what is known as an *oblate ellipsoid*, not a sphere.

An even more accurate representation of the Earth's shape is the *geoid*, which is a reference surface based on the pull of gravity over the globe (Figure 1.2). It is defined by a set of mathematical equations and has many applications in mapmaking, as well as navigation.

Earth Rotation

The Earth spins slowly on its *axis*—an imaginary straight line through its center and poles—a motion we refer to as **rotation**. We define a solar day by one complete rotation, and for centuries we have chosen to divide the solar day into exactly 24 hours. The North and South **Poles** are defined as the two points on the Earth's surface where the axis of rotation emerges. The direction of the Earth's rotation is shown in Figure 1.3.

The Earth's rotation is important for three reasons. First, the axis of rotation serves as a reference in setting up the geographic grid of latitude and longitude, which we will discuss later in the chapter. Second, it provides the day as a convenient measure of the passage of time, with the day in turn divided into hours, minutes, and seconds. Third, it has important effects on the physical and life processes on Earth.

ENVIRONMENTAL EFFECTS OF EARTH ROTATION

All walks of life on the planet's surface are governed by the daily rhythms of the Sun. Green plants receive and store solar energy during the day and consume some of

1.1 Our spherical Earth

▼ **Photo of Earth's curvature** This astronaut photo shows the Earth's curved horizon from low-Earth orbit.

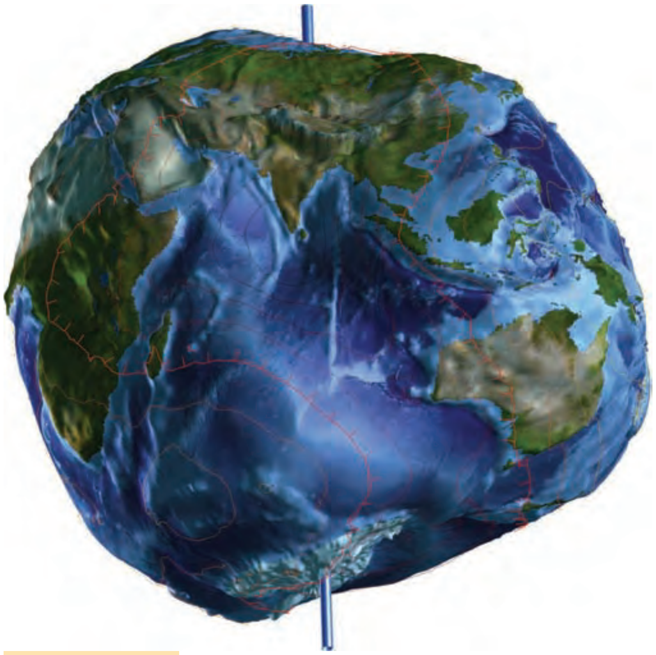
▲ **Distant Ship** Seen through a telescope, the decks of a distant ship seem to be under water. This phenomenon is easily explained by a curved Earth surface that appears to "rise up" between the observer and the ship.

▼ **Cloud illumination** As you watch a sunset from the ground, the Sun lies below the horizon, no longer illuminating the land around you. But at the height of the clouds, the Sun has not yet dipped below the horizon, so it still bathes them in red and pinkish rays. As the Sun descends, the red band of light slowly moves farther toward the horizon. In this dramatic sunset photo, the far distant clouds are still directly illuminated by the Sun's last rays. For the clouds directly overhead, however, the Sun has left the sky.

it at night. Among animals, some are active during the day, others at night. The day–night cycle also creates the daily air temperature cycle that is observed in most places on the Earth.

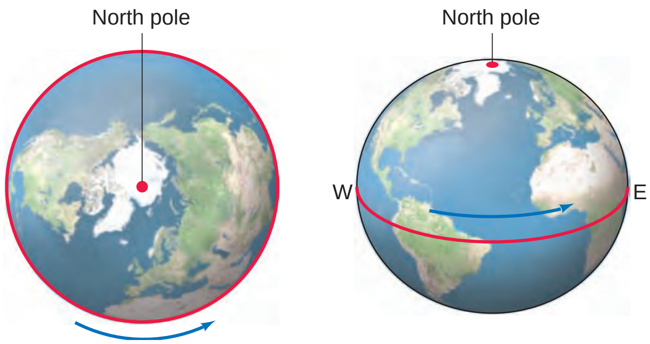
The directions of large motions of the atmosphere and oceans are also affected, as the turning of the planet makes their paths curve. As we will see in Chapter 5, weather systems and ocean currents respond to this phenomenon, which is known as the *Coriolis effect*.

Finally, the Earth's rotation combined with the Moon's gravitational pull on the planet creates the rhythmic rise and fall of the ocean surface that we know as the tides. The ebb and flow of tidal currents is a life-giving pulse for many plants and animals and provides a clock regulating many daily human activities in the coastal zone. When we examine the tide and its currents further in Chapter 16, we will see that the Sun also has an influence on the tides.



1.2 The geoid

Pictured here is a greatly exaggerated geoid, in which small departures from a sphere are shown as very large deviations.



▲ As seen from above, the rotation is counterclockwise.

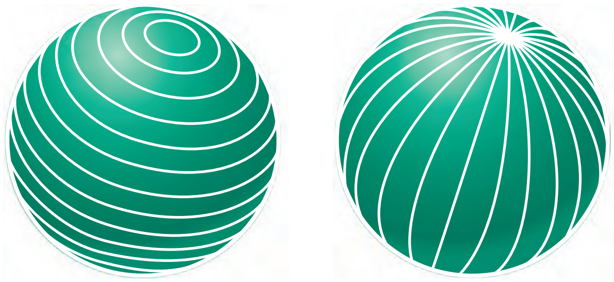
▲ As seen from the side, the rotation is eastward.

1.3 Direction of Earth rotation

You can picture the direction of Earth rotation in two ways.

The Geographic Grid

It is impossible to lay a flat sheet of paper over a sphere without creasing, folding, or cutting it—as you know if you have tried to gift-wrap a ball. This simple fact has caused mapmakers problems for centuries. Because the Earth's surface is curved, we cannot divide it into a rectangular grid anymore than we could smoothly wrap a globe in a sheet of graph paper. Instead, we divide the Earth into what is known as the *geographic grid*. This is made up of a system of imaginary circles, called parallels and meridians, which are shown in Figure 1.4.



▲ Parallels of latitude divide the globe crosswise into rings.

▲ Meridians of longitude divide the globe from pole to pole.

1.4 Parallels and meridians

PARALLELS AND MERIDIANS

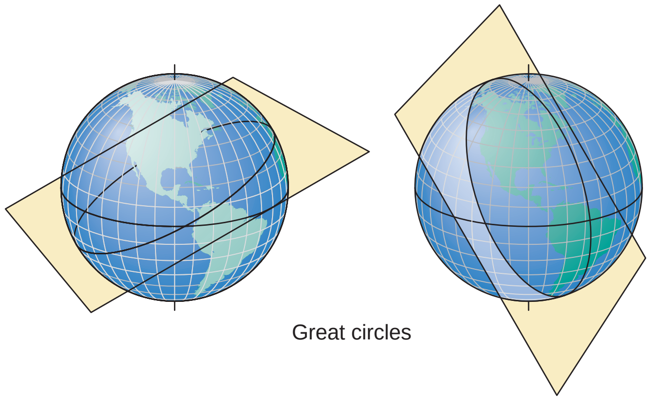
Imagine cutting the globe just as you might slice an onion to make onion rings (Figure 1.4A). Lay the globe on its side, so that the axis joining the North and South Poles runs parallel to your imaginary chopping board and begin to slice. Each cut creates a circular outline that passes around the surface of the globe. This circle is known as a parallel of latitude, or a **parallel**. The Earth's longest parallel of latitude is the **Equator**, which lies midway between the two poles. We use the Equator as a fundamental reference line for measuring position.

Now imagine slicing the Earth through the axis of rotation instead of across it, just as you would cut up a lemon to produce wedges (Figure 1.4B). The outlines of the cuts form circles on the globe, each of which passes through both poles. Half of this circular outline, connecting one pole to the other, is known as a meridian of longitude, or, more simply, a **meridian**.

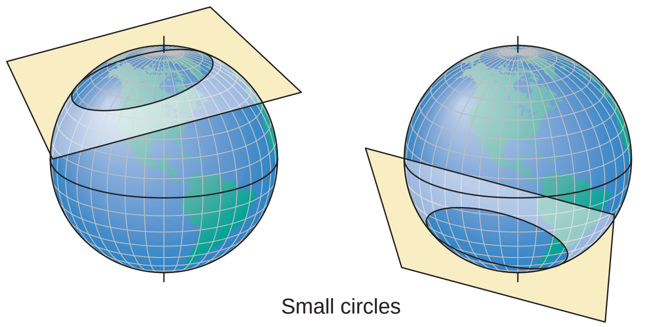
The geographic grid consists of an orderly system of circles—meridians and parallels—that are used to locate position on the globe.

Meridians and parallels define geographic directions. When you walk directly north or south, you follow a meridian; when you walk east or west you follow a parallel. There are an infinite number of parallels and meridians that can be drawn on the Earth's surface, just as there are an infinite number of positions on the globe. Every point on the Earth is associated with a unique combination of one parallel and one meridian. The position of the point is defined by their intersection.

Meridians and parallels are made up of two types of circles—great and small (Figure 1.5). A **great circle** is created when a plane passing through the center of the Earth intersects the Earth's surface. It bisects the globe into two equal halves. A **small circle** is created when a plane passing through the Earth, but not through the



▲ A great circle is created when a plane passes through the Earth, intersecting the Earth's center.



▲ Small circles are created when a plane passes through the Earth but does not intersect the center point.

1.5 Great and small circles

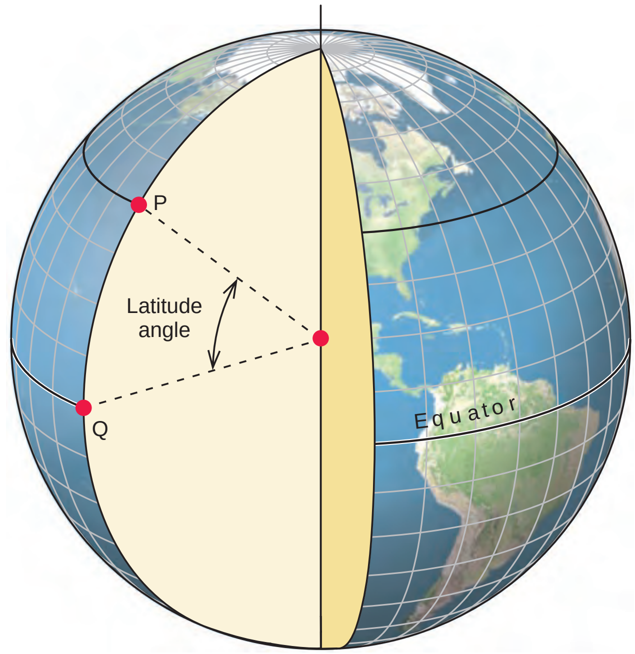
Earth's center, intersects the Earth's surface. Meridians are actually halves of great circles, while all parallels except the Equator are small circles.

Because great circles can be aligned in any direction on the globe, we can always find a great circle that passes through two points on the globe. As we will see shortly in our discussion of map projections, the portion of the great circle between two points is the shortest distance between them.

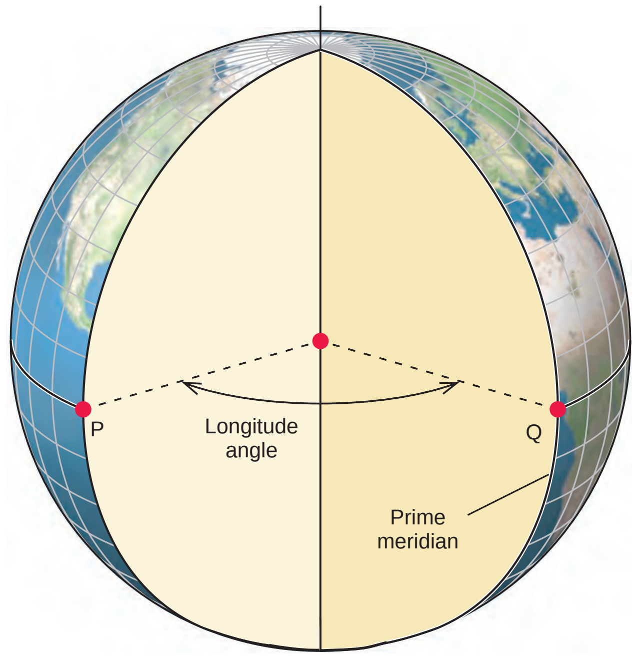
LATITUDE AND LONGITUDE

We label parallels and meridians by their **latitude** and **longitude** (Figure 1.6). The Equator divides the globe into two equal portions—the *northern hemisphere* and the *southern hemisphere*. Parallels are identified by their angular distance from the Equator, which ranges from 0° to 90°. All parallels in the northern hemisphere are described by a north latitude, and all parallels south of the Equator are given as south latitude (N or S).

> **Latitude and longitude uniquely determine the position of a point on the globe. Latitude records the parallel, and longitude the meridian, associated with the point.**



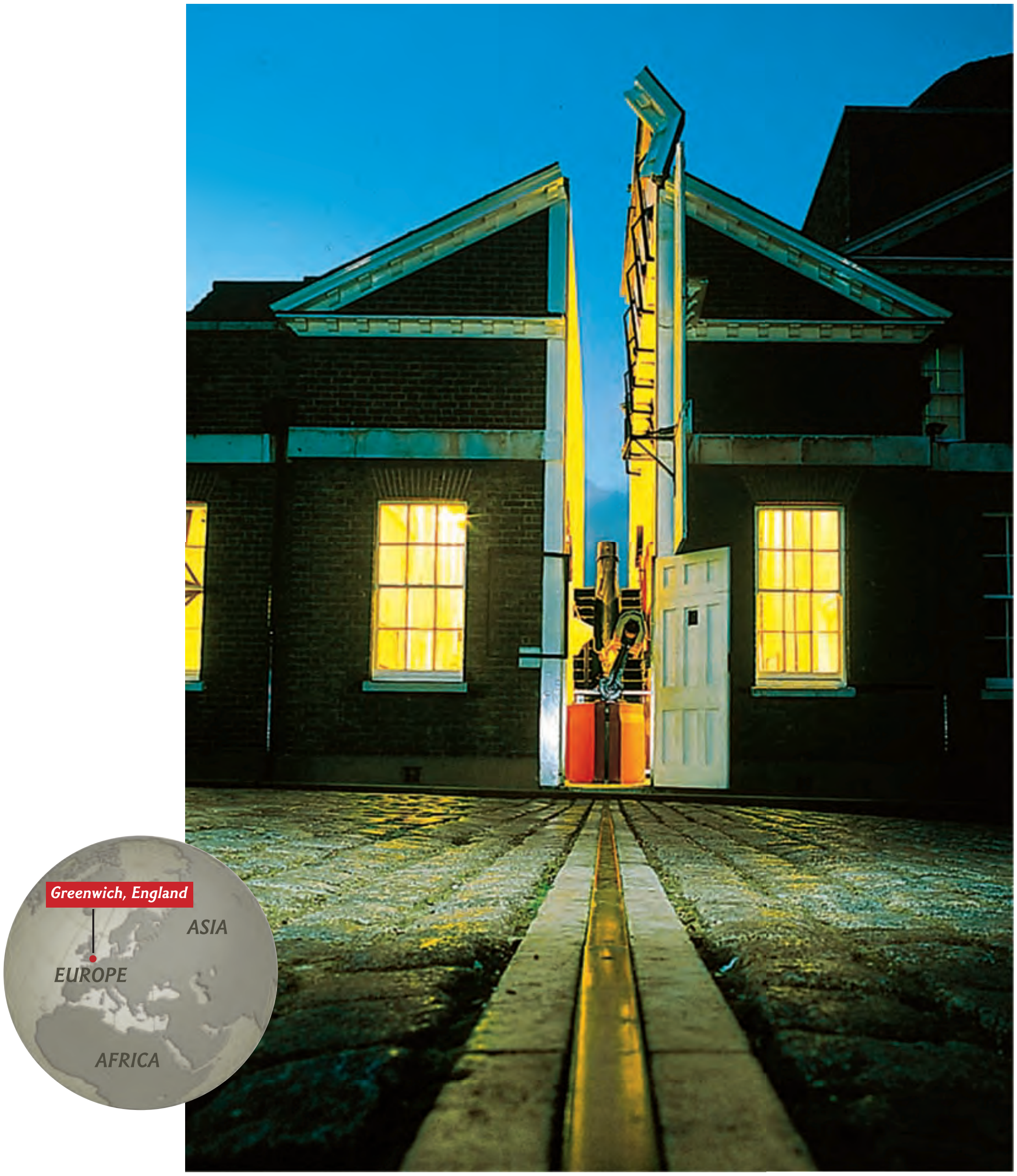
▲ The latitude of a parallel is the angle between a point on the parallel (P) and a point on the Equator at the same meridian (Q) as measured from the Earth's center.



▲ The longitude of a meridian is the angle between a point on that meridian at the Equator (P) and a point on the prime meridian at the Equator (Q) as measured at the Earth's center.

1.6 Latitude and longitude angles

Meridians are identified by longitude, which is an angular measure of how far eastward or westward the meridian is from a reference meridian, called the *prime meridian*. The prime meridian is sometimes known as the *Greenwich meridian* because it passes through the



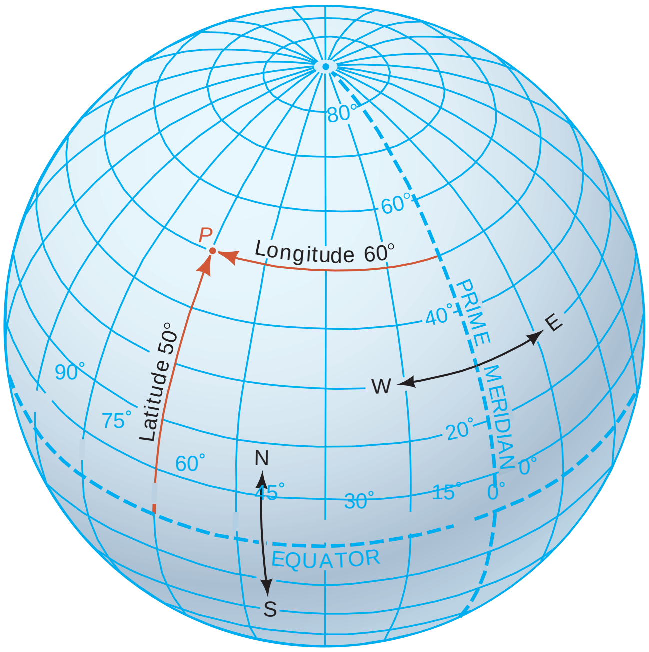
1.7 The prime meridian

This stripe in the forecourt of the old Royal Observatory at Greenwich, England, marks the prime meridian.

old Royal Observatory at Greenwich, near London, England (Figure 1.7). It has a longitude value of 0°. The longitude of a meridian on the globe is measured eastward or westward from the prime meridian, depending on which direction gives the smaller angle. Longitude then ranges from 0° to 180°, east or west (E or W).

Used together, latitude and longitude pinpoint locations on the geographic grid (Figure 1.8). Fractions of latitude or longitude angles are described using minutes and seconds. A *minute* is 1/60 of a degree, and a *second* is 1/60 of a minute, or 1/3600 of a degree. So, the latitude 41°, 27 minutes ('), and 41 seconds (") north (lat. 41° 27' 41" N) means 41° north plus 27/60 of a degree plus 41/3600 of a degree. This cumbersome system has now largely been replaced by decimal notation. In this example, the latitude 41° 27' 41" N translates to 41.4614° N.

Degrees of latitude and longitude can also be used as distance measures. A degree of latitude, which measures distance in a north-south direction, is equal to about 111 km (69 mi). The distance associated with a degree of longitude, however, will be progressively reduced with latitude because meridians converge toward the poles. For example, at 60° latitude, a degree of longitude has a length exactly half of that at the Equator, or 55.5 km (34.5 mi).



1.8 Latitude and longitude of a point

The point *P* lies on the parallel of latitude at 50° north (50° from the Equator) and on the meridian at 60° west (60° from the prime meridian). Its location is therefore lat. 50° N, long. 60° W.

Map Projections

The problem of how to best display the Earth's surface has puzzled cartographers, or mapmakers, throughout history (Figure 1.9). The oldest maps were limited by a lack of knowledge of the world, rather than by difficulties caused by the Earth's curvature. They tended to represent political or religious views rather than geographic reality. Ancient Greek maps from the sixth century B.C. show the world as an island, with Greece at its center, while medieval maps from the fourteenth century placed Jerusalem at the focus.

But by the fifteenth century, ocean-faring explorers such as Columbus and Magellan were extending the reaches of the known world. These voyagers took mapmakers with them to record the new lands that they discovered, and navigation charts were highly valued. Mapmakers, who now had a great deal of information about the world to set down, were forced to tackle the difficulty of representing the curved surface of the Earth on a flat page.

One of the earliest attempts to tackle the curvature problem for large-scale maps was made by the Belgian cartographer, Gerardus Mercator, in the sixteenth century, and it is still used today. A number of other systems, or **map projections**, have been developed to translate the curved geographic grid to a flat one. We will concentrate on the three most useful types, including Mercator's. Each has its own advantages and drawbacks. You can read more about maps and map projections in the introductory chapter.

1.9 Ptolemy's map of the world

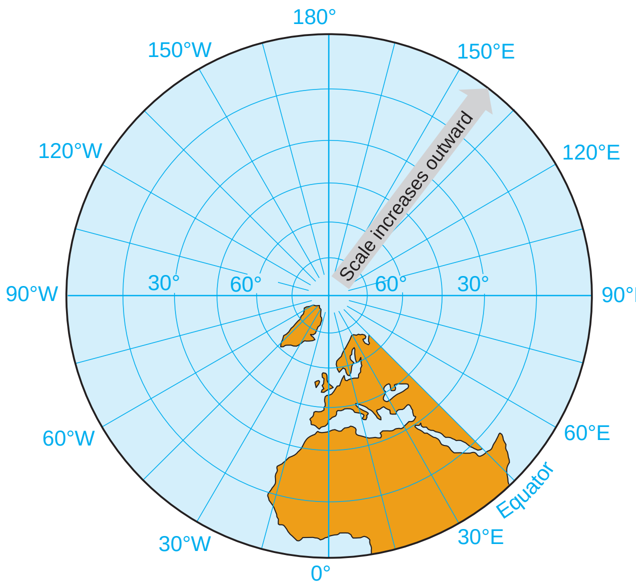
This atlas page shows a reproduction of a map of the world as it was known in ancient Greece.

GEODISCOVERIES **Map Projections**

Watch an animation showing how map projections are constructed.

POLAR PROJECTION

The *polar projection* (Figure 1.10) is normally centered on either the North or the South Pole. Meridians are



1.10 A polar projection

The map is centered on the North (or South) Pole. All meridians are straight lines radiating from the center point, and all parallels are concentric circles. The scale fraction increases in an outward direction, making shapes toward the edges of the map appear larger.

straight lines radiating outward from the pole, and parallels are nested circles centered on the pole. The map is usually cut off to show only one hemisphere so that the Equator forms the outer edge of the map. Because the intersections of the parallels with the meridians always form true right angles, this projection shows the true shapes of all small areas. That is, the shape of a small island would always be shown correctly, no matter where it appeared on the map. However, because the scale fraction increases in an outward direction, the island would look larger toward the edge of the map than near the center.

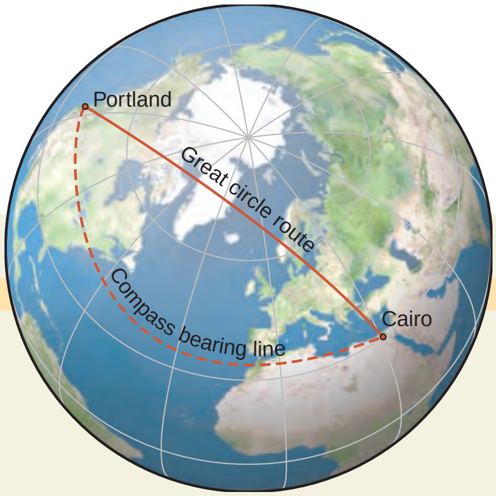
MERCATOR PROJECTION

In the *Mercator projection*, the meridians form a rectangular grid of straight vertical lines, while the parallels form straight horizontal lines (Figure 1.11). The meridians are evenly spaced, but the spacing between parallels increases at higher latitude so that the spacing at 60° is double that at the Equator. As the map reaches closer to the poles, the spacing increases so much that the map must be cut off at some arbitrary parallel, such as 80° N. This change of scale enlarges features near the pole.

The Mercator projection has several special properties. Mercator's goal was to create a map that sailors could use to determine their course. A straight line drawn anywhere on his map gives you a line of constant compass direction. So a navigator can simply draw a line between any two points on the map and measure the

1.11 The Mercator projection

▼ The compass line connecting two locations, such as Portland and Cairo, shows the compass bearing of a course directly connecting them. However, the shortest distance between them lies on a great circle, which is a longer, curving line on this map projection. The diagram at the right side of the map shows how rapidly the map scale increases at higher latitudes. At lat. 60°, the scale is double the equatorial scale. At lat. 80°, the scale is six times greater than at the Equator.



▲ The true shortest distance, drawn over the globe as the crow flies, appears as a curved line on the Mercator projection.

bearing, or direction angle of the line, with respect to a nearby meridian on the map. Since the meridian is a true north-south line, the angle will give the compass bearing to be followed. Once aimed in that compass direction, a ship or an airplane can be held to the same compass bearing to reach the final point or destination (Figure 1.11).

The Mercator projection shows a line of constant compass bearing as a straight line and so is used to display directional features such as wind direction.

But this line does not necessarily follow the shortest actual distance between two points, which we can easily plot out on a globe. We have to be careful—Mercator's map can falsely make the shortest distance between two points seem much longer than the compass line joining them.

Because the Mercator projection shows the true compass direction of any straight line on the map, it is used to show many types of straight-line features. Among these features are flow lines of winds and ocean currents, directions of crustal features (such as chains of volcanoes), and lines of equal values, such as lines of equal air temperature or equal air pressure. That's why the Mercator projection is chosen for maps of temperatures, winds, and pressures.

WINKEL TRIPEL PROJECTION

The *Winkel Tripel projection* (Figure 1.12) is named after its inventor, Oswald Winkel (1873–1953). The German word *tripel* is translated as "triplet" and refers to the property that the projection minimizes the sum of distortions to area, distance, and direction. The projection has parallels that are nearly straight, curving slightly toward the edges of the map. The meridians are increasingly curved with distance from the central meridian.

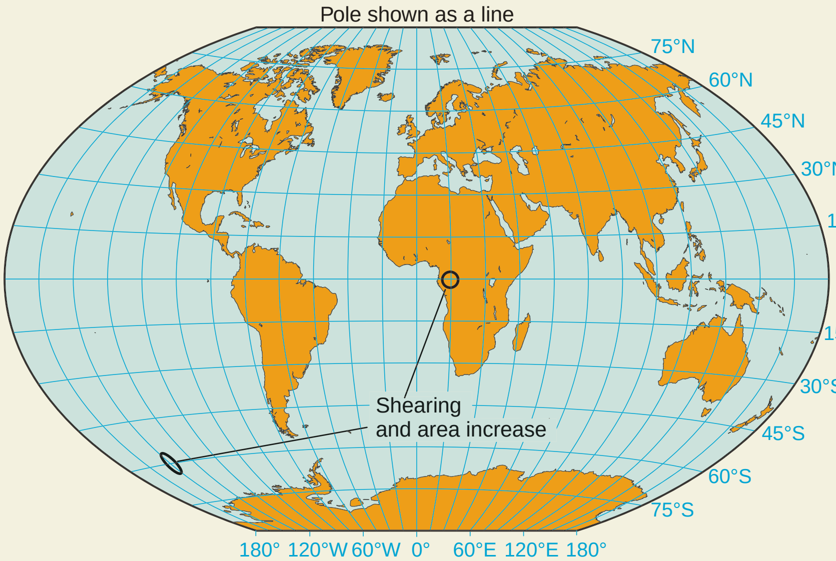
Compared to the Mercator projection (Figure 1.11), we can see two major differences. In the Mercator map, the shapes of coastlines and countries are shown correctly, but their areas increase toward the poles. That is, the Mercator map is *conformal* but not *equal-area*. In the Winkel Tripel map, the shapes are somewhat distorted by shearing away from the central meridian and toward the poles. However, the areas of continents and countries are shown much more accurately. Only in the polar regions near the east and west edges of the map do areas grow significantly with latitude.

The Winkel Tripel projection shows the countries and continents of the globe with minimal distortion of shape and area.

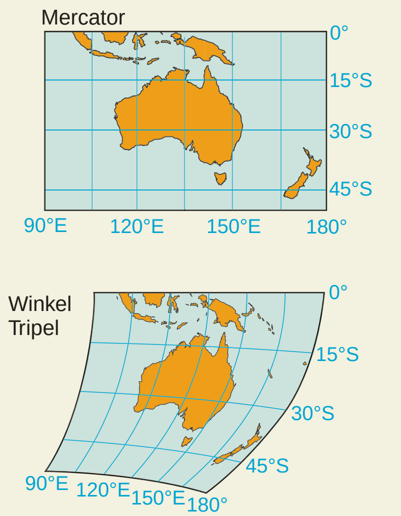
Because it shows areas and shapes with only a

1.12 The Winkel Tripel projection

▼ This projection is very useful for displaying world maps because it shows the true shapes and areas of countries and continents, with only small distortions as compared to the Mercator or other global projections. Shearing and relative area increase toward the map's east and west edges and near the poles.



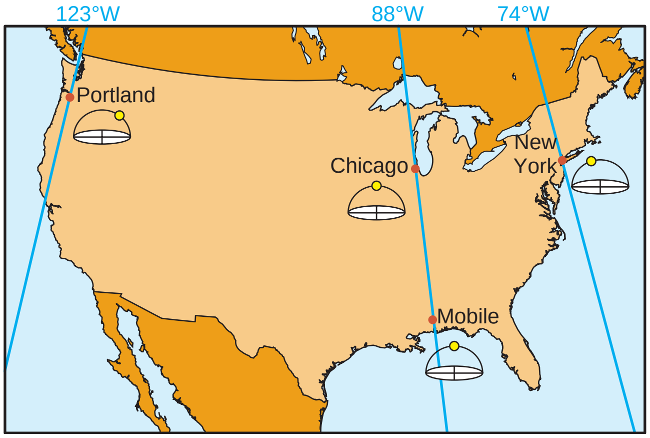
▼ Shearing occurs when meridians and parallels are curved, distorting true shape. The Mercator map shows the shape of Australia correctly, but the area of Australia is shown more accurately in the Winkel Tripel map.



small amount of distortion, the Winkel Tripel projection is well suited to displaying global data. It is an ideal choice for world maps showing the world's climate, soils, and vegetation, and we use it in many places in this book.

GEOGRAPHIC INFORMATION SYSTEMS

Maps are in wide use today for many applications as a simple and an efficient way of compiling and storing spatial information. However, in the past two decades, maps are being supplemented by more powerful computer-based methods for acquiring, storing, processing, analyzing, and outputting spatial data. These are contained within *geographic information systems (GISs)*. *Tools in Physical Geography* in our Introduction, presents some basic concepts of geographic information systems and how they work.



1.13 Time and the Sun

When it is noon in Chicago, it is 1:00 P.M. in New York and only 10:00 A.M. in Portland. Yet in Mobile, about 1600 km (1000 mi) away, it is also noon. This is because time is determined by longitude, not latitude.

Global Time

There's an old Canadian joke that goes, "Repent! The world will end at midnight! or 12:30 A.M. in Newfoundland." It's humorous because independent-minded Newfoundlers use a time zone that is a half-hour ahead of the other Canadian maritime provinces. It highlights the fact that one single instant across the world—no matter how cataclysmic—is simultaneously labeled by different times in different local places.

Humans long ago decided to divide the solar day into 24 units, called hours, and devised clocks to keep track of hours in groups of 12. Yet, different regions set their clocks differently—when it is 10:03 A.M. in New York, it is 9:03 A.M. in Chicago, 8:03 A.M. in Denver, and 7:03 A.M. in Los Angeles. These times differ by exactly one hour. How did this system come about? How does it work?

Even in today's advanced age, our global time system is oriented to the Sun. Think for a moment about the Sun moving across the sky. In the morning, the Sun is low on the eastern horizon, and as the day progresses, it rises higher until at solar noon it reaches its highest point in the sky. If you check your watch at that moment, it will read a time somewhere near 12 o'clock (12:00 noon). After solar noon, the Sun's elevation in the sky decreases. By late afternoon, the Sun hangs low in the sky, and at sunset it rests on the western horizon.

Imagine for a moment that you are in Chicago (Figure 1.13). The time is noon, and the Sun is at or near its highest point in the sky. You call a friend in New York and ask about the position of the Sun. Your friend will say that the Sun has already passed solar noon, its highest point, and is beginning its descent down. Meanwhile, a friend in Portland will report that the Sun is still working its way up to its highest point. But a friend in Mobile, Alabama, will tell you that the time in Mobile is the same as in Chicago and that the Sun is at about solar noon. How do we explain these different observations?

The difference in time makes sense because solar noon can only occur simultaneously at places with the same longitude. Only one meridian can be directly under the Sun and experience solar noon at a given moment. Locations on meridians to the east of Chicago, like New York, have passed solar noon, and locations to the west of Chicago, like Vancouver, have not yet reached solar noon. Since Mobile and Chicago have nearly the same longitude, they experience solar noon at approximately the same time.

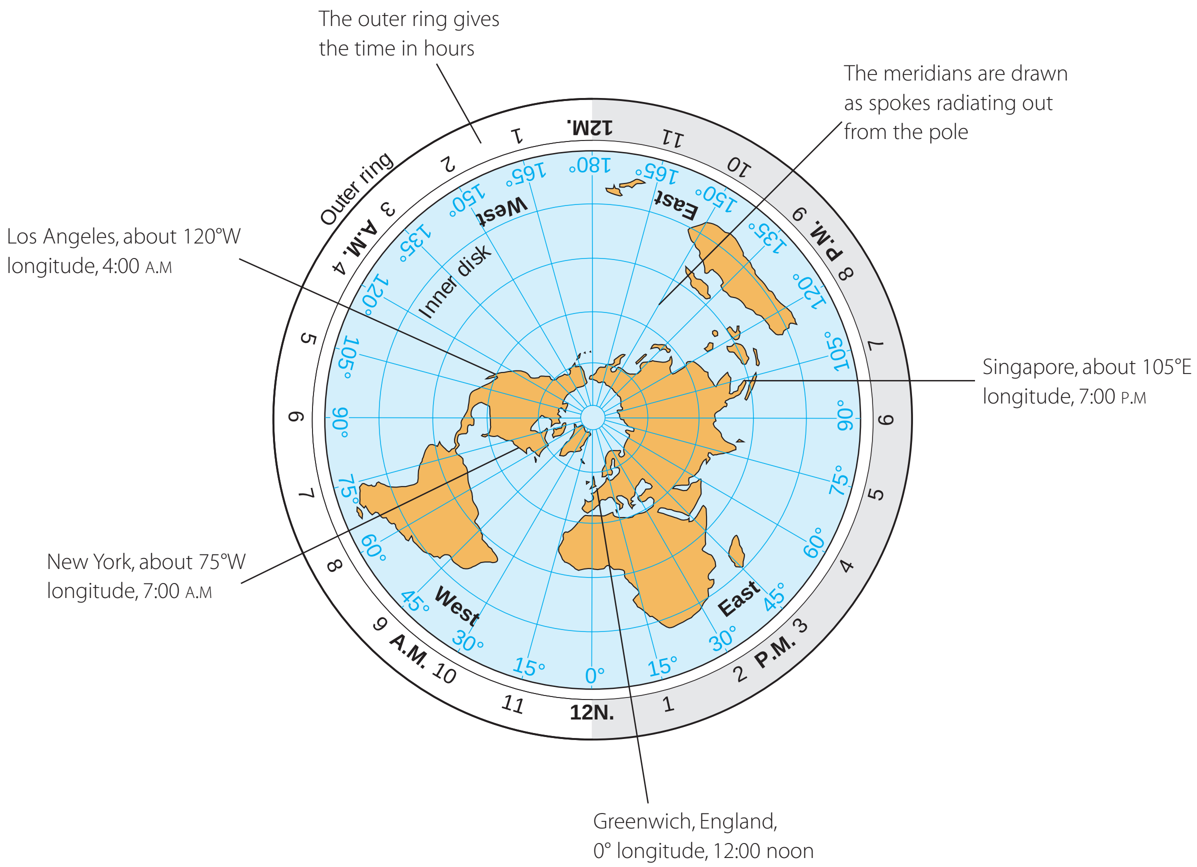
Figure 1.14 indicates how time varies with longitude. Since the Earth turns 360° in a 24-hour day, the rotation rate is 360°/24 = 15° per hour. So 15° of longitude equates to one hour of time.

STANDARD TIME

We've just seen that locations with different longitudes experience solar noon at different times. But what would happen if each town or city set its clocks to read 12:00 at its own local solar noon? All cities and towns on different meridians would have different local time systems. With today's instantaneous global communication, chaos would soon result.

> **In the standard time system, we keep global time according to nearby standard meridians that normally differ by one hour from each other.**

Standard time simplifies the global timekeeping problem. In the **standard time system**, the globe is



1.14 The relation of longitude to time

This polar projection illustrates how longitude is related to time for an example of noon on the prime meridian. The alignment of meridians with hours shows the time at other locations.

divided into **time zones**. People within a zone keep time according to a *standard meridian* that passes through their zone. Since the standard meridians are usually 15 degrees apart, the difference in time between adjacent zones is normally one hour. In some geographic regions, however, the difference is only one-half hour.

Figure 1.15 shows the time zones observed in northern North America. The United States and its Caribbean possessions fall within seven time zones. Six zones cover Canada. Their names and standard meridians of longitude are as follows:

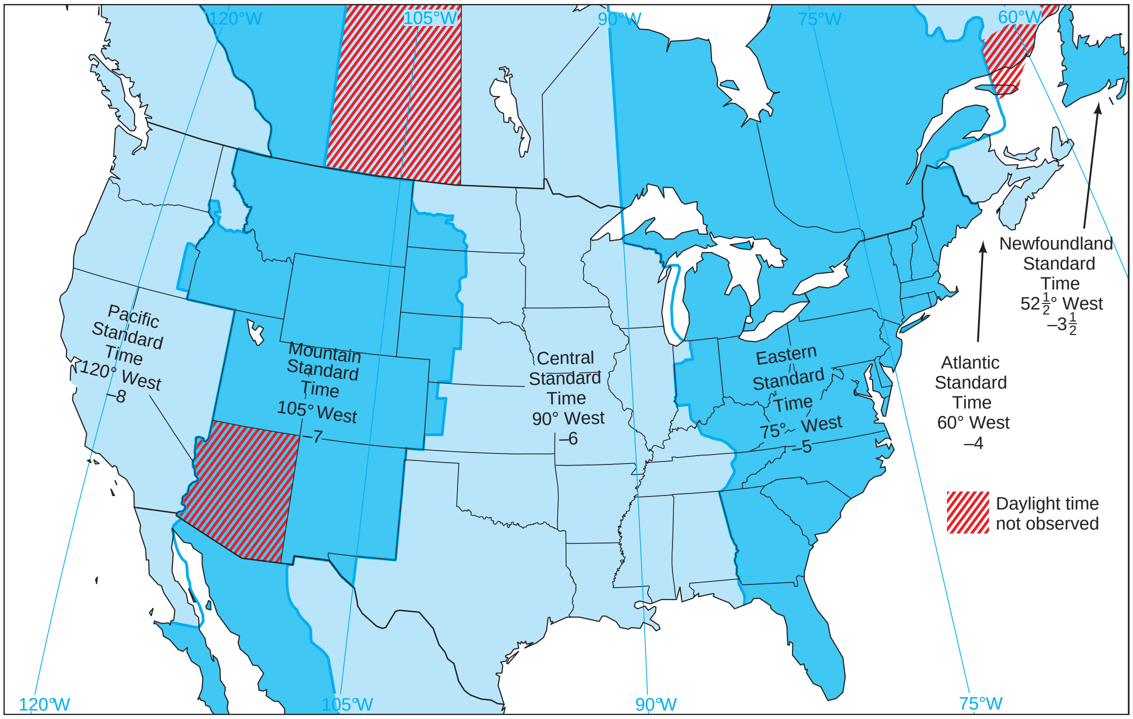
U.S. Zones	Meridian	Canadian Zones
	52½°	Newfoundland
Atlantic	60°	Atlantic
Eastern	75°	Eastern
Central	90°	Central
Mountain	105°	Mountain
Pacific	120°	Pacific-Yukon
Alaska-Bering	135°	
Hawaii	150°	

WORLD TIME ZONES

According to our map of the world's time zones (Figure 1.16), the country spanning the greatest number of time zones is Russia. From east to west, Russia spans 11 zones, but groups them into eight standard time zones. China covers five time zones but runs on a single national time using the standard meridian of Beijing.

A few countries, such as India and Iran, keep time using a meridian that is positioned midway between standard meridians, so that their clocks depart from those of their neighbors by 30 or 90 minutes. Some states or provinces within countries also keep time by 7½° meridians, such as the Canadian province of Newfoundland and the interior Australian states of South Australia and Northern Territory.

World time zones are often referred to by number to indicate the difference in hours between time in a zone and time in Greenwich. A number of −7, for example, indicates that local time is seven hours behind Greenwich time, while a +3 indicates that local time is three hours ahead of Greenwich time.



1.15 Time zones of the contiguous United States and southern Canada

The name, standard meridian, and number code are shown for each time zone. Time zone boundaries often follow preexisting natural or political boundaries. For example, the Eastern time–Central time boundary line follows Lake Michigan down its center, and the Mountain time–Pacific time boundary follows a ridge-crest line also used by the Idaho–Montana state boundary.

1.16 Time zones of the world

Dashed lines represent 15° meridians, and bold lines represent 7½° meridians. Alternate zones appear in color.

INTERNATIONAL DATE LINE

Take a world map or globe with 15° meridians. Start at the Greenwich 0° meridian and count along the 15° meridians in an eastward direction. You will find that the 180th meridian is number 12 and that the time at this meridian is therefore 12 hours later than Greenwich time. Counting in a similar manner westward from the Greenwich meridian, we find that the 180th meridian is again number 12 but that the time is 12 hours earlier than Greenwich time. We seem to have a paradox. How can the same meridian be both 12 hours ahead of Greenwich time and 12 hours behind it? The answer is that each side of this meridian is experiencing a different day.

Doing the same experiment an hour later, at 1:00 A.M., stepping east you will find that you are in the early morning of June 26. But if you step west you will find that midnight of June 26 has passed, and it is now the early morning of June 27. So on the west side of the 180th meridian, it is also 1:00 A.M. but it is one day later than on the east side. For this reason, the 180th meridian serves as the *international date line*. This means that if you travel westward across the date line, you must advance your calendar by one day. If traveling eastward, you set your calendar back by a day.

Air travelers between North America and Asia cross the date line. For example, flying westward from Los Angeles to Sydney, Australia, you may depart on a Tuesday evening and arrive on a Thursday morning after a flight that lasts only 14 hours. On an eastward flight from Tokyo to San Francisco, you may actually arrive the day before you take off, taking the date change into account!

When crossing the international date line in an eastward direction, travelers set their calendars back one day.

Actually, the international date line does not follow the 180th meridian exactly. Like many time zone boundaries, it deviates from the meridian for practical reasons. As shown in Figure 1.16, it has a zigzag offset between Asia and North America, as well as an eastward offset in the South Pacific to keep clear of New Zealand and several island groups.

DAYLIGHT SAVING TIME

The **daylight saving time** system allows us to cheat standard time and transfer an hour of light to a time when it will be more useful. In our modern world, we often wake up well after sunrise and continue being active until long after sunset, especially if we live in urban areas. So we adjust our clocks during the part of the year that has a longer daylight period to correspond more closely with the modern pace of society. By setting all clocks ahead by one hour, we steal an hour from the early morning daylight period—which is theoretically wasted while schools, offices, and factories are closed—and give it to the early evening, when most people are awake and busy.

In the United States, daylight saving time comes into effect on the second Sunday in March and is discontinued on the first Sunday of November. Arizona (except the Navajo Nation), Puerto Rico, Hawaii, U.S. Virgin Islands, Guam, the Northern Mariana Islands, and American Samoa do not observe daylight saving time. Although many other nations observe daylight time, they do not always begin and end daylight time on the same days of the year. In the European Union, daylight saving time is called *summer time*. It begins on the last Sunday in March and ends on the last Sunday in October.

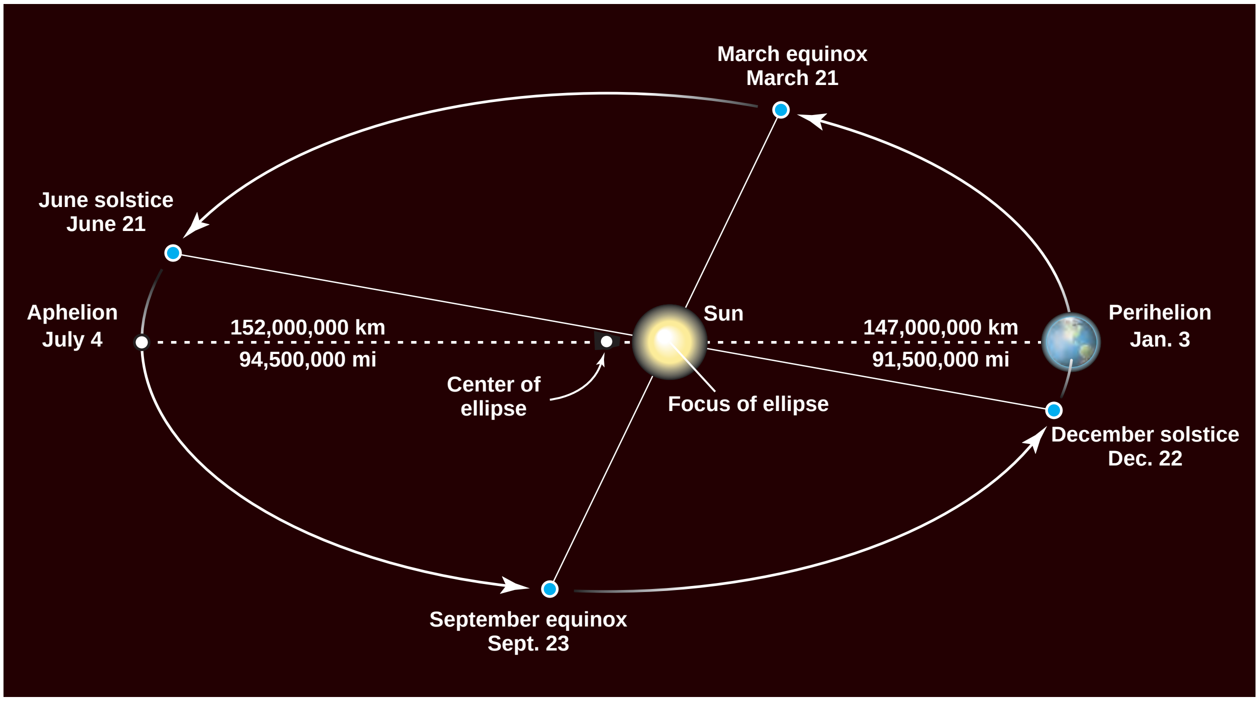
PRECISE TIMEKEEPING

Many scientific and technological applications require precise timekeeping. Today, a worldwide system of master atomic clocks measures time to better than one part in 1,000,000,000,000. However, our Earth is a much less precise timekeeper, demonstrating small changes in the angular velocity of its rotation on its axis and variations in the time it takes to complete one circuit around the Sun. As a result, constant adjustments to the timekeeping system are necessary. The legal time standard recognized by all nations is *coordinated universal time*, which is administered by the Bureau International de l'Heure, located near Paris.

The Earth's Revolution around the Sun

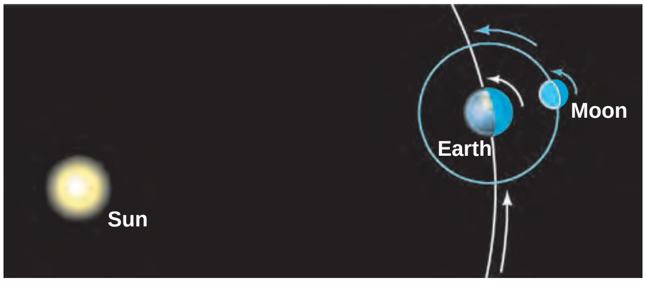
So far, we have discussed the importance of the Earth's rotation on its axis. But what about the Earth's movement as it orbits the Sun? We refer to this motion as the Earth's **revolution** around the Sun. The Earth takes 365.242 days to travel around the Sun—almost a quarter of a day longer than the calendar year of 365 days. Every four years, this time adds up to nearly one extra day, which we account for by inserting a 29th day into February in leap years. Further minor corrections—such as omitting the extra day in century years—are necessary to keep the calendar on track.

The Earth's orbit around the Sun is shaped like an ellipse, or oval (Figure 1.17). This means that the distance between the Earth and Sun varies somewhat through the year. The Earth is nearest to the Sun at *perihelion*, which occurs on or near January 3. It is farthest away from the Sun at *aphelion*, on or near July 4. However, the distance between Sun and Earth varies only by about 3 percent during one revolution because



1.17 Orbit of the Earth around the Sun

The Earth's orbit around the Sun is not quite circular, but is in the shape of an ellipse. As a result, the distance between the Sun and the Earth varies with the time of year.



1.18 Revolution of the Earth and Moon

Viewed from a point over the Earth's North Pole, the Earth both rotates and revolves in a counterclockwise direction. From this viewpoint, the Moon also rotates counterclockwise.

the elliptical orbit is shaped very much like a circle. For most purposes we can regard the orbit as circular.

Which way does the Earth revolve? Imagine yourself in space, looking down on the North Pole. From this viewpoint, the Earth travels counterclockwise around the Sun (Figure 1.18). This is the same direction as the Earth's rotation.

MOTIONS OF THE MOON

The Moon rotates on its axis and revolves about the Earth in the same direction as the Earth rotates and revolves around the Sun. But the Moon's rate of rotation is synchronized with the Earth's rotation so that one side of the Moon is permanently directed toward the Earth while the opposite side of the Moon remains hidden. It was only when a Soviet spacecraft passing the Moon transmitted photos back to Earth in 1959 that we caught our first glimpse of the far side.

The phases of the Moon are determined by the position of the Moon in its orbit around the Earth, which in turn determines how much of the sunlit Moon is seen from the Earth. It takes about 29.5 days for the Moon to go from one full Moon to the next. In the twilight photo of a moonlit scene in Figure 1.19, the Moon is nearly full. From the way that the Sun illuminates the Moon as a sphere, it is easy to see that the Sun is down and to the right.

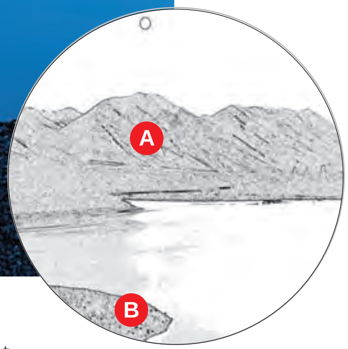
GEODISCOVERIES **The Earth's Revolution Around the Sun**

Watch a narrated animation to see how the Earth revolves around the Sun to cause the seasons.

TILT OF THE EARTH'S AXIS

Depending on where you live in the world, the effects of the changing seasons can be large. But why do we experience seasons on Earth? And why do the hours of daylight change throughout the year—most extremely at the poles, and less so near the Equator?

Seasons arise because the Earth's axis is not perpendicular to the plane containing the Earth's orbit around the Sun, which is known as the *plane of the ecliptic.*



1.19 Midnight in June, Lake Clark National Park, Alaska

Although it is midnight, the Sun is only just below the horizon, bathing the scene in soft twilight. The way the spherical Moon is lit by the Sun also shows that the Sun is located below the horizon and to the right.

EYE ON THE LANDSCAPE **What else would the geographer see?** These mountain landforms (A) show the effects of glacial ice and frost action during the most recent Ice Age. The patches of snow mark the sites where small glaciers once formed, carving shallow basins in the bedrock of the peaks. The gravel in the foreground (B) has a particularly fresh look and was probably deposited recently by running water, perhaps during the most recent spring flood.

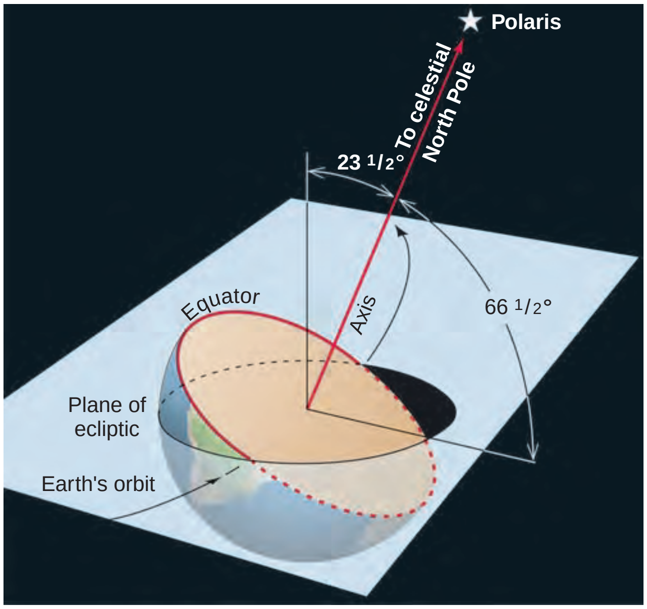
Figure 1.20 shows this plane as it intersects the Earth. If we extend the imaginary axis out of the North Pole into space, it always aims toward Polaris, the North Star. The direction of the axis does not change as the Earth revolves around the Sun. Let's investigate this phenomenon in more detail.

THE FOUR SEASONS

Figure 1.21 shows the full Earth orbit traced on the plane of the ecliptic. On December 22, the north polar end of the Earth's axis leans at the maximum angle away from the Sun, 23½°. This event is called the **December solstice**, or *winter solstice* in the northern hemisphere. At this time, the southern hemisphere is tilted toward the Sun and enjoys strong solar heating.

The axis of the Earth's rotation is tilted by 23½° away from the plane of the ecliptic. This tilt causes the seasons.

Six months later, on June 21, the Earth has traveled to the opposite side of its



1.20 The tilt of the Earth's axis of rotation with respect to its orbital plane

As the Earth moves in its orbit on the plane of the ecliptic around the Sun, its rotational axis remains pointed toward Polaris, the North Star, and makes an angle of 66½° with the ecliptic plane. The axis of the Earth is thus tilted at an angle of 23½° away from a right angle to the plane of the ecliptic.

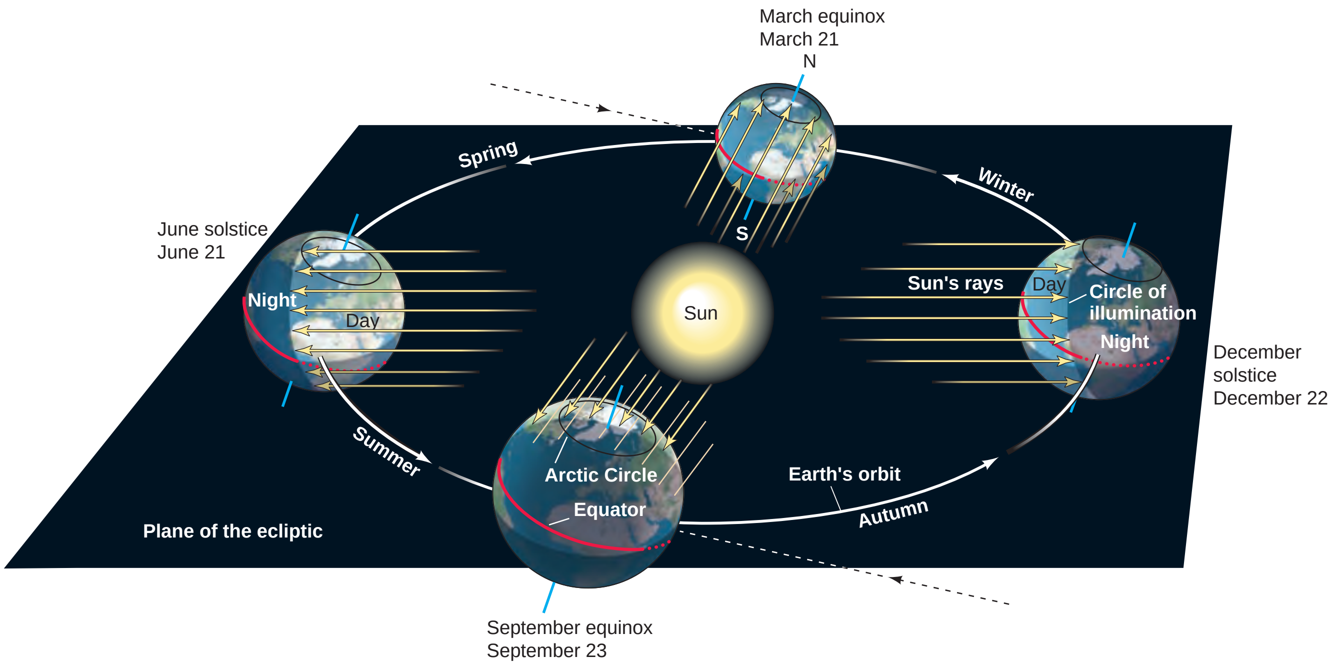
orbit. This is known as the **June solstice**, or *summer solstice* in the northern hemisphere. The north polar end of the axis is tilted at 23½° toward the Sun, while the South Pole and southern hemisphere are tilted away.

The equinoxes occur midway between the solstice dates. At an equinox, the Earth's axis is not tilted toward the Sun or away from it. The **March equinox** (vernal equinox in the northern hemisphere) occurs near March 21, and the **September equinox** (autumnal equinox) occurs near September 23. The conditions at the two equinoxes are identical as far as the Earth–Sun relationship is concerned. The date of any solstice or equinox in a particular year may vary by a day or so, since the revolution period is not exactly 365 days.

EQUINOX CONDITIONS

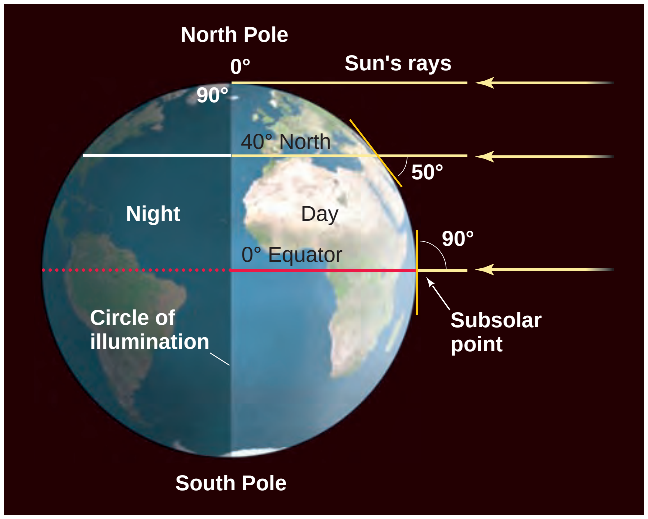
The Sun's rays always divide the Earth into two hemispheres—one that is bathed in light and one that is shrouded in darkness. The *circle of illumination* is the circle that separates the day hemisphere from the night hemisphere. The *subsolar point* is the single point on the Earth's surface where the Sun is directly overhead at a particular moment.

At equinox, the circle of illumination passes through the North and South Poles, as we see in Figure 1.22.



1.21 The four seasons

The Earth revolves once around the Sun in a year, passing through each of its four seasons. The four seasons occur because the Earth's tilted axis is always pointed toward the same point in space, very close to the North Star. That is, a line through the Earth's axis of rotation at each season is parallel to a line through the axis at any of the other seasons. Because of this fixed direction of rotation, the northern hemisphere is tipped toward the Sun for the June solstice and away from the Sun for the December solstice. Both hemispheres are illuminated equally at the equinoxes.



1.22 Equinox conditions

At equinox, the Earth's axis of rotation is exactly at right angles to the direction of solar illumination. The circle of illumination passes through the North and South Poles. The subsolar point lies on the equator. At both poles, the Sun is seen at the horizon. The viewpoint for this diagram is away from the plane of the ecliptic, so that both poles can be seen.

The Sun's rays graze the surface at both poles, so the surfaces at the poles receive very little solar energy. The subsolar point falls on the Equator. Here, the angle between the Sun's rays and the Earth's surface is 90°, so that point receives the full force of solar illumination. At noon at latitudes in between, such as 40° N, the Sun strikes the surface at an angle that is less than 90°. The angle that marks the Sun's elevation above the horizon is known as the *noon angle*. Simple geometry shows that for equinox conditions the noon angle is equal to 90° minus the latitude, so that at 40° N, the noon angle is 50°.

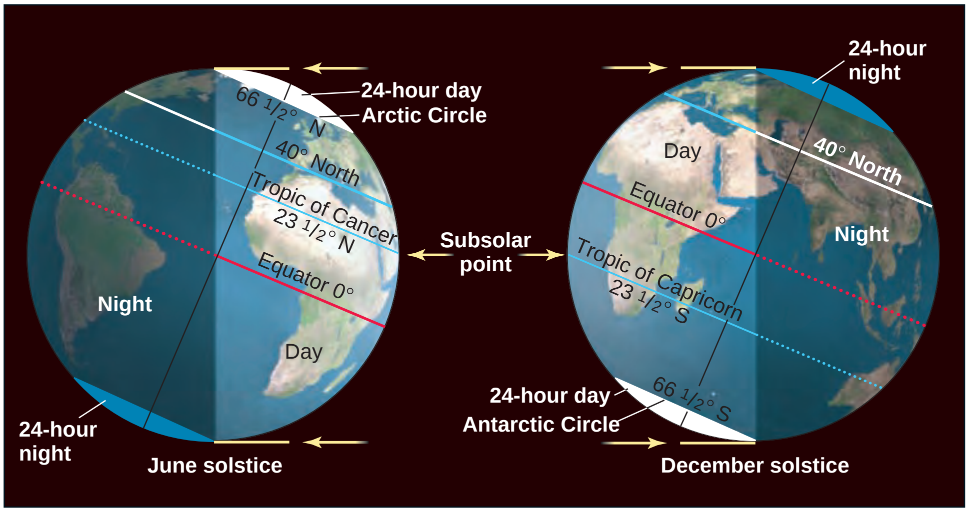
One important feature of the equinox is that day and night are of equal length everywhere on the globe. You can see this by imagining yourself located at a point on the 40° N parallel. As the world turns, you will be in daylight for exactly half the day and in night for the other half.

SOLSTICE CONDITIONS

Now let's examine the solstice conditions in Figure 1.23. The June solstice is shown on the left. Imagine that you are back at a point on the lat. 40° N parallel. Unlike at equinox, the circle of illumination no longer divides your parallel into equal halves because of the tilt of the northern hemisphere toward the Sun. Instead, daylight covers most of the parallel, with a smaller amount passing through twilight and darkness. For you, the day is now considerably longer (about 15 hours) than the night (about 9 hours). Now step onto the Equator. You can see that this is the only parallel that is divided exactly into two. On the Equator, daylight and nighttime hours will be equal throughout the year.

At the June solstice, the North Pole is tilted toward the Sun. At the December solstice, it is tilted away from the Sun.

The farther north you go, the more the effect increases. Once you move north of lat. 66½°, the day continues unbroken for 24 hours. Looking at Figure 1.23, we can see that is because the lat. 66½°



1.23 Solstice conditions

At the solstice, the north end of the Earth's axis of rotation is fully tilted either toward or away from the Sun. Because of the tilt, polar regions experience either 24-hour day or 24-hour night. The subsolar point lies on one of the tropics, at lat. 23½° N or S.

parallel is positioned entirely within the daylight side of the circle of illumination. This parallel is known as the **Arctic Circle**. Even though the Earth rotates through a full cycle during a 24-hour period, the area north of the Arctic Circle will remain in continuous daylight. We can also see that the subsolar point is at a latitude of 23½° N. This parallel is known as the **Tropic of Cancer**. Because the Sun is directly over the Tropic of Cancer at this solstice, solar energy is most intense here.

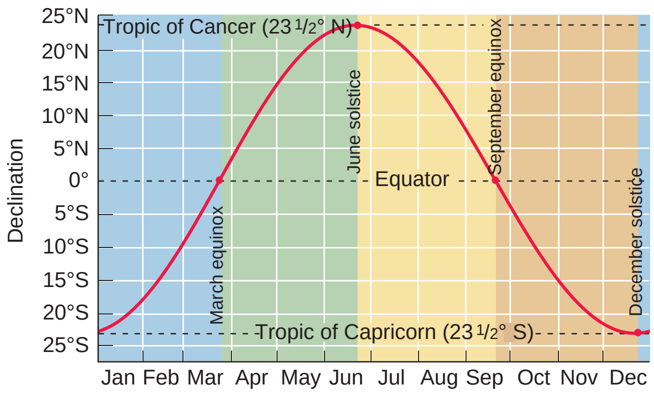
The conditions are reversed at the December solstice. Back at lat. 40° N, the night is about 15 hours long, while daylight lasts about 9 hours. All the area south of lat. 66½° S lies under the Sun's rays, inundated with 24 hours of daylight. This parallel is known as the **Antarctic Circle**. The subsolar point has shifted to a point on the parallel at lat. 23½° S, known as the **Tropic of Capricorn**.

We have carefully used the term *daylight* to describe the period of the day during which the Sun is above the horizon. When the Sun is not too far below the horizon, the sky is still lit by *twilight*. At high latitudes during the polar night, twilight can be several hours long and provide enough illumination for many outdoor activities.

The solstices and equinoxes are four special events that occur only once during the year. Between these times, the latitude of the subsolar point travels northward and southward in an annual cycle, looping between the Tropics of Cancer and Capricorn. We call the latitude of the subsolar point the Sun's *declination* (Figure 1.24).

The Sun's declination describes the latitude of the subsolar point as it ranges from 23½° S (December solstice) to 23½° N (June solstice) throughout the year.

As the seasonal cycle progresses, the polar regions that are bathed in 24-hour daylight or shadowed in 24-hour night shrink and then grow. At other latitudes, the length of daylight changes slightly from one day to the next, except at the Equator, where it remains the same. In this way, the Earth experiences the rhythm of the seasons as it continues its revolution around the Sun.



1.24 The Sun's declination through the year

The latitude of the subsolar point marks the Sun's declination, which changes slowly through the year from −23½° to +23½° to −23½°.

GEODISCOVERIES Observing Earth–Sun Relationships
Watch a video to learn how ancient peoples used the position of the rising and setting Sun on the horizon to devise annual calendars to predict wet and dry seasons, planting, and harvesting.

GEODISCOVERIES Web Quiz
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

This chapter has focused on the daily rotation of the Earth on its axis and the annual revolution of the Earth around the Sun. The daily and annual rhythms of the Earth's motion create a global pattern of energy flow from the Sun to the Earth that changes from minute to minute, day to day, and season to season. This flow powers most of the natural processes that we experience every day, from changes in the weather to the work of streams in carving the landscape.

GEODISCOVERIES Web Links
Visit web sites to find out more about longitude, maps, and globes. Find the time at any location in the world. Find the position of the Sun in the sky for any location, time, and date. Learn more about GPS.

IN REVIEW THE EARTH AS A ROTATING PLANET

- Although the Earth appears in space photos to be a sphere, it is slightly flattened at the poles into a shape resembling an *oblate ellipsoid*. The *geoid* is a closer approximation of the Earth's true shape.
- The Earth rotates on its *axis* once in 24 hours. The intersection of the axis of rotation with the Earth's surface marks the North and South **Poles**. The direction of rotation is counterclockwise when viewed from above the North Pole.
- The Earth's **rotation** provides the daily alternation of sunlight and darkness, the tides, and a sideward turning of ocean and air currents.
- The *geographic grid*, which consists of **meridians** and **parallels**, helps us mark locations on the globe. *Great circles* always bisect the globe, but *small circles* do not.
- Geographic location is labeled using **latitude** and **longitude**. The **Equator** and the *prime meridian* act as references to locate any point on Earth.

- **Map projections** display the Earth's curved surface on a flat page. The *polar projection* pictures the globe as we might view it from the top or bottom. The *Mercator projection* converts the curved geographic grid into a flat, rectangular grid and best displays directional features. The *Winkel Tripel projection* shows the entire globe while minimizing distortion in shape and area.
- We keep time in **time zones** according to *standard meridians* that are normally 15° apart. Since the Earth rotates by 15° each hour, time zones normally differ by one hour.
- At the *International Date Line*, the calendar day changes—advancing a day for westward travel, dropping back a day for eastward travel. *Daylight saving time* advances the clock by one hour.
- The seasons arise from the **revolution** of the Earth in its orbit around the Sun and the tilt of the Earth's axis. The solstices and equinoxes mark the cycle of this revolution.
- At the **June** (summer) **solstice**, the *northern hemisphere* is tilted toward the Sun. At the **December** (winter) **solstice**, the *southern hemisphere* is tilted toward the Sun. At the **March** and **September equinoxes**, the Earth is tilted neither toward nor away from the Sun, and day and night are of equal length.

KEY TERMS

rotation, p. 38
pole, p. 38
parallel, p. 40
Equator, p. 40
meridian, p. 40
great circle, p. 40
small circle, p. 40
latitude, p. 41
longitude, p. 41
map projection, p. 43
standard time system, p. 46
time zones, p. 47
daylight saving time, p. 49
revolution, p. 49
December solstice, p. 51
June solstice, p. 52
March equinox, p. 52
September equinox, p. 52
Arctic Circle, p. 54
Tropic of Cancer, p. 54
Antarctic Circle, p. 54
Tropic of Capricorn, p. 54

REVIEW QUESTIONS

1. How do we know that the Earth is "round"? What is the approximate shape of the Earth? Define the term *geoid*.
2. What is meant by *Earth rotation?* Describe three environmental effects of the Earth's rotation.
3. Describe the geographic grid, including parallels and meridians.
4. How do latitude and longitude determine position on the globe? In what units are they measured? What function do the Equator and the prime meridian serve in determining latitude and longitude?
5. Identify three types of map projections and describe each briefly. Give reasons why you might choose different map projections to display different types of geographical information.
6. Explain the global timekeeping system. Define and use the terms *standard time*, *standard meridian*, and *time zone* in your answer.
7. What is the *international date line?* Where is it found? Why is it necessary?
8. What is meant by the "tilt of the Earth's axis"? How is the tilt responsible for the seasons?

VISUALIZING EXERCISES

1. Sketch a diagram of the Earth at an equinox. Show the North and South Poles, the Equator, and the circle of illumination. Indicate the direction of the Sun's incoming rays and shade the night portion of the globe.
2. Sketch a diagram of the Earth at the June (summer) solstice, showing the same features. Also include the Tropics of Cancer and Capricorn, and the Arctic and Antarctic Circles.

ESSAY QUESTION

1. Suppose that the Earth's axis were tilted at 40° to the plane of the ecliptic instead of 23½°. What would be the global effects of this change? How would the seasons change at your location?

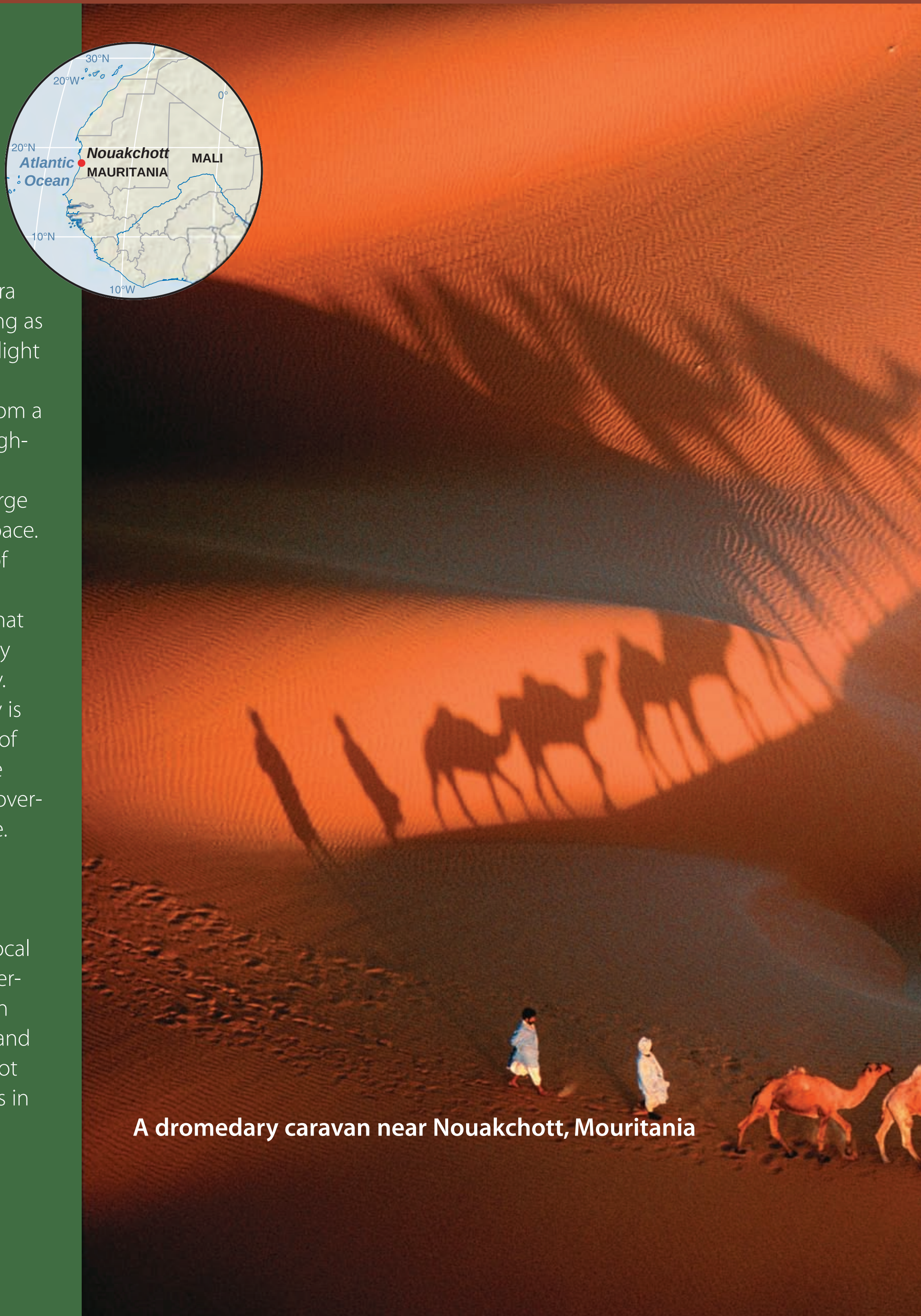
Chapter 2
The Earth's Global Energy Balance

Vast expanses of moving sand occur in parts of the Sahara Desert. Fed by sandstone formations that slowly release sand particles, the wind-driven sand sheets form an ever-changing landscape of dunes.

The sand sheets of the Sahara are very bright objects, reflecting as much as 40 percent of the sunlight they receive. The proportion of solar energy that is reflected from a surface is termed its albedo. High-albedo surfaces like sand help cool the planet by reflecting large amounts of sunlight back to space.

The long, striking shadows of the caravan in this photo point out another important fact—that the strength of the Sun's energy depends on its angle in the sky. When the Sun is low, its energy is spread across a larger amount of surface, like the shadows of the dromedaries. When the Sun is overhead, its energy is most intense.

On a global scale, the Earth's climate is determined by the balance between solar energy absorbed and reflected. On a local or regional scale, climate is determined by how the Sun's path in the sky varies from day to day and season to season. We'll have a lot more to say about these effects in this chapter.



A dromedary caravan near Nouakchott, Mouritania

The Earth's Global Energy Balance

Our planet receives a nearly constant flow of solar energy that powers all life processes and most processes of the atmosphere and Earth's surface. What are the characteristics of this energy? How and where does the Earth and atmosphere absorb this solar energy? How is solar energy converted to heat that is ultimately radiated back to space? How does the Earth–atmosphere system trap heat to produce the greenhouse effect? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

The Ozone Layer—Shield to Life

High above the Earth's surface lies an atmospheric layer rich in **ozone**—a form of oxygen in which three oxygen atoms are bonded together (O3). Ozone is a highly reactive gas that can be toxic to life and damaging to materials, but high in the atmosphere it serves an essential purpose—sheltering life on the Earth's surface from powerful ultraviolet radiation emitted by the Sun. Without the ozone layer to absorb this radiation, bacteria exposed at the Earth's surface would be destroyed, and unprotected animal tissues would be severely damaged.

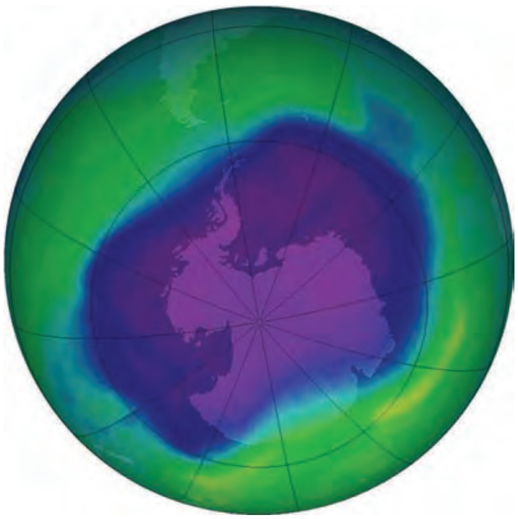
The ozone layer is presently under attack by air pollutant gases produced by human activity. The most important gases are **chlorofluorocarbons**, or **CFC**s—synthetic industrial chemical compounds containing chlorine, fluorine, and carbon atoms. Although CFCs were banned in aerosol sprays in the United States beginning in 1976, they are still used as cooling fluids in some refrigeration systems. When appliances containing CFCs leak or are discarded, their CFCs are released into the air.

Ozone is constantly being formed and destroyed by chemical reactions in the upper atmosphere, and the balance between formation and destruction determines the concentration of ozone. CFC molecules move up to the ozone layer where they decompose to chlorine oxide (ClO), which attacks ozone, converting it to ordinary oxygen (O_2) by a chain reaction. This lowers the concentration of ozone, and with less ozone, there is less absorption of ultraviolet radiation.

A "hole" in the ozone layer was discovered over the continent of Antarctica in the mid-1980s (Figure 2.1). In recent years, the ozone layer there has been found to thin during the early spring of the southern hemisphere, reaching a minimum during the month of September or October. Typically, the ozone hole slowly shrinks and ultimately disappears in early December.

In the northern hemisphere, conditions for the formation of an ozone hole are not as favorable. But arctic ozone holes have occurred several times in the past decade, with a strong arctic ozone hole observed in 2005. Atmospheric computer models have projected more such events in the period 2010–2019.

Aerosols inserted into the stratosphere by volcanic activity also can act to reduce ozone concentrations. The June 1991 eruption of Mount Pinatubo, in the Philippines, reduced global ozone in the stratosphere by 4 percent during the following year, with reductions over midlatitudes of up to 9 percent.



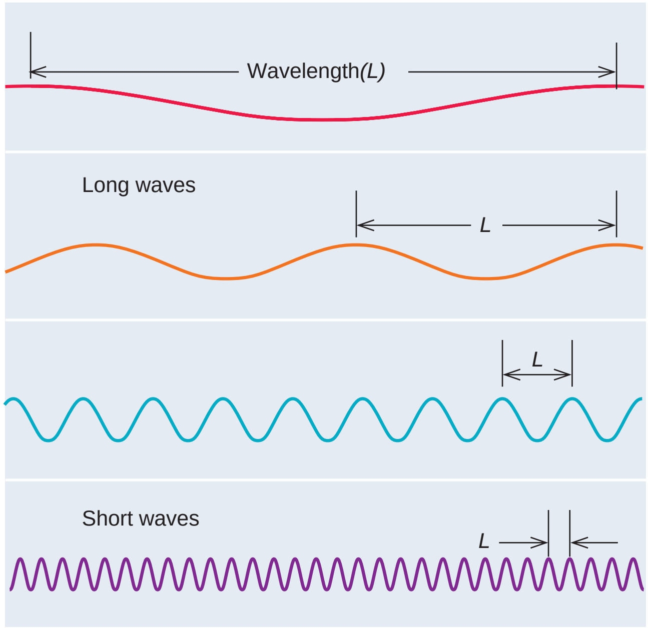
2.1 Ozone hole, September 24, 2006

The Antarctic ozone hole of 2006 was the largest on record, covering about 29.5 million km^2 (about 11.4 million mi^2). Low values of ozone are shown in purple ranging through blue, green, and yellow. Ozone concentration is measured in Dobson units, and October 8, 2006, saw its lowest value—85 units.

Since 1978, surface-level ultraviolet radiation has been increasing. Over most of North America, the increase has been about 4 percent per decade. This trend is expected to increase the number of skin cancer cases. Crop yields and some forms of aquatic life may also suffer. Today, we are all aware of the dangers of harmful ultraviolet rays to our skin and the importance of using sunscreen before going outdoors.

In response to the global threat of ozone depletion, 23 nations signed a treaty in 1987 to cut global CFC consumption by 50 percent by 1999. The treaty was effective, and by 1997, stratospheric chlorine concentrations had topped out and started to fall. In 2003, scientists using three NASA satellite instruments and three international ground stations confirmed a slowing in the rate of ozone depletion starting in 1997.

In operation for two decades, the international agreements have had an effect. Though not a reversal of ozone loss, the trend is encouraging. Current predictions show that the ozone layer will be restored by the middle of the century.



2.2 Wavelength of electromagnetic radiation

Electromagnetic radiation can be described as a collection of energy waves with different wavelengths. Wavelength is the distance from one wave crest to the next.

Electromagnetic Radiation

All surfaces—from the fiery Sun in the sky to the skin covering our bodies—constantly emit radiation. Very hot objects, such as the Sun or a light bulb filament, give off radiation that is nearly all in the form of light. Most of this energy is visible light, which we perceive with the colors of the rainbow, but the Sun also emits ultraviolet and infrared light that cannot be seen directly.

Cooler objects than the Sun, such as Earth surfaces and even our own bodies, emit heat radiation. So, our planet's surface and its atmosphere constantly emit heat. Over the long run, the Earth emits exactly as much energy as it absorbs from the sun, creating a global **energy balance**.

Light and heat are both forms of **electromagnetic radiation**. You can think of electromagnetic radiation as a collection of waves, of a wide range of wavelengths, that travel away from the surface of an object. Radiant energy can exist at any wavelength. Heat and light are identical forms of electromagnetic radiation except for their wavelengths.

Wavelength is the distance separating one wave crest from the next wave crest, as you can see in Figure 2.2. In this book, we will measure wavelength in micrometers. A *micrometer* is one millionth of a meter (10^{-6} m). The tip of your little finger is about 15,000 micrometers wide. We use the abbreviation μm for the micrometer. The first letter is the Greek letter μ, or mu.

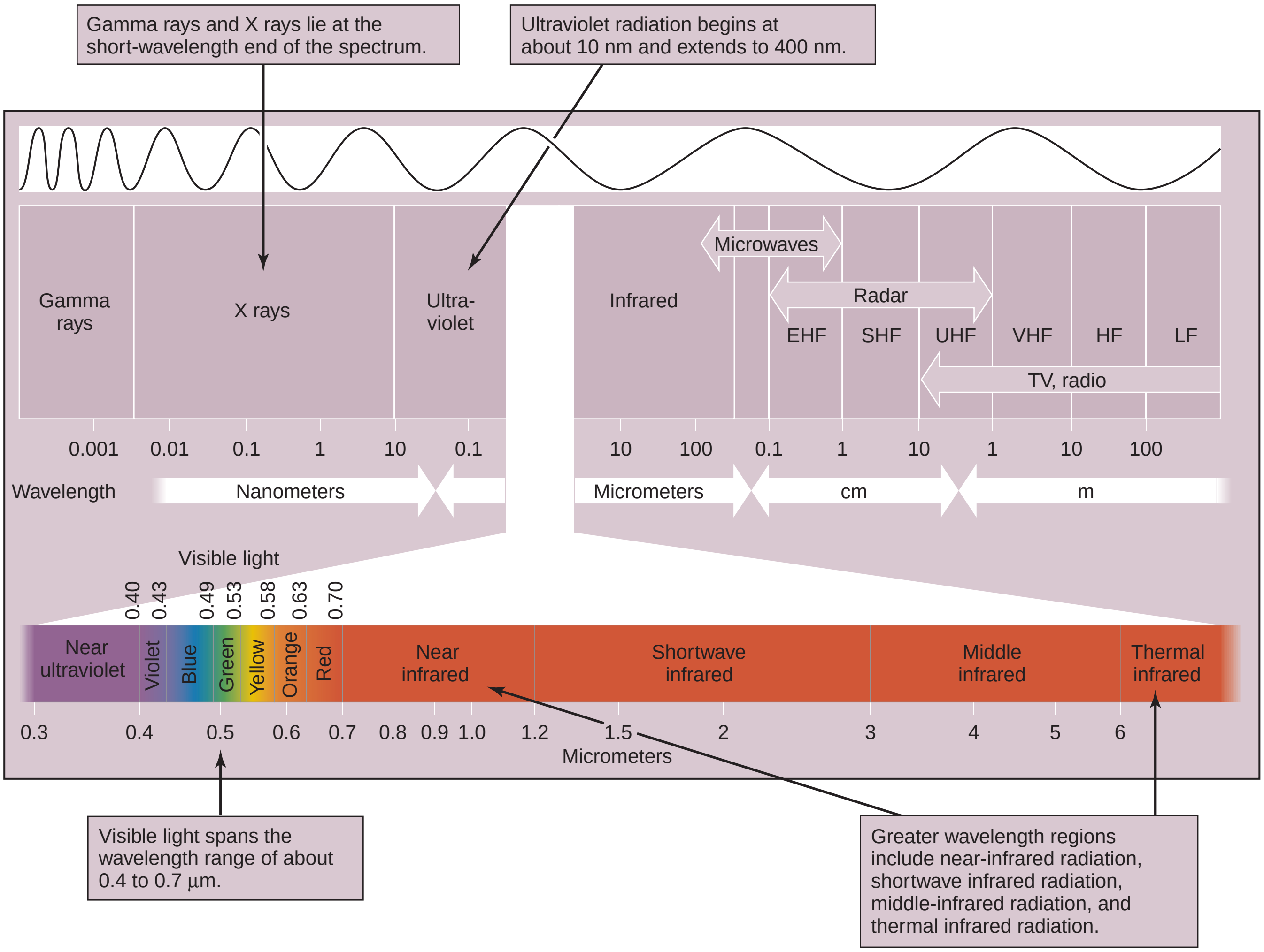
Electromagnetic waves differ in wavelength throughout their entire range, or *spectrum* (Figure 2.3). *Gamma rays* and *X rays* lie at the short-wavelength end of the spectrum. Their wavelengths are normally expressed in *nanometers*. A nanometer is one one-thousandth of a micrometer, or 10^{-9} m, and is abbreviated nm. Gamma and X rays have high energies and can be hazardous to health. *Ultraviolet radiation* begins at about 10 nm and extends to 400 nm (or 0.4 μm). It can also damage living tissues.

Visible light begins at about 0.4 μm with the color violet. Colors then gradually change through blue, green, yellow, orange, and red, until we reach the end of the visible spectrum at about 0.7 μm. Next is *near-infrared* radiation, with wavelengths from 0.7 to 1.2 μm. This radiation is very similar to visible light—most of it comes from the Sun. We can't see near-infrared light because our eyes are not sensitive to radiation beyond about 0.7 μm.

Shortwave infrared radiation also mostly comes from the Sun and lies between 1.2 and 3.0 μm. *Middle-infrared* radiation, from 3.0 μm to 6 μm, can come from the Sun or from very hot sources on the Earth, such as forest fires and gas well flames.

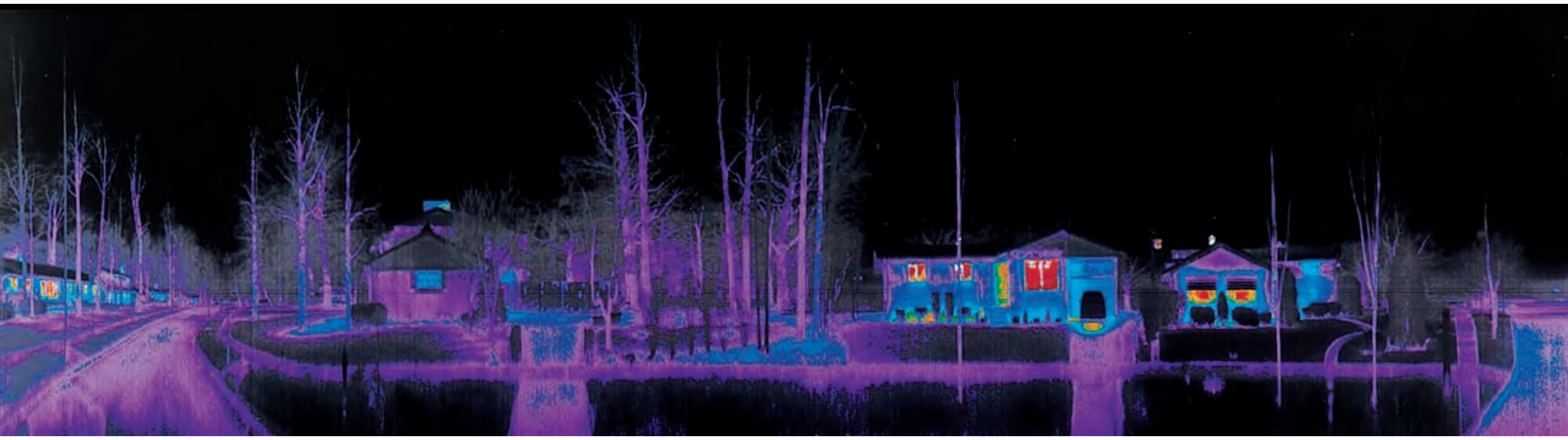
Visible light includes colors ranging from violet to red and spans the wavelength range of about 0.4 to 0.7 μm.

Next we have *thermal infrared* radiation, between 6 μm and 300 μm. This is given off by bodies at temperatures normally found at the Earth's surface. Figure 2.4 shows a thermal infrared image of a suburban scene obtained at night using a special sensor. Here red tones indicate the warmest temperatures and black tones the coldest. Windows appear red because they are warm and radiate more intensely. House walls are intermediate in temperature and appear blue. Roads and driveways are cool, as



2.3 The electromagnetic spectrum

Electromagnetic radiation can exist at any wavelength. By convention, names are assigned to specific wavelength regions.



2.4 A thermal infrared image

This thermal image shows a suburban scene at night. Black and violet tones show lower temperatures, while yellow and red tones show higher temperatures. Ground and sky are coldest, while the windows of the heated homes are warmest.

are the trees, shown in purple tones. Ground and sky are coldest (black).

GEODISCOVERIES The Electromagnetic Spectrum
Expand your vision! Go to this animation and click on parts of the electromagnetic spectrum to reveal images that can't be sensed directly with your eyes.

RADIATION AND TEMPERATURE

There are two important physical principles to remember about the emission of electromagnetic radiation. The first is that hot objects radiate more energy than cooler objects. The flow of radiant energy from the surface of an object is directly related to the absolute temperature of the surface, measured on the Kelvin absolute temperature scale, raised to the fourth power. So if you double the absolute temperature of an object, it will emit 16 times more energy from its surface. Even a small increase in temperature can mean a large increase in the rate at which radiation is given off by an object or surface.

The second principle is that the hotter the object, the shorter are the wavelengths of radiation that it emits. This inverse relationship between wavelength and temperature means that very hot objects like the Sun emit radiation at short wavelengths. Because the Earth is a much cooler object, it emits radiation with longer wavelengths. This principle explains why the Sun emits light and the Earth emits heat.

Hotter objects radiate substantially more energy than cooler objects. Hotter objects also radiate energy at shorter wavelengths.

SOLAR RADIATION

Our Sun is a ball of constantly churning gases that are heated by continuous nuclear reactions. It is about average in size compared to other stars, and it has a surface temperature of about 6000°C (about 11,000°F). The Sun's energy travels outward in straight lines or rays at a speed of about 300,000 km (about 186,000 mi) per second—the speed of light. At that rate, it takes the energy about 8 ½ minutes to travel the 150 million km (93 million mi) from the Sun to the Earth.

The rays of solar radiation spread apart as they move away from the Sun. This means that a square meter on Mars will intercept less radiation than on Venus because Mars lies farther from the Sun. The Earth only receives about one-half of one-billionth of the Sun's total energy output.

Solar energy is generated by nuclear fusion reactions inside the Sun, as hydrogen is converted to helium at very high temperatures and pressures. A vast quantity of energy is generated this way, which finds its way to the Sun's surface. The rate of solar energy production is nearly constant, so the output of solar radiation also remains nearly constant, as does the amount of solar energy received by the Earth. The rate of incoming energy, known as the *solar constant,* is measured beyond the outer limits of the Earth's atmosphere, before any energy has been lost in the atmosphere.

You've probably seen the *watt* (W) used to describe the *power*, or rate of energy flow, of a light bulb or other home appliance. When we talk about the intensity of received (or emitted) radiation, we must take into account both the power of the radiation and the surface area being hit by (or giving off) energy. So we use units of watts per square meter (W/m^2). The solar constant has a value of about 1367 W/m^2. Because there are no common equivalents for this energy flow rate in the English system, we will use only metric units.

CHARACTERISTICS OF SOLAR ENERGY

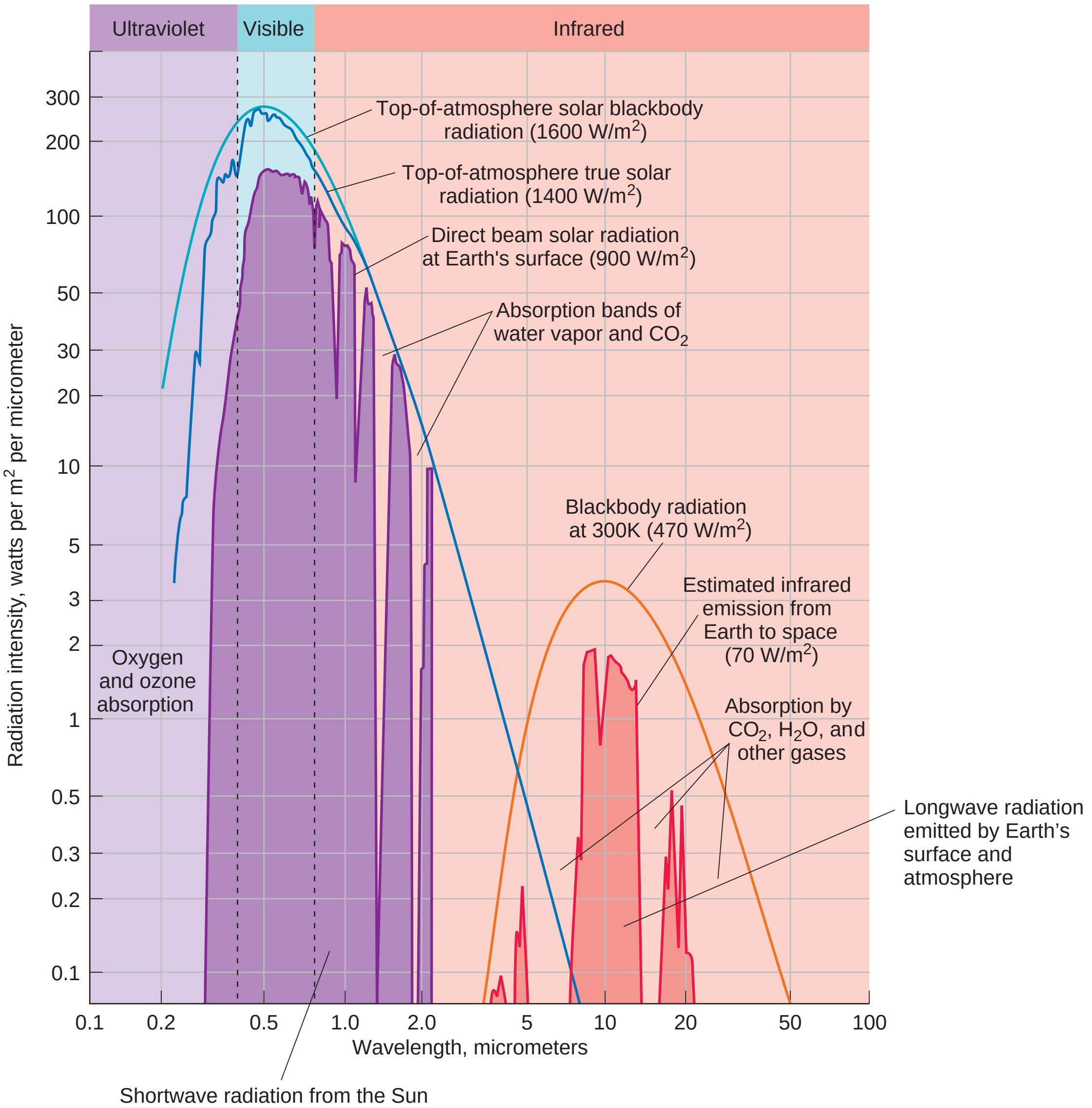
Let's look in more detail at the Sun's output as it is received by the Earth (illustrated in Figure 2.5). Energy intensity is shown on the graph on the vertical scale. Note that it is a logarithmic scale—that is, each whole unit marks an intensity 10 times greater than the one below. Wavelength is shown on the horizontal axis, also on a logarithmic scale.

The left side of Figure 2.5 shows how the Sun's incoming electromagnetic radiation varies with wavelength. The uppermost line indicates how a "perfect" Sun would supply solar energy at the top of the atmosphere. By "perfect," we mean a Sun at a temperature of 6000 K radiating as a *blackbody*—an ideal surface that follows physical theory exactly. The solid line shows the actual output of the Sun as measured at the top of the atmosphere. It is quite close to the "perfect" Sun, except for ultraviolet wavelengths, where the real Sun emits less energy. The Sun's output peaks in the visible part of the spectrum. We can see that human vision is adjusted to the wavelengths where solar light energy is highest.

The solar radiation actually reaching the Earth's surface is quite different from the solar radiation measured above the Earth's atmosphere. This is because solar radiation is both absorbed and scattered by varying amounts at different wavelengths as it passes through the atmosphere.

Molecules and particles in the atmosphere intercept and absorb radiation at particular wavelengths. This atmospheric **absorption** directly warms the atmosphere in a way that affects the global energy balance, as we will discuss

Shortwave radiation refers to wavelengths emitted by the Sun, which are in the range of about 0.3 to 3 μm. Longwave radiation refers to wavelengths emitted by cooler objects, such as Earth surfaces, which range from about 3 to 30 μm.



2.5 Spectra of solar and Earth radiation

The Earth radiates less energy than the Sun, and this energy is emitted at longer wavelengths. This figure plots both shortwave radiation, which comes from the Sun (left side), and longwave radiation, which is emitted by the Earth's surface and atmosphere (right side). Note that radiation intensity is shown on a logarithmic scale. We have not taken scattering into account in this illustration.

toward the end of this chapter. Solar rays can also be **scattered** into different directions when they collide with molecules or particles in the atmosphere. Rays can be diverted back up into space or down toward the surface, and may be scattered several times.

Solar energy received at the surface ranges from about 0.3 μm to 3 μm. This is known as **shortwave radiation**. We will now turn to the longer wavelengths of energy that are emitted by the Earth and atmosphere.

LONGWAVE RADIATION FROM THE EARTH

Remember that both the range of wavelengths and the intensity of radiation emitted by an object depend on the object's temperature. Because the Earth's surface and atmosphere are much colder than the Sun, our planet radiates less energy than the Sun and this energy is emitted at longer wavelengths.

The right side of Figure 2.5 shows exactly that. The upper line shows the radiation of a blackbody at a temperature of about 300 K (23°C, 73°F), which is a good approximation for the Earth as a whole. At this temperature, radiation ranges from about 3 to 30 μm and peaks at about 10 μm in the thermal infrared region. This thermal infrared radiation emitted by the Earth is **longwave radiation**.

Beneath the blackbody curve is an irregular series of peaks that show upwelling energy emitted by the

Earth and atmosphere as measured at the top of the atmosphere. Some wavelengths in this range seem to be missing, especially between 6–8 μm, 14–17 μm, and above 21 μm. These wavelengths are almost completely absorbed by the atmosphere before they can escape. Water vapor and carbon dioxide are the main absorbers, playing a large part in the greenhouse effect, which we will discuss shortly.

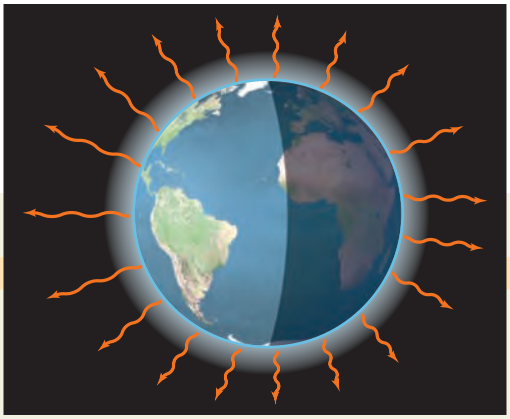
There are still three regions where outgoing energy flow from the Earth to space is significant—4 to 6 μm, 8 to 14 μm, and 17 to 21 μm. We call these *windows* through which longwave radiation leaves the Earth and flows to space.

THE GLOBAL RADIATION BALANCE

The Earth constantly absorbs solar shortwave radiation and emits longwave radiation. Figure 2.6 presents a diagram of this energy flow process, which we refer to as the Earth's **global radiation balance**.

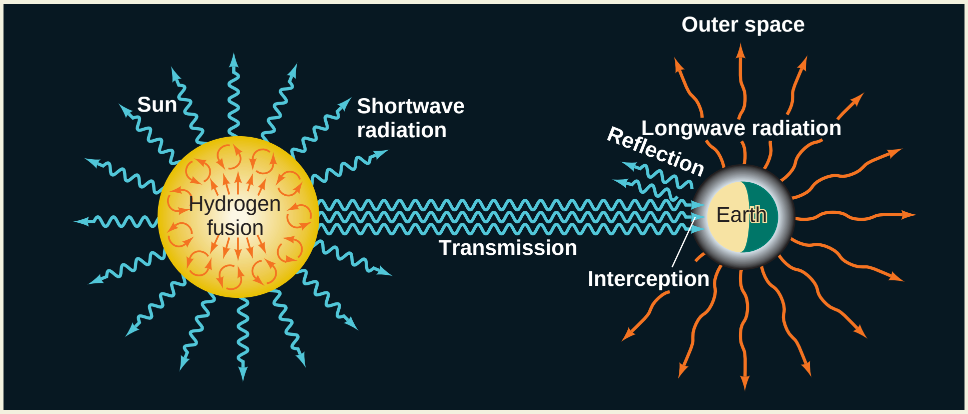
The Sun provides a nearly constant flow of shortwave radiation that is intercepted by the Earth. Scattering

2.6 The global radiation balance

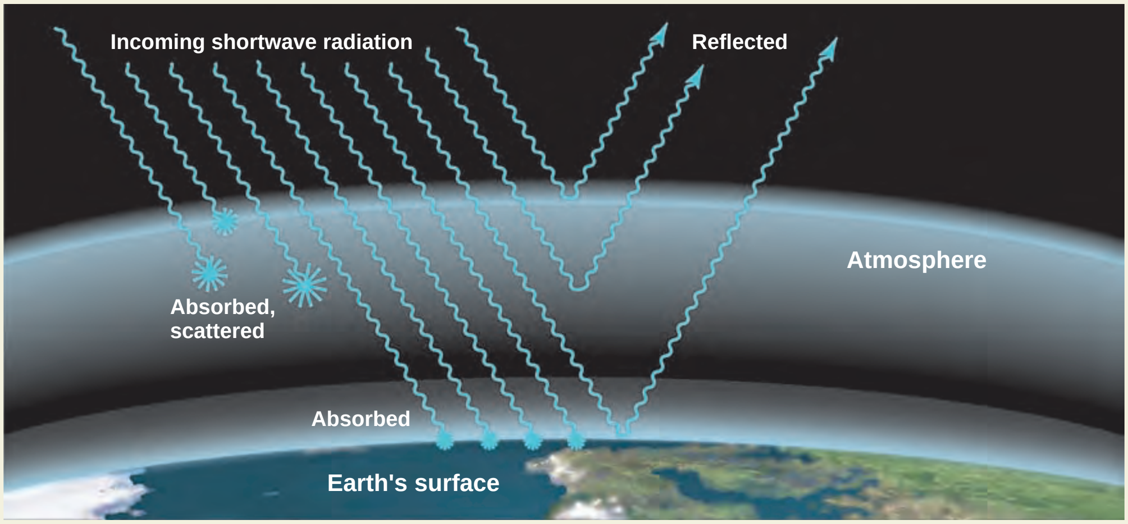


▲ Absorption of shortwave radiation by the Earth and atmosphere provides energy that the Earth–atmosphere system radiates away in all directions.

▼ Shortwave radiation from the Sun is transmitted through space, where it is intercepted by the Earth. The absorbed radiation is then ultimately emitted as longwave radiation to outer space.



▼ Incoming solar radiation is either reflected back to space or absorbed by the atmosphere or surface.



reflects part of this radiation back into space without absorption. The remaining energy is absorbed by atmosphere, land, or ocean, and ultimately emitted as longwave radiation to space. In the long run, absorbed incoming radiation is balanced by emitted outgoing radiation. Since the temperature of a surface is determined by the amount of energy it absorbs and emits, the Earth's overall temperature tends to remain constant.

Insolation over the Globe

Most natural phenomena on the Earth's surface—from the downhill flow of a river to the movement of a sand dune to the growth of a forest—are powered by the Sun, either directly or indirectly. It is the power source for wind, waves, weather, rivers, and ocean currents, as we will see here and in later chapters.

Although the flow of solar radiation to the Earth as a whole remains constant, different places on the planet receive different amounts of energy at different times. What causes this variation?

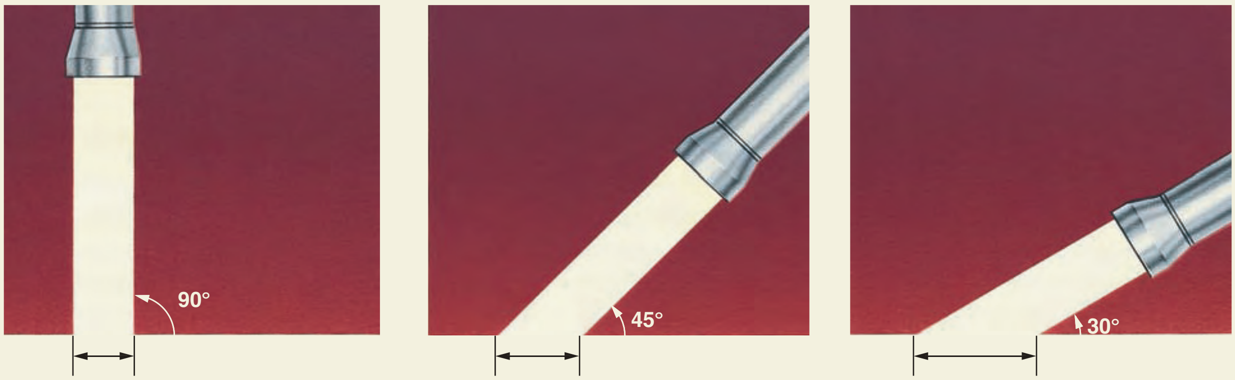
Insolation refers to the flow rate of incoming solar radiation. It is high when the Sun is high in the sky.

Incoming solar radiation is known as **insolation**. It is a rate of flow of energy and is measured in units of watts per square meter (W/m^2). *Daily insolation* is the average flow rate over a 24-hour day, while *annual insolation* is the average flow rate over the entire year.

Insolation depends on the angle of the Sun above the horizon. It is greatest when the Sun is directly overhead, and it decreases when the Sun is low in the sky, since the same amount of solar energy is spread out over a greater area of ground surface (Figure 2.7).

2.7 Solar intensity and Sun angle

The intensity of the solar beam depends on the angle between the beam and the surface.



1 unit of surface area

One unit of light is concentrated over one unit of surface area.

▲ Sunlight, represented by the flashlight, is most intense when the beam is vertical.

1.4 units of surface area

One unit of light is dispersed over 1.4 units of surface area.

▲ When the beam strikes the surface at an angle of 45°, it covers a larger surface, and so it is less intense.

2 units of surface area

One unit of light is dispersed over 2 units of surface area.

▲ At 30°, the beam covers an even greater surface and is even weaker.

◀ Because the angle of the solar beam striking the Earth varies with latitude, insolation is strongest near the Equator and weakest near the poles.

GEODISCOVERIES **The Sun's Noon Angle and the Length of Day**

Imagine yourself watching the Earth from a point far out in space, where it is easy to see how both the Sun's angle at noon and the length of day vary with the seasons and latitude for any point on Earth. An animation.

DAILY INSOLATION THROUGH THE YEAR

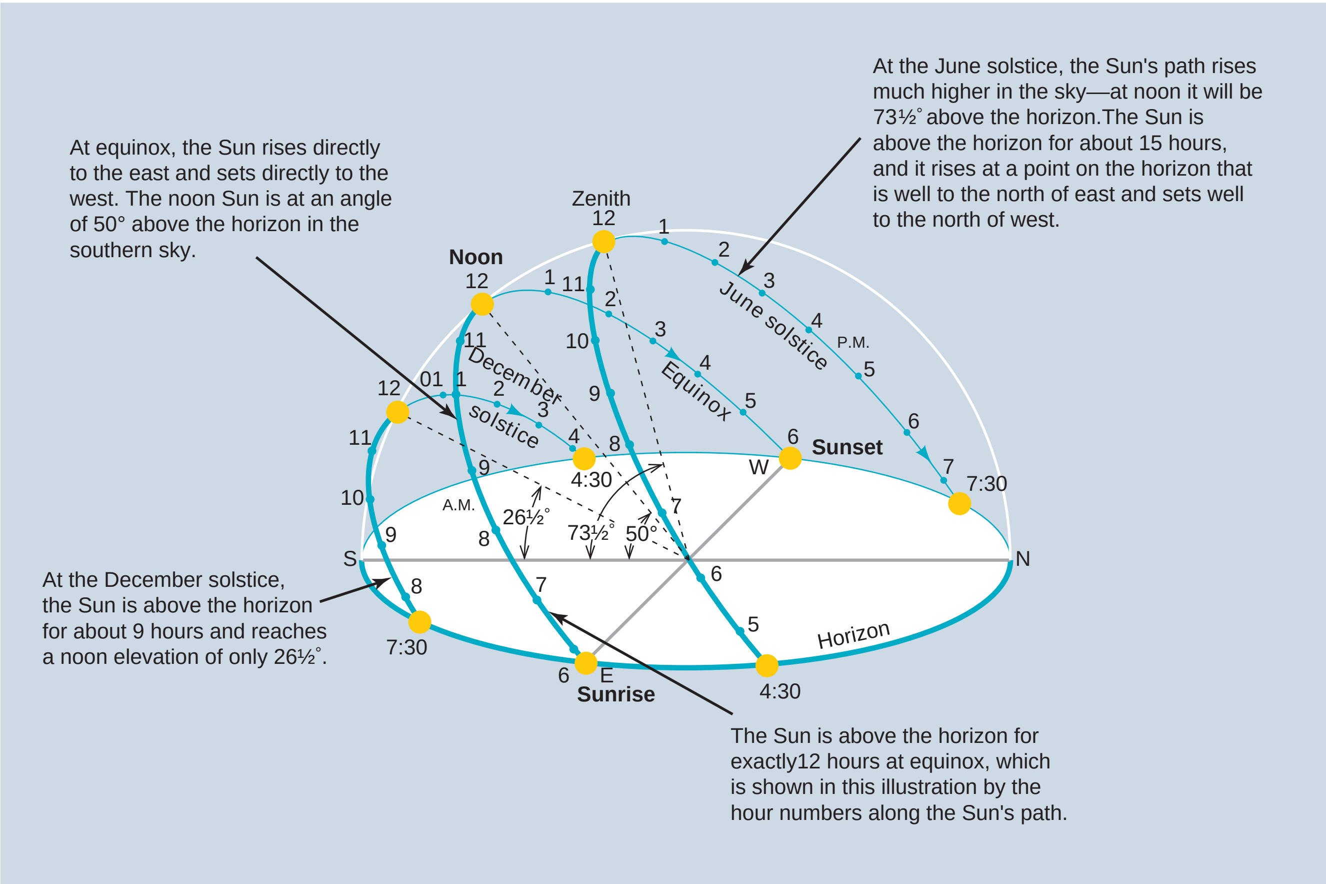
Daily insolation at a location depends on two factors: (1) the angle at which the Sun's rays strike the Earth, and (2) how long the place is exposed to the rays. In Chapter 1 we saw that both of these factors are controlled by latitude and the time of year. At midlatitude locations in summer, for example, days are long and the Sun rises to a position high in the sky, heating the surface more intensely.

How does the angle of the Sun vary during the day? It depends on the Sun's path. Near noon, the Sun is high above the horizon—the Sun's angle is greater, and so insolation is higher. Figure 2.8 shows the typical conditions found in midlatitudes in the northern hemisphere, for example, at New York or Denver. An observer standing on a wide plain will see a small area of the Earth's surface bounded by a circular horizon. The Earth's surface appears flat, and the Sun seems to travel inside a vast dome in the sky.

Comparing the three paths shown in the figure, we find that both the length of time the Sun is in the sky and the angle of the Sun during the main part of the day change with the time of year. At the June solstice, average daily insolation will be greatest, since the Sun is in the sky longer and reaches higher elevations. At the December solstice, daily insolation will be least, with a shorter daily path and lower elevations. At the equinox, the insolation will be intermediate.

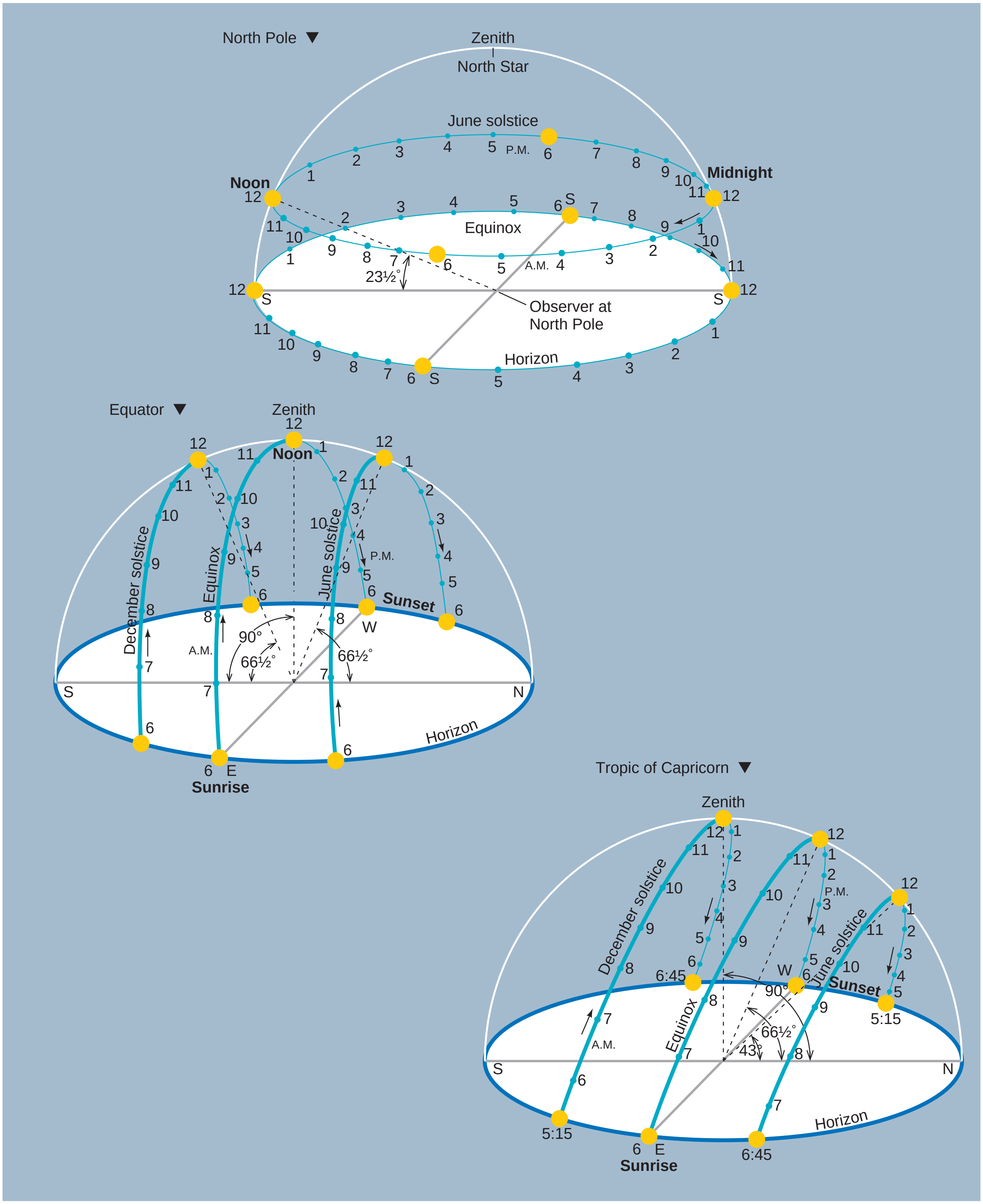
Figure 2.9 shows the Sun's path for three other latitudes. At the North Pole, the Sun moves in a circle in the sky at an elevation that changes with the seasons. At the Equator, the Sun is always in the sky for 12 hours, but its noon angle varies through the year. At the Tropic of Capricorn, the Sun is in the sky longest and reaches its highest elevations at the December solstice.

Based on this analysis, daily insolation will vary strongly with season at most latitudes. As shown in Figure 2.10, daily insolation at 40° will range from about 160 W/m² on the December solstice to about 460 W/m² on the June solstice. Insolation drops to zero at the North Pole

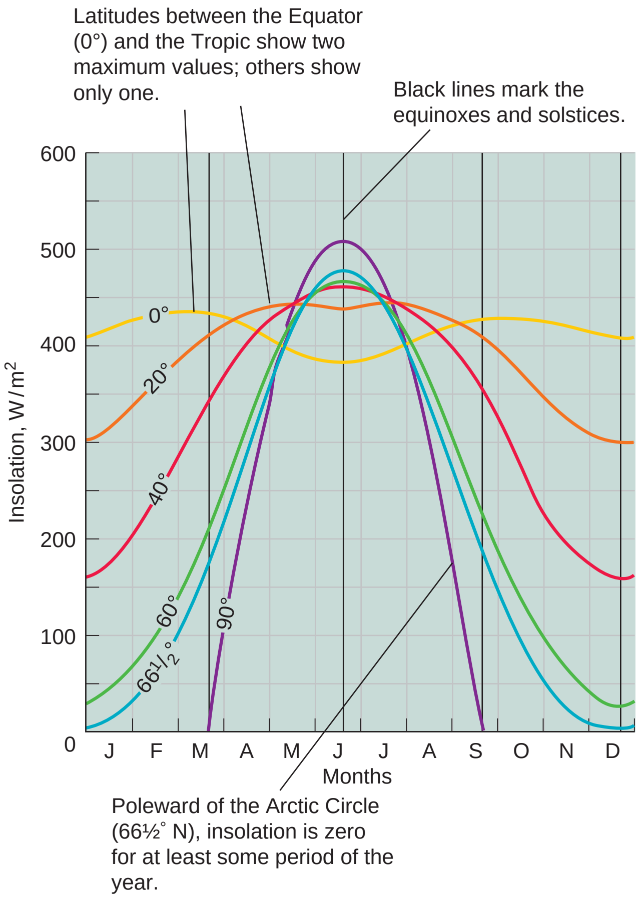


2.8 The path of the Sun in the sky at 40° N latitude

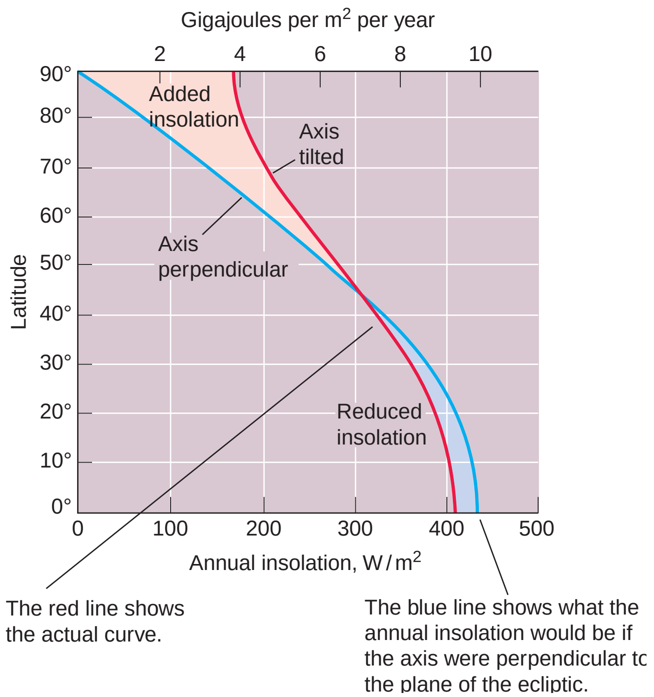
The Sun's path changes greatly in position and height above the horizon through the seasons.



2.9 The Sun's path at the North Pole, Equator, and Tropic of Capricorn



2.10 Daily insolation through the year at various latitudes (northern hemisphere)



2.11 Annual insolation from Equator to pole for the Earth

at the September equinox, when the Sun's circular path sinks below the horizon, and does not increase again until the March equinox. However, the peak insolation at the June solstice is greater at the North Pole, about 500 W/m², than at any other latitude. At the Equator, daily insolation varies from about 380 W/m² to about 430 W/m² and there are two maximums—each near the time of an equinox, when the Sun is directly overhead at noon. At the solstice, insolation is lower because the Sun's path is lower in the sky (Figure 2.9).

GEODISCOVERIES The Path of the Sun in the Sky
View this animation to follow the daily path of the Sun in the sky. Shows how both latitude and season affect the Sun's motion as seen by an observer on the ground.

ANNUAL INSOLATION BY LATITUDE

How does latitude affect annual insolation—the rate of insolation averaged over an entire year? Figure 2.11 shows two curves of annual insolation by latitude—one for the actual case of the Earth's axis tilted at 23½° and the other for an Earth with an untilted axis.

Let's look first at the real case of a tilted axis. We can see that annual insolation varies smoothly from the Equator to the pole and is greater at lower latitudes. But high latitudes still receive a considerable flow of solar energy—the annual insolation value at the pole is about 40 percent of the value at the equator.

Now let's look at what would happen if the Earth's axis was not tilted. With the axis perpendicular to the plane of the ecliptic, there are no seasons. Annual insolation is very high at the Equator because the Sun passes directly overhead at noon every day throughout the year. Annual insolation at the poles is zero because the Sun's rays always skirt the horizon.

We can see that without a tilted axis our planet would be a very different place. The tilt redistributes a very significant portion of the Earth's insolation from the equatorial regions toward the poles. So even though the pole does not receive direct sunlight for six months of the year, it still receives nearly half the amount of annual solar radiation as the Equator.

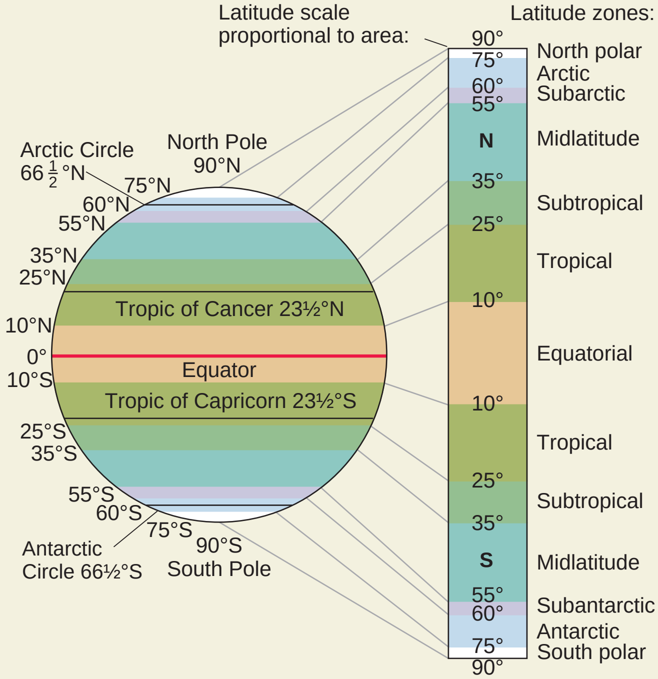
WORLD LATITUDE ZONES

The seasonal pattern of daily insolation provides a convenient way to divide the globe into broad latitude zones (Figure 2.12) that we will use in this book. The *equatorial zone* encompasses the Equator and covers the latitude belt roughly 10° north to 10° south. Here the Sun provides intense insolation throughout most of the year, and days and nights are of roughly equal

2.12 World latitude zones

▲ **Subarctic zone** Much of the subarctic zone is covered by evergreen forest, seen here with a ground cover of snow. Near Churchill, Hudson Bay region, Canada (National Geographic Image Collection).

A geographer's system of latitude zones, based on the seasonal patterns of daily insolation observed over the globe.



▲ **Midlatitude zone** A summer midlatitude landscape in the Tuscany region of Italy (National Geographic Image Collection).

▲ **Tropical zone** The tropical zone is the home of the world's driest deserts. Pictured here is the Rub' al Khali, Saudi Arabia (National Geographic Image Collection).

▲ **Equatorial zone** An equatorial rainforest, as seen along a stream in the Gunung Palung National Park, Borneo, Indonesia.

length. Spanning the Tropics of Cancer and Capricorn are the *tropical zones*, ranging from latitudes 10° to 25° north and south. A marked seasonal cycle exists in these zones, combined with high annual insolation.

Moving toward the poles, we come to the *subtropical zones*, which lie roughly between the latitudes 25° to 35° north and south. These zones have a strong seasonal cycle and a large annual insolation. The *midlatitude zones* are next, between 35° and 55° north and south latitude. The length of daylight varies significantly from winter to summer here, so seasonal contrasts in insolation are quite strong. As a result, these regions experience a large range in annual surface temperature.

The *subarctic* and *subantarctic zones* border the midlatitude zones at 55° to 60° north and south latitudes. The *arctic* and *antarctic zones* lie between latitudes 60° and 75° N and S, astride the Arctic and Antarctic Circles. These zones have an extremely large yearly variation in day lengths, yielding enormous contrasts in insolation over the year. Finally, the *north* and *south polar* zones range from about 75° latitude to the poles. They experience the greatest seasonal insolation contrast of all, and have 24-hour days or nights for much of the year.

Composition of the Atmosphere

The Earth is surrounded by air—a mixture of various gases that reaches up to a height of many kilometers. This envelope of air makes up our atmosphere (Figure 2.13). It is held in place by the Earth's gravity. Almost all the atmosphere (97 percent) lies within 30 km (19 mi) of the Earth's surface. The upper limit of the atmosphere is at a height of approximately 10,000 km (about 6000 mi) above the Earth's surface—a distance that is nearly as large as Earth's diameter.

The proportion of gases in dry air is highly uniform up to an altitude of about 80 km (50 mi). About 99 percent of pure, dry air is nitrogen (about 78 percent by volume) and oxygen (about 21 percent). These two main component gases of the lower atmosphere are perfectly mixed, so pure, dry air behaves as if it is a single gas with very definite physical properties.

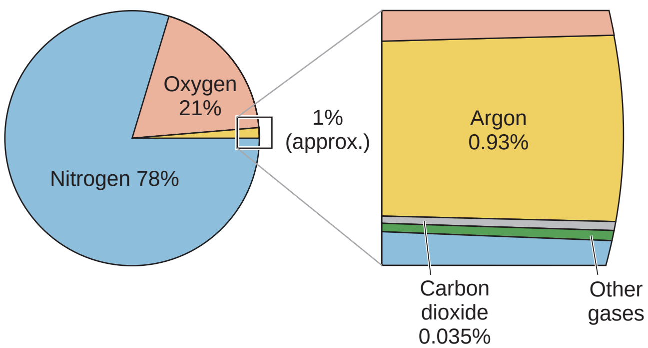
Nitrogen gas is a molecule consisting of two nitrogen atoms (N_2). It does not easily react with other substances. Soil bacteria do take up very small amounts of nitrogen, which can be used by plants, but otherwise nitrogen is largely a "filler," adding inert bulk to the atmosphere.

In contrast, *oxygen gas* (O_2) is chemically very active, combining readily with other elements in the process of *oxidation*. Fuel combustion is a rapid form of oxidation, while certain types of rock decay (weathering) are very slow forms of oxidation. Living tissues require oxygen to convert foods into energy.

The remaining 1 percent of dry air is mostly argon, an inactive gas of little importance in natural processes, with a very small amount of *carbon dioxide* (CO_2), amounting to about 0.0385 percent. Although the amount of CO_2 is small, it is a very important atmospheric gas because it absorbs much of the incoming shortwave radiation from the Sun and outgoing longwave radiation from the Earth. The greenhouse effect is caused when longwave radiation is absorbed by CO_2 molecules in the lower atmosphere, which reradiate some of that heat back to the surface. Carbon dioxide is also used by green plants, which convert it to its chemical compounds to build up their tissues, organs, and supporting structures during photosynthesis.

Water vapor is another important atmospheric gas. Individual water vapor molecules mix freely with other atmospheric gases, but water vapor can vary highly in concentration. Water vapor usually makes up less than 1 percent of the atmosphere, but under very warm, moist conditions, as much as 2 percent of the air can be water vapor. Since it is a good absorber of heat radiation, like carbon dioxide, it plays a major role in warming the lower atmosphere and enhancing the greenhouse effect.

Another small, but important, constituent of the atmosphere is *ozone*, which we described in our *Eye on Global Change* opening feature. Ozone in the upper atmosphere is beneficial because it shields life at the Earth's surface from harmful solar ultraviolet radiation. But in the lowest layers of the atmosphere, ozone is an air pollutant that damages lung tissue and aggravates bronchitis, emphysema, and asthma.



2.13 Component gases of the lower atmosphere

Values show percentage by volume for dry air. Nitrogen and oxygen form 99 percent of our air, with other gases, principally argon and carbon dioxide, accounting for the final 1 percent.

Sensible Heat and Latent Heat Transfer

The most familiar form of heat storage and transport is known as **sensible heat**—it's what you feel when you touch a warm object. When we use a thermometer, we are measuring sensible heat. *Sensible heat transfer* moves heat from warmer to colder objects by *conduction* when they are in direct contact. Sensible heat is also transferred by *convection* when a fluid such as the atmosphere or ocean carries heat energy away from a surface.

Sensible heat transfer refers to the flow of heat between the Earth's surface and the atmosphere by conduction or convection. Latent heat transfer refers to the flow of heat carried by changes of state of water.

In contrast, **latent heat**—or hidden heat—cannot be measured by a thermometer. It is heat that is taken up and stored as molecular motion when a substance changes state from a solid to a liquid, from a liquid to a gas, or from a solid directly to a gas. For example, when liquid water changes to water vapor, or ice changes to liquid water, heat energy is absorbed from the surroundings. This is why sweat cools the skin. Latent heat energy is stored in free fluid motion of the liquid water molecules or in the fast random motion of free water vapor molecules. When the vapor turns back to a liquid or solid, the latent heat is released, warming the surroundings.

In the Earth–atmosphere system, *latent heat transfer* occurs when water evaporates from a moist land surface or from open water, moving heat from the surface to the atmosphere. That latent heat is later released as sensible heat, often far away, when the water vapor condenses to form water droplets or snow crystals. On a global scale, latent heat transfer is a very important mechanism for transporting large amounts of heat from one region of the Earth to another.

GEODISCOVERIES **Latent Heat**

Brush up on how water changes state between solid, liquid, and gaseous forms and how latent heat is either absorbed or released in the change process. An animation.

The Global Energy System

Human activity around the globe has changed the planet's surface cover and added carbon dioxide to the atmosphere. Have we irrevocably shifted the balance of energy flows? Is our Earth absorbing more solar energy and becoming warmer? Or is it absorbing less and becoming cooler? If we want to understand human impact on the Earth–atmosphere system, then we need to examine the global energy balance in detail.

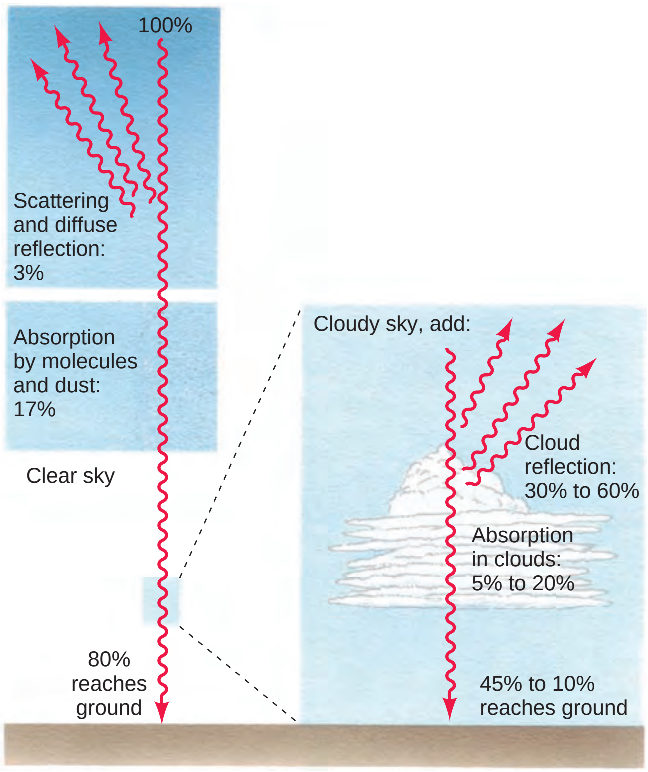
The flow of energy from the Sun to the Earth and then back out into space is a complex system. Solar energy is the ultimate power source for the Earth's surface processes, so when we trace the energy flows between the Sun, surface, and atmosphere, we are really studying how these processes are driven.

SOLAR ENERGY LOSSES IN THE ATMOSPHERE

Let's examine the flow of insolation through the atmosphere on its way to the surface. Figure 2.14 gives typical values for losses of incoming shortwave radiation in the solar beam as it penetrates the atmosphere. Gamma rays and X rays from the Sun are almost completely absorbed by the thin outer layers of the atmosphere, while much of the ultraviolet radiation is also absorbed, particularly by ozone.

As the radiation moves deeper through denser layers of the atmosphere, it can be scattered by gas molecules, dust, or other particles in the air, deflecting it in any direction. Apart from this change in direction, it is unchanged. Scattered radiation moving in all directions through the atmosphere is known as *diffuse radiation*. Some scattered radiation flows down to the Earth's surface, while some flows upward. This upward flow of diffuse radiation escaping back to space, also known as *diffuse reflection*, amounts to about 3 percent of incoming solar radiation.

What about absorption? As we saw earlier, molecules and particles can absorb radiation as it passes through the atmosphere. Carbon dioxide and water are the biggest absorbers, but because the water vapor content of air can vary greatly, absorption also varies from one global environment to another. About 17 percent of incoming



2.14 Fate of incoming solar radiation

Losses of incoming solar energy are much lower with clear skies (left) than with cloud cover (right).

solar radiation is absorbed, raising the temperature of atmospheric layers. After taking into account absorption and scattering, about 80 percent of the incoming solar radiation reaches the ground.

Clouds can greatly increase the amount of incoming solar radiation reflected back to space. Reflection from the bright white surfaces of thick low clouds deflects about 30 to 60 percent of incoming radiation back into space. Clouds also absorb as much as 5 to 20 percent of the radiation.

When accounting for both cloudy skies and clear skies on a global scale, only about 50 percent of the total insolation at the top of the atmosphere reaches the surface. When this energy strikes the surface, it can be either absorbed or scattered upward. Absorption heats the surface, raising the surface temperature. The scattered radiation reenters the atmosphere, and much of it passes through, directly to space.

ALBEDO

The proportion of shortwave radiant energy scattered upward by a surface is called its **albedo**. Snow and ice have high albedos (0.45 to 0.85), reflecting most of the solar radiation that hits them and absorbing only a small amount. In contrast, a black pavement, which has a low albedo (0.03), absorbs nearly all the incoming solar energy (Figure 2.15). Water also has a low albedo (0.02), unless the Sun illuminates it at a low angle, producing Sun glint. The energy absorbed by a surface warms the air immediately above it by conduction and convection, so surface temperatures are warmer over low-albedo than over high-albedo surfaces. Fields, forests, and bare ground have intermediate albedos, ranging from 0.03 to 0.25.

The Earth and atmosphere system, taken as a whole, has an albedo of between 0.29 and 0.34. This means that our planet sends back to space slightly less than one-third of the solar radiation it receives. It also means that our planet absorbs slightly more than two-thirds of the solar radiation it receives. This balance between reflected and absorbed solar radiation is what determines the overall temperature of Earth.

COUNTERRADIATION AND THE GREENHOUSE EFFECT

As well as being warmed by shortwave radiation from the Sun, the Earth's surface is significantly heated by the longwave radiation emitted by the atmosphere and absorbed by the ground. Let's look at this in more detail.

Figure 2.16 shows the energy flows between the surface, atmosphere, and space. On the left we can see the flow of shortwave radiation from the Sun to the surface. Some of this radiation is reflected back to space, but much is absorbed, warming the surface.

Counterradiation from the atmosphere to the Earth's surface helps warm the surface and creates the greenhouse effect. It is enhanced by carbon dioxide and water in the atmosphere.

Meanwhile, the Earth's surface emits longwave radiation upwards. Some of this radiation escapes directly to space, while the remainder is absorbed by the atmosphere.

What about longwave radiation emitted by the atmosphere? Although the atmosphere is colder than the surface, it also emits longwave radiation, which is emitted in all directions, and so some radiates upward to space while the remainder radiates downward toward the Earth's surface. We call this downward flow **counterradiation**. It replaces some of the heat emitted by the surface.

Counterradiation depends strongly on the presence of carbon dioxide and water vapor in the atmosphere. Remember that much of the longwave radiation emitted upward from the Earth's surface is absorbed by these two gases. This absorbed energy raises the temperature of the atmosphere, causing it to emit more counterradiation. So, the lower atmosphere, with its longwave-absorbing gases, acts like a blanket that traps heat underneath it. Cloud layers, which are composed of tiny water droplets, are even more important than carbon dioxide and water vapor in producing a blanketing effect because liquid water is also a strong absorber of longwave radiation.

This mechanism, in which the atmosphere traps longwave radiation and returns it to the surface through counterradiation is termed the **greenhouse effect** (Figure 2.17). Unfortunately, the term *greenhouse* is not quite accurate. Like the atmosphere, the window glass in a greenhouse is transparent to solar shortwave radiation while absorbing and reradiating longwave radiation. But a greenhouse is warmed mainly by keeping the warm air inside the greenhouse from mixing with the outside air, not by counterradiation from the glass.

GLOBAL ENERGY BUDGETS OF THE ATMOSPHERE AND SURFACE

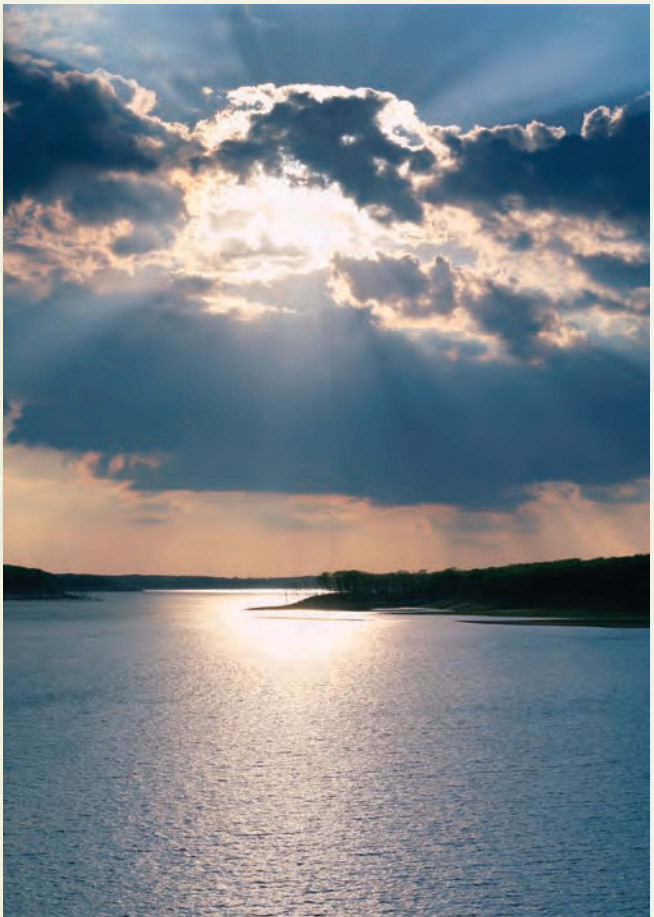
Although energy may change its form from shortwave to longwave radiation or to sensible heat or latent heat, it cannot be created or destroyed. Like a household budget of income and expenses, the energy flows between the Sun and the Earth's atmosphere and surface must balance over the long term. The global energy budget shown in Figure 2.18 takes into account all the important energy flows and helps us to understand how changes in these flows might affect the Earth's climate. It uses a scale in which the amount of incoming solar radiation is represented as 100 units.

Let's look first at the top of the atmosphere, where we see the balance for the Earth–atmosphere system as a whole. Incoming solar radiation (100 units) is balanced

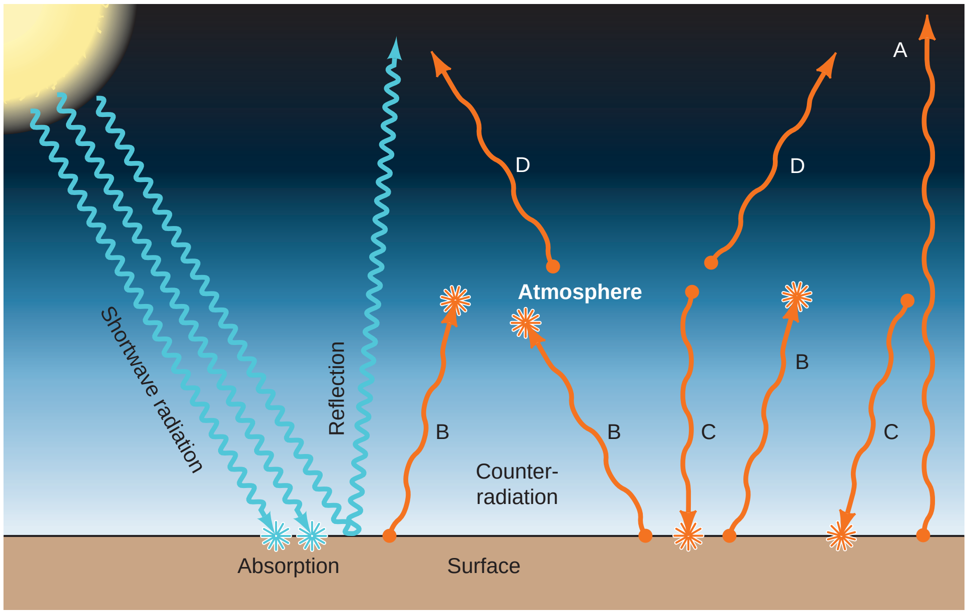
2.15 Albedo contrasts

◀ **Bright snow** A layer of new, fresh snow has a high albedo, reflecting most of the sunlight it receives. Only a small portion is absorbed (National Geographic Image Collection).

▼ **Water** Water absorbs solar radiation and has a low albedo unless the radiation strikes the water surface at a low angle. In that case, Sun glint raises the albedo.

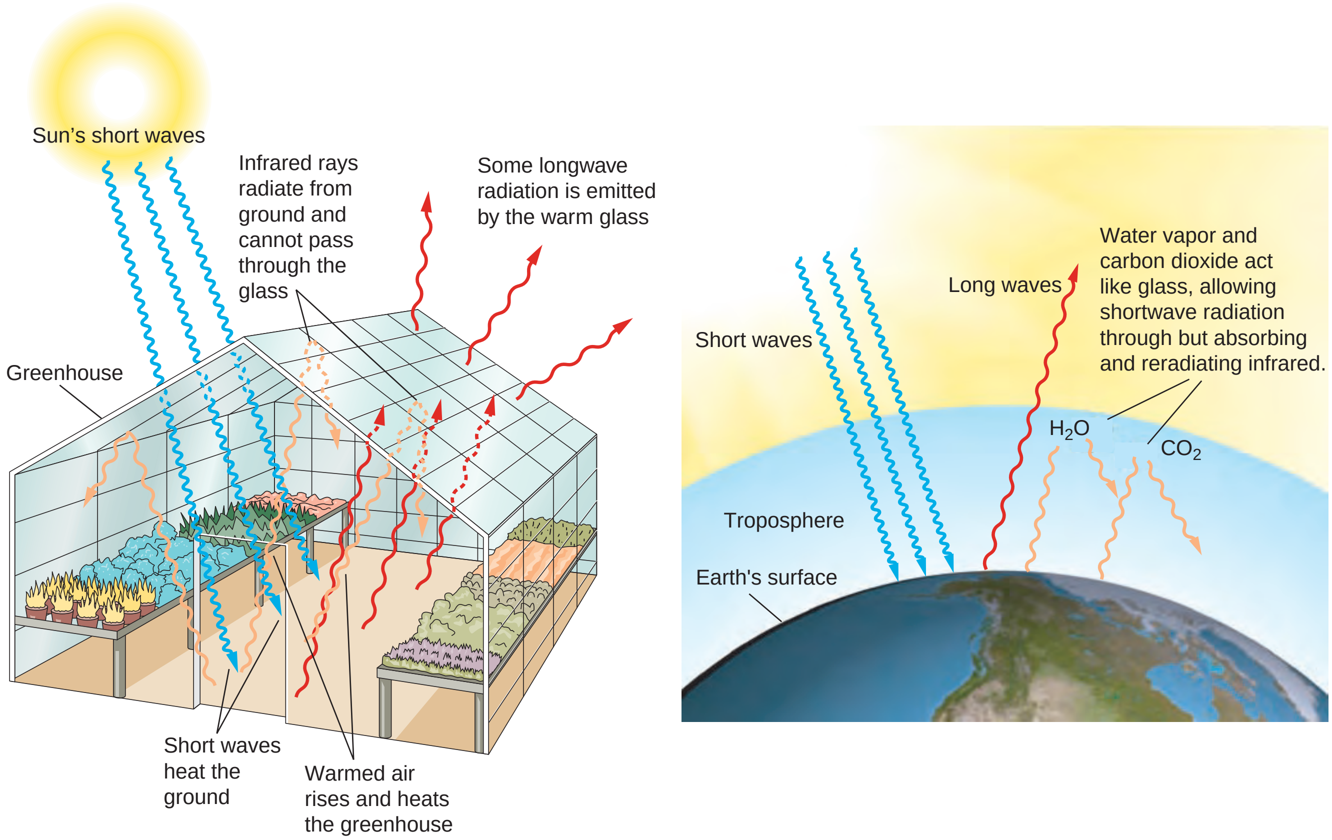


▼ **Blacktop road** Asphalt paving reflects little light, so it appears dark or black and has a low albedo. It absorbs nearly all of the solar radiation it receives.



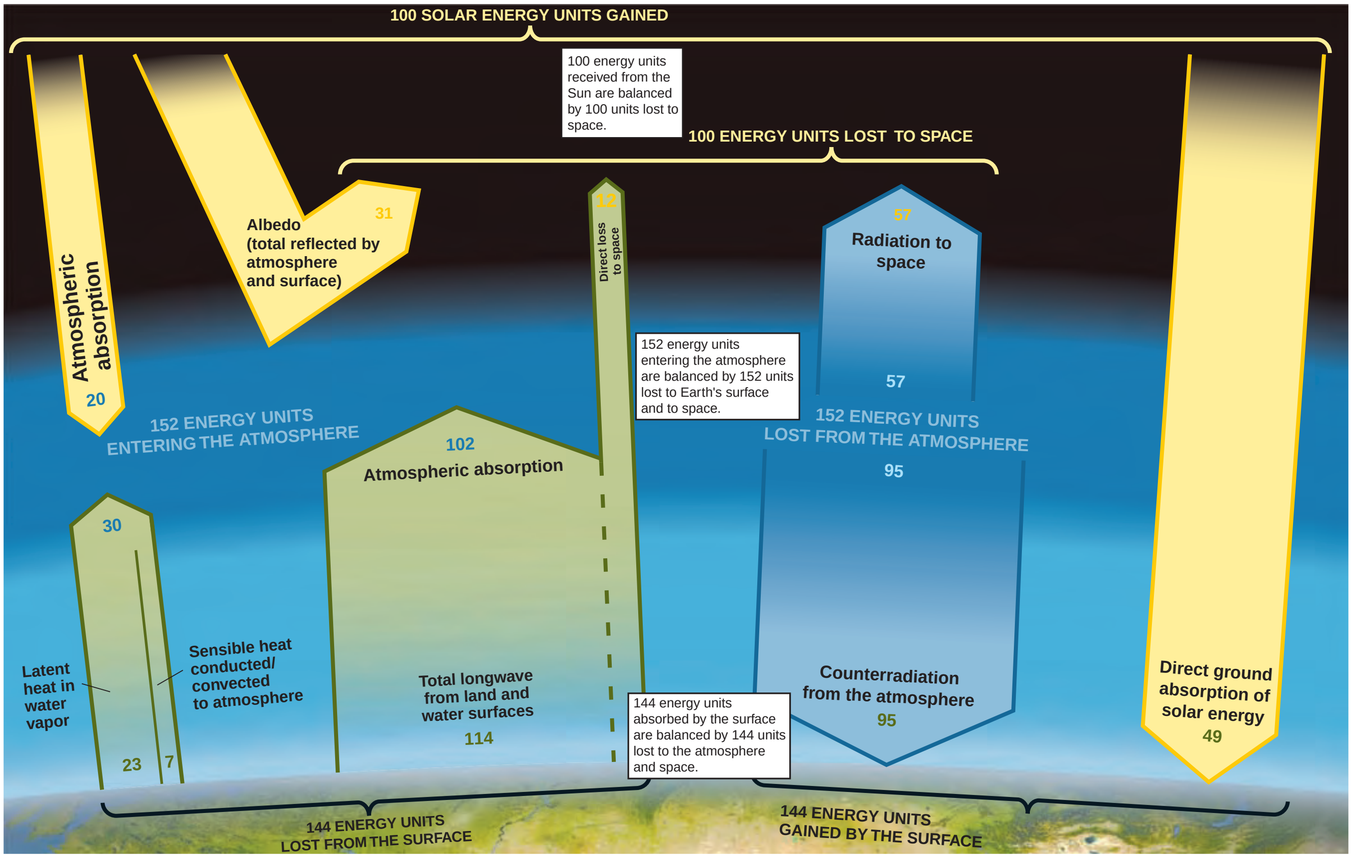
2.16 Counterradiation and the greenhouse effect

Shortwave radiation passes through the atmosphere and is absorbed or reflected at the surface. Absorption warms the surface, which emits longwave radiation. Some of this flow passes directly to space (A), but most is absorbed by the atmosphere (B). In turn, the atmosphere radiates longwave energy back to the surface as counterradiation (C) and also to space (D). The counterradiation produces the greenhouse effect.



2.17 A greenhouse and the greenhouse effect

Water vapor and carbon dioxide act like glass, allowing shortwave radiation through but absorbing and radiating longwave radiation.



2.18 The global energy balance

Energy flows continuously among the Earth's surface, atmosphere, and space. The relative size of each flow is based on an arbitrary "100 units" of solar energy reaching the top of the Earth's atmosphere. The difference between solar energy absorbed by the Earth system (100 units incoming – 31 reflected = 69 absorbed) and the energy absorbed at the surface (144 units) is the energy (75 units) that is recycled within the Earth system (144 – 69 = 75). The larger this number, the warmer is the Earth system's climate.

by exiting shortwave reflection from the Earth's surface and atmosphere and outgoing longwave radiation coming from the atmosphere and surface.

The atmosphere's budget is also balanced, since it receives 152 units and loses 152 units. Received energy includes absorbed incoming solar radiation, absorbed longwave radiation from the surface, and latent and sensible heat transfer from the surface. The atmosphere loses longwave energy by radiation to space and counterradiation to the surface.

The surface receives 144 units and loses 144 units. Incoming energy consists of direct solar radiation absorbed at the surface and longwave radiation from the atmosphere. Exiting energy includes latent and sensible heat transfer to the atmosphere and longwave radiation to the atmosphere and space.

The greenhouse effect is readily visible in the two largest arrows in the center of the figure. The surface loses 102 units of longwave energy, but receives 95 units of counterradiation from the atmosphere. These flows amount to a loop that traps and returns most of the heat radiation leaving the surface, keeping surface temperatures warm.

CLIMATE AND GLOBAL CHANGE

The global energy budget helps us understand how global change might affect the Earth's climate. For example, suppose that clearing forests for agriculture and turning agricultural lands into urban and suburban areas decreases surface albedo. In that case, more energy would be absorbed by the ground, raising its temperature. That, in turn, would increase the flow of surface longwave radiation to the atmosphere, which would be absorbed and would then boost counterradiation. The total effect would probably be to amplify warming through the greenhouse effect.

What if industrial aerosols cause more low, thick clouds to form? Low clouds increase shortwave reflection back to space, causing the Earth's surface and atmosphere to cool. What about increasing condensation trails from jet aircraft? These could cause more high, thin clouds, which absorb more longwave energy and make the atmosphere warmer, boosting counterradiation and increasing the greenhouse effect. The energy flow linkages between the Sun, surface, atmosphere, and space are critical components of our climate system, and human activities can modify these flows significantly.

Net Radiation, Latitude, and the Energy Balance

Although the energy budgets of the Earth's surface and atmosphere are in balance overall, their budgets do not have to balance at each particular place on the Earth, nor do they have to balance at all times. At night, for example, there is no incoming radiation from the Sun, yet the Earth's surface and atmosphere still emit outgoing radiation.

Net radiation is the difference between all incoming radiation and all outgoing radiation. In places where radiant energy flows in faster than it flows out, net radiation is positive, providing an energy surplus. In other places, net radiation can be negative. For the entire Earth and atmosphere, the net radiation is zero over a year.

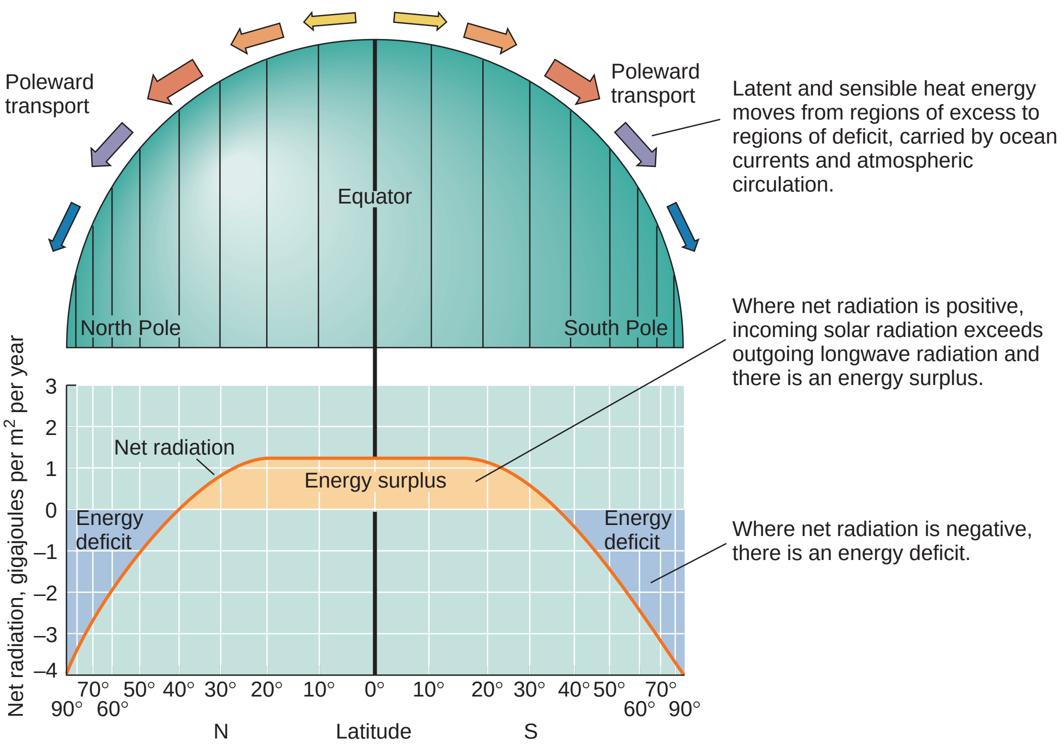
We saw earlier that solar energy input varies strongly with latitude. What is the effect of this variation on net radiation? To answer this question, let's look at Figure 2.19, which shows the net radiation profile from pole to pole. Between about 40° N and 40° S there is a net radiant energy gain, labeled "energy surplus." In other words, incoming solar radiation exceeds outgoing longwave radiation throughout the year. Poleward of 40° N and 40° S, the net radiation is negative and is labeled "energy deficit"—meaning that outgoing longwave radiation exceeds incoming shortwave radiation.

If you examine the graph carefully, you will find that the area labeled "surplus" is equal in size to the combined areas labeled "deficit." So the net radiation for the Earth's surface as a whole is zero, as expected, with global incoming shortwave radiation exactly balancing global outgoing longwave radiation.

Because there is an energy surplus at low latitudes and an energy deficit at high latitudes, energy will flow from low latitudes to high. This energy is transferred poleward as latent and sensible heat—warm ocean water and warm, moist air move poleward, while cooler water and cooler, drier air move toward the Equator.

We'll return to these flows in later chapters. But keep in mind that this **poleward heat transfer**, driven by the imbalance in net radiation between low and high latitudes, is the power source for broad-scale atmospheric circulation patterns and ocean currents. Without this circulation, low latitudes would heat up and high latitudes would cool down until a radiative balance was achieved, leaving the Earth with much more extreme temperature contrasts—very different from the planet that we are familiar with now. Figure 2.20 illustrates some of the ways that natural processes and human uses are driven by solar power.

Poleward heat transfer moves heat from the low latitudes toward the poles. The heat transfer is in the form of warm ocean water and warm, moist air that flow poleward and is replaced by cooler water and cooler, drier air moving equatorward.



2.19 Annual surface net radiation from pole to pole

2.20 Solar power

▲ **Solar-powered call box** This emergency telephone is powered by the solar cell atop its pole.

▼ **Wave erosion** Ocean waves, powered by the Sun through the Earth's wind system, attack and erode the coastline, carving distinctive coastal landforms.

▶ **Tropical cyclone** Solar power also indirectly powers severe storms like Typhoon Odessa, shown here in a space photo.

◀ **Water power** The hydrologic cycle, powered by solar evaporation of water over oceans, generates runoff from rainfall that erodes and deposits sediment.

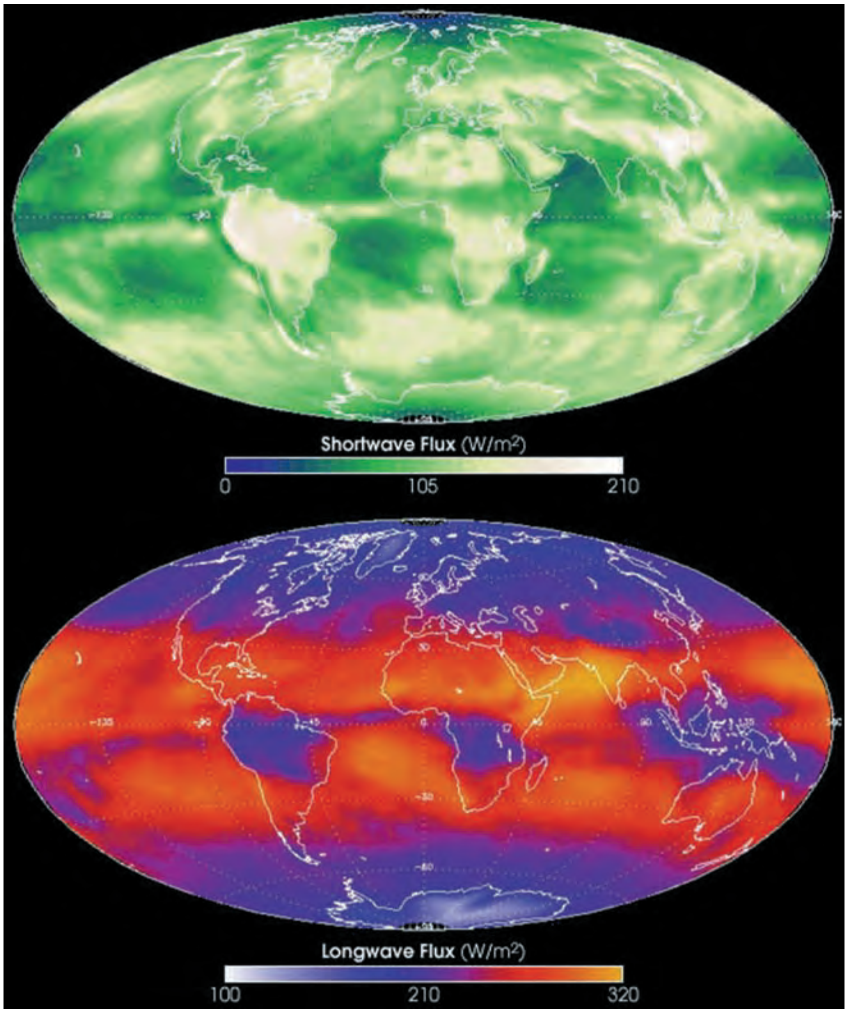
FOCUS ON REMOTE SENSING

CERES—Clouds and the Earth's Radiant Energy System

The Earth's global radiation balance is the primary determinant of long-term surface temperature, which is of great importance to life on Earth. Because this balance can be affected by human activities, such as converting forests to pasturelands or releasing greenhouse gases into the atmosphere, it is important to monitor the Earth's radiation budget over time as accurately as possible.

For nearly 20 years, NASA has studied the Earth's radiation budget from space. An ongoing NASA experiment entitled *CERES—Clouds and the Earth's Radiant Energy System*—is placing a new generation of instruments in space that scan the Earth and measure the amount of shortwave and longwave radiation leaving the Earth at the top of the atmosphere.

Figure 2.21 shows global reflected solar energy and emitted longwave energy averaged over the month of March 2000 as obtained by CERES. The top image shows average shortwave flux ("flux" means "flow"), ranging from 0 to 210 W/m^2. The largest flows occur over regions of thick clouds near the Equator, where the bright, white clouds reflect much of the solar radiation back to space. In the midlatitudes, persistent cloudiness during this month also shows up as light tones. Tropical deserts, the Sahara for example, are also bright. Snow and ice surfaces in polar regions are quite reflective, but in March the amount of radiation received in polar regions is low. As a result, they don't appear as bright in this image. Oceans, especially where skies are clear, absorb solar radiation and thus show low shortwave fluxes.



2.21 Global shortwave and longwave energy fluxes from CERES

These images show average shortwave and longwave energy flows from Earth for March 2000, as measured by the CERES instrument on NASA's Terra satellite platform.

Longwave flux is shown in the bottom image on a scale from 100 to 320 W/m^2. Cloudy equatorial regions have low values, showing the blanketing effect of thick clouds that trap longwave radiation beneath them. Warm tropical oceans in regions of clear sky emit the most longwave flux. Poleward, surface and atmospheric temperatures drop, so longwave energy emission also drops significantly.

As you can see from these images, clouds are very important determiners of the global radiation balance. A primary goal of the CERES experiment is to learn more about the Earth's cloud cover, which changes from minute to minute and hour to hour. This knowledge can be used to improve global climate models that predict the impact of human and natural change on the Earth's climate.

The most important contribution of CERES, however, is continuous and careful monitoring of the Earth's radiant energy flows. In this way, small, long-term changes, induced by human or natural change processes, can be detected in spite of large variations in energy flows from place to place and time to time caused by clouds.

GEODISCOVERIES **Energy Balance Model Interactivity**
Work with a simple global energy balance model to see how solar output, albedo, and poleward atmospheric heat transport affect the Earth's surface temperature.

GEODISCOVERIES **Web Quiz**
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

The Earth's energy balance is a sensitive one involving many factors that determine how energy is transmitted and absorbed. Have human activities already altered the components of the planetary radiation balance? Scientists have shown convincingly that industrial releases of certain gases, such as carbon dioxide, have enhanced the greenhouse effect, causing global temperatures to warm. Human habitation, through cultivation and urbanization of land, has raised surface albedo and affected the transfer of latent and sensible heat to the atmosphere, modifying the global energy balance. But to understand these effects and others fully requires further study of the processes of heating and cooling of the Earth's atmosphere, lands, and oceans. Our next chapter concerns air temperature and how and why it varies daily and annually depending on the surface energy balance.

GEODISCOVERIES **Web Links**
View NASA's images of Earth acquired by astronauts and orbiting satellites. Explore energy balance climate models. Find out more about the CERES instrument and mission. Get the details on stratospheric ozone depletion.

IN REVIEW THE EARTH'S GLOBAL ENERGY BALANCE

- The **ozone** (O_3) layer in the upper atmosphere absorbs solar ultraviolet radiation, shielding surface life from these harmful rays. Industrial **chlorofluorocarbons** (CFCs) speed the breakdown of ozone, reducing the amount of shielding. During certain conditions, an ozone hole of reduced ozone concentration forms over the Antarctic continent.
- **Electromagnetic radiation** is a form of energy emitted by all objects. The wavelength of the radiation determines its characteristics. The hotter an object, the shorter the *wavelengths* of the radiation and the greater the amount of radiation that it emits.
- Radiation emitted by the Sun includes *ultraviolet, visible, near-infrared,* and *shortwave infrared* radiation. *Thermal infrared* radiation, which is emitted by Earth surfaces, is familiar as heat. The atmosphere absorbs and scatters radiation in certain wavelength regions. Radiation flows are measured in *watts* per square meter.
- The amount of radiation emitted by an object increases very rapidly with its temperature. The wavelengths emitted decrease with increasing temperature.
- Continuous nuclear reactions within the Sun emit vast quantities of energy, largely in the form of light. The Earth receives solar radiation at a near-constant rate known as the *solar constant.* Solar radiation is strongest in the wavelength range of visible light.
- Molecules and particles in the atmosphere both **absorb** and **scatter** incoming **shortwave radiation**. The Earth's surface and atmosphere emit **longwave radiation**.
- The Earth continuously absorbs and scatters solar shortwave radiation and emits longwave radiation. In the long run, the gain and loss of radiant energy remains in a **global radiation balance**, and the Earth's average temperature remains constant.
- **Insolation**, the rate of solar radiation flow available at a location at a given time, is greater when the Sun is higher in the sky. *Daily insolation* is also greater when the period of daylight is longer.
- Near the Equator, daily insolation is greater at the equinoxes than at the solstices. Between the tropics and poles, the Sun rises higher in the sky and stays longer in the sky at the summer solstice than at the equinox and longer at the equinox than at the winter solstice.
- *Annual insolation* is greatest at the Equator and least at the poles. However, the poles still receive 40 percent of the annual radiation received at the Equator.
- The pattern of annual insolation with latitude leads to a natural naming convention for latitude zones: *equatorial, tropical, subtropical, midlatitude, subarctic (subantarctic), arctic (antarctic),* and *polar.*
- The Earth's atmosphere is dominated by *nitrogen* and *oxygen* gases. *Carbon dioxide* and *water vapor* are only small constituents by volume, but are very important because they absorb longwave radiation and enhance the greenhouse effect.
- **Sensible heat** and **latent heat** are additional forms of energy. Sensible heat is contained within a substance. It can be transferred to another substance by *conduction* or *convection.* Latent heat is taken up or released when a change of state occurs.
- Part of the solar radiation passing through the atmosphere is absorbed or scattered by molecules, dust, and larger particles. Some of the scattered radiation returns to space as diffuse reflection. The land surfaces, ocean surfaces, and clouds also reflect some solar radiation back to space.

- The proportion of radiation that a surface absorbs is termed its **albedo**. The albedo of the Earth and atmosphere as a whole planet is about 30 percent.
- The atmosphere absorbs longwave energy emitted by the Earth's surface, causing the atmosphere to **counterradiate** some of that longwave radiation back to Earth, thereby creating the **greenhouse effect**. Because of this heat trapping, the Earth's surface temperature is considerably warmer than we might expect for an Earth without an atmosphere.
- Flows of energy to and from the Earth–atmosphere system, as well as the atmosphere and surface taken individually, must balance over the long run. Energy flows within the Earth–atmosphere system include shortwave radiation, longwave radiation, sensible heat, and latent heat. Human activities can significantly affect these flows.
- **Net radiation** describes the balance between incoming and outgoing radiation. At latitudes lower than 40 degrees, annual net radiation is positive, while it is negative at higher latitudes. This imbalance creates **poleward heat transfer** of latent and sensible heat in the motions of warm water and warm, moist air, which provides the power that drives ocean currents and broad-scale atmospheric circulation patterns.
- NASA scientists monitor and map the upward flows of shortwave and longwave radiation over the globe to detect small, long-term changes that could affect global climate.

KEY TERMS

ozone, p. 58
chlorofluorocarbons (CFCs), p. 58
energy balance, p. 59
electromagnetic radiation, p. 59
absorption, p. 61
scattering, p. 62
shortwave radiation, p. 62
longwave radiation, p. 62
global radiation balance, p. 63
insolation, p. 64
sensible heat, p. 69
latent heat, p. 70
albedo, p. 71
counterradiation, p. 71
greenhouse effect, p. 71
net radiation, p. 75
poleward heat transfer, p. 75

REVIEW QUESTIONS

1. What are *CFCs,* and how do they impact the ozone layer?
2. When and where have ozone reductions been reported? Have corresponding reductions in ultraviolet radiation been noted?
3. What is *electromagnetic radiation?* How is it characterized? Identify the major regions of the electromagnetic spectrum.
4. How does the temperature of an object influence the nature and amount of electromagnetic radiation that it emits?
5. What is the *solar constant?* What is its value? What are the units with which it is measured?
6. How does solar radiation received at the top of the atmosphere differ from solar radiation received at the Earth's surface? What are the roles of absorption and scattering?
7. Compare the terms *shortwave radiation* and *longwave radiation.* What are their sources?
8. How does the atmosphere affect the flow of longwave energy from the Earth's surface to space?
9. What is the Earth's global energy balance, and how are shortwave and longwave radiation involved?
10. How does the Sun's path in the sky influence daily insolation at a location? Compare summer solstice and equinox paths of the Sun in the sky for 40° N lat. and the Equator.
11. What influence does latitude have on the annual cycle of daily insolation? on annual insolation?
12. Identify the two largest components of dry air. Why are carbon dioxide and water vapor important atmospheric constituents?
13. Describe *latent heat transfer* and *sensible heat transfer.*
14. What is the fate of incoming solar radiation? Discuss scattering and absorption, including the role of clouds.
15. Define *albedo* and give two examples.
16. Describe the counterradiation process and how it relates to the greenhouse effect.
17. Discuss the energy balance of the Earth's surface. Identify the types and sources of energy flows that the surface receives, and do the same for energy flows that it loses.
18. Discuss the energy balance of the atmosphere. Identify the types and sources of energy flows that the atmosphere receives, and do the same for energy flows that it loses.
19. What is *net radiation?* How does it vary with latitude?

20. What is the role of poleward heat transport in balancing the net radiation budget by latitude?

21. Using CERES as an example, explain the effect of clouds on shortwave and longwave radiation leaving the Earth-atmosphere system.

VISUALIZING EXERCISES

1. Place yourself in Figure 2.8. Imagine that you are standing in the center of the figure where the N–S and E–W lines intersect. Turn so that you face south. Using your arm to point at the Sun's position, trace the path of the Sun in the sky at the equinox. It will rise exactly to your left, swing upward to about a 50° angle, and then descend to the horizon exactly at your right. Repeat for the summer and winter solstices, using the figure as a guide. Then try it for the North Pole, Equator, and Tropic of Capricorn.
2. Sketch the world latitude zones on a circle representing the globe and give their approximate latitude ranges.
3. Sketch a simple diagram of the Sun above a layer of atmosphere above the Earth's surface, somewhat like Figure 2.16. Using Figure 2.18 as a guide, draw arrows indicating flows of energy among Sun, atmosphere, and surface. Label each arrow using terms from Figure 2.18.

ESSAY QUESTIONS

1. Suppose the Earth's axis of rotation was perpendicular to the orbital plane instead of tilted at 23½° away from perpendicular. How would global insolation be affected? How would insolation vary with latitude? How would the path of the Sun in the sky change with the seasons?
2. Imagine that you are following a beam of either (a) shortwave solar radiation entering the Earth's atmosphere heading toward the surface, or (b) a beam of longwave radiation emitted from the surface heading toward space. How will the atmosphere influence the beam?

Chapter 3
Air Temperature

The tallest peak in this spectacular image is Mount Everest. At an altitude of 8848 m (29,028 ft), its summit is the highest point on the planet.

Everest also has one of the Earth's most extreme climates. In January, temperatures average about –36° C (–33° F), but can drop as low as –60° C (–76° F). In July, the summit warms up to an average temperature of about –19° C (–2° F). As we will see in this chapter, high-mountain air temperatures are low largely because the amount of atmosphere above a mountain peak is much less than at sea level. This reduces the greenhouse effect. In winter, net radiation is strongly negative during the long nights, and during the day, the snow cover reflects most of the solar radiation back out to space. In summer, days lengthen and the Sun rises to higher angles in the sky, providing more solar heating.

Although Mount Everest is one of the coldest places on Earth, there is good evidence that climatic change is having its effects on the mountain. Recent studies of ice cores from glaciers on the mountain's flanks indicate that the short summer melt period is becoming warmer and longer. This trend started about a century ago.

Mount Everest, Himalayas, Nepal

Air Temperature

One of the first things we notice when stepping outdoors is the temperature of the air. But why does air temperature vary from day to day and from season to season? Why are cities warmer than suburbs? Why are mountains cooler than surrounding plains? Why is it always warm at the Equator? Why does Siberia get so cold in winter? Have human activities caused global warming? If so, what are the effects? This chapter will answer these questions and more.

EYE ON GLOBAL CHANGE

Carbon Dioxide—On the Increase

One of the most important factors affecting air temperatures over the long run is the greenhouse effect, in which atmospheric gases absorb outgoing longwave radiation and reradiate a portion back to the surface. This makes surface temperatures warmer. Apart from water vapor, carbon dioxide gas plays the largest role in the greenhouse effect and CO_2 concentration is increasing.

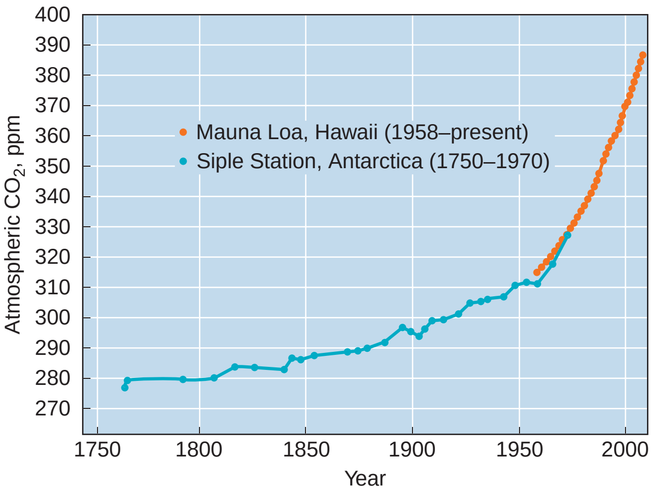
In the centuries before global industrialization, carbon dioxide concentration in the atmosphere was at a level below 300 parts per million (ppm) by volume (Figure 3.1). Since then, the amount has increased substantially to about 385 ppm. Why? When fossil fuels are burned, they yield water vapor and carbon dioxide. Water vapor does not present a problem because a large amount of water vapor is normally present in the atmosphere. But because the normal amount of CO_2 was so small, fossil fuel burning has raised the level substantially. According to studies of bubbles of atmospheric gases trapped in glacial ice, the present level of about 385 ppm is the highest attained in the last 420,000 years and nearly double the amount of CO_2 present during glaciations of the most recent Ice Age.

Even with future concerted global action to reduce CO_2 emissions, scientists estimate that levels will stabilize at a value not lower than about 550 ppm by the late twenty-first century. This will nearly double preindustrial levels and is very likely to cause a significant increase in global temperatures.

Predicting the future buildup of CO_2 is difficult because not all the carbon dioxide emitted into the air by fossil fuel burning remains there. Plants take up CO_2 in photosynthesis to build their tissues, and under present conditions, global plant matter is accumulating. Phytoplankton in ocean waters also take up CO_2, converting it into carbonate that sinks to the ocean floor. Together, these processes remove about half the CO_2 released to the atmosphere by fossil fuel burning.

Another source of uncertainty is forecasting fossil fuel consumption. Future energy needs depend on global economic growth, which is difficult to predict, as well as the future efficiency of energy use. The amount of CO_2 released also depends on the effectiveness of global action to reduce the rate of emissions through conservation and use of alternative energy sources.

Although there is a great deal of uncertainty about future atmospheric concentrations of carbon dioxide, one thing is certain. Fuel consumption will continue to release carbon dioxide, and its effect on climate will continue to increase.



3.1 Increases in atmospheric carbon dioxide

Atmospheric concentrations of CO_2 have increased from 280 to 385 ppm since 1750.

Surface and Air Temperature

This chapter focuses on **air temperature**—that is, the temperature of the air as observed at 1.2 m (4 ft) above the ground surface. Air temperature conditions many aspects of human life, from the clothing we wear to the fuel costs we pay. Air temperature and air temperature cycles also act to select the plants and animals that make up the biological landscape of a region. And air temperature, along with precipitation, is a key determiner of climate, which we will explore in more depth in Chapter 7.

Five key factors influence a station's air temperature and its variation: latitude, surface type, coastal or interior location, elevation, and atmospheric and oceanic circulations.

Five important factors influence air temperature (Figure 3.2):

1. **Latitude.** Daily and annual cycles of insolation vary systematically with latitude, causing air temperatures and air temperature cycles to vary as well. Yearly insolation decreases toward the poles, so less energy is available to heat the air. But because the seasonal cycle of insolation becomes stronger with latitude, high latitudes experience a much greater range in air temperatures through the year.
2. **Surface type.** Urban air temperatures are generally higher than rural temperatures. City surface materials—asphalt, roofing shingles, stone, brick—hold little water, compared to the moist soil surfaces of rural areas and forests, so there is little cooling through evaporation. Urban materials are also darker and absorb a greater portion of the Sun's energy than vegetation-covered surfaces. The same is true for areas of barren or rocky soil surfaces, such as those of deserts.
3. **Coastal or interior location.** Locations near the ocean experience a narrower range of air temperatures than locations in continental interiors. Because water heats and cools more slowly than land, air temperatures over water are less extreme than temperatures over land. When air flows from water to land, a coastal location will feel the influence of the adjacent water.
4. **Elevation.** Temperature decreases with elevation. At high elevation, there is less atmosphere above the surface, and greenhouse gases provide a less effective insulating blanket. More surface heat is lost to space. On high peaks, snow accumulates and remains

3.2 Factors influencing air temperature

Five main factors affect temperature and its variability at a given location. Chugach Mountains, Alaska (National Geographic Image Collection).

longer. The reduced greenhouse effect also results in greater daily temperature variation.

5. **Atmospheric and oceanic circulations.** Local temperatures can rise or fall rapidly when air from one region is brought into another. Temperatures of coastal regions can be influenced by warm or cold coastal currents. (We will investigate this factor more fully in Chapter 5.)

SURFACE TEMPERATURE

Temperature is a familiar concept. It is a measure of the level of kinetic energy of the atoms in a substance, whether it is a gas, liquid, or solid. When a substance receives a flow of radiant energy, such as sunlight, its temperature rises. Similarly, if a substance loses energy, its temperature falls. This energy flow moves in and out of a solid or liquid substance at its **surface**—for example, the very thin surface layer of soil that actually absorbs solar shortwave radiation and radiates longwave radiation out to space.

The temperature of a surface is determined by the balance among the various energy flows that move across it. **Net radiation**—the balance between incoming shortwave radiation and outgoing longwave radiation—produces a radiant energy flow that can heat or cool a surface. During the day, incoming solar radiation normally exceeds outgoing longwave radiation, so the net radiation balance is positive and the surface warms (Figure 3.3). Energy flows through the surface into the cooler soil below. At night, net radiation is negative, and the soil loses energy as the surface temperature falls and the surface radiates longwave energy to space.

Energy may also move to or from a surface in other ways. **Conduction** describes the flow of sensible heat from a warmer substance to a colder one through direct contact. When heat flows into the soil from its warm surface during the day, it flows by conduction. At night, heat is conducted back to the colder soil surface.

Latent heat transfer is also important. When water evaporates at a surface, it removes the heat stored in the change of state from liquid to vapor, thus cooling the surface. When water condenses at a surface, latent heat is released, warming the surface.

Another form of energy transfer is **convection**, in which heat is distributed in a fluid by mixing. If the surface is in contact with a fluid, such as a soil surface with air above, upward- and downward-flowing currents can act to warm or cool the surface.

3.3 Solar energy flow

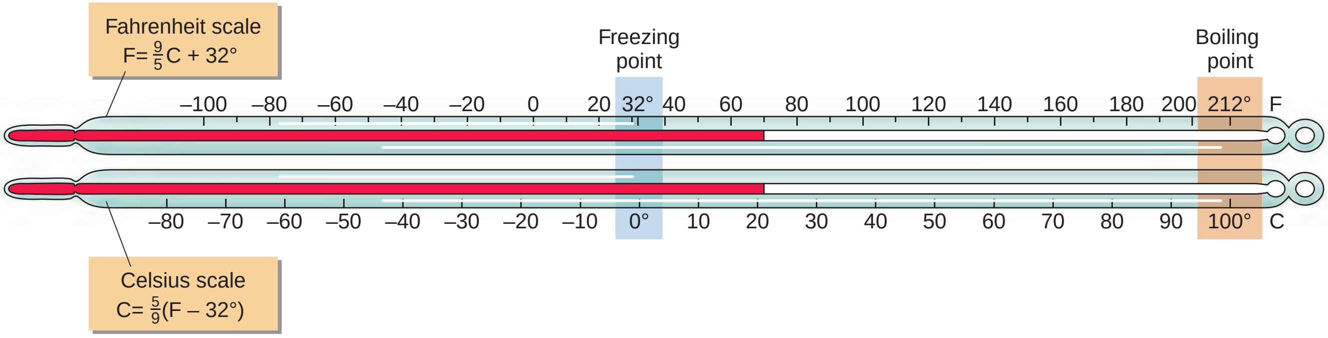
Solar light energy strikes the Earth's surface and is largely absorbed, warming the surface.

AIR TEMPERATURE

In contrast to surface temperature is *air temperature*, which is measured at a standard height of 1.2 m (4.0 ft) above the ground surface. Air temperature can be quite different from surface temperature. When you walk across a parking lot on a clear summer day, you will notice that the pavement is a lot hotter than the air against the upper part of your body. In general, air temperatures above a surface reflect the same trends as ground surface temperatures, but ground temperatures are likely to be more extreme.

Surface air temperature is measured under standard conditions at 1.2 m (4 ft) above the ground. Maximum and minimum temperatures are typically recorded. The mean daily temperature is taken as the average of the minimum and maximum temperatures.

In the United States, temperature is still widely measured and reported using the Fahrenheit scale. In this book, we use the Celsius temperature scale, which is the international standard. On the Celsius scale, the freezing point of water is 0°C and the boiling point is



3.4 Celsius and Fahrenheit temperature scales compared

At sea level, the freezing point of water is at Celsius temperature (C) 0°, while it is 32° on the Fahrenheit (F) scale. Boiling occurs at 100°C, or 212°F.

100°C. Conversion formulas between these two scales are given in Figure 3.4.

Air temperature measurements are made routinely at weather stations (Figure 3.5). Although some weather stations report temperatures hourly, most only report the highest and lowest temperatures recorded during a 24-hour period. These are the most important values in observing long-term trends in temperature.

Temperature measurements are reported to governmental agencies charged with weather forecasting, such as the U.S. Weather Service or the Meteorological Service of Canada. These agencies typically make available daily, monthly, and yearly temperature statistics for each station using the daily maximum, minimum, and mean temperature. The *mean daily temperature* is defined as the average of the maximum and minimum daily values. The *mean monthly temperature* is the average of mean daily temperatures in a month. These statistics, along with others such as daily precipitation, are used to describe the climate of the station and its surrounding area.

3.5 Weather station

This weather station at Furnace Creek, in Death Valley National Park, has an evaporation pan in the foreground that measures the rate of evaporation in this desert climate. Just to the left of the pan is a 3-cup anemometer that measures wind speed very near the evaporating water surface. The tall cylinder behind the pan and to the right is a rain gauge. The white louvered box, called a Stevenson shelter, will contain thermometers measuring temperatures and possibly relative humidity.

GEODISCOVERIES **Weather Station Interactivity**
Check out a modern automatic weather station. See how it measures air and ground temperatures.

TEMPERATURES CLOSE TO THE GROUND

Soil, surface, and air temperatures within a few meters of the ground change through the day (Figure 3.6). The daily temperature variation is greatest just above the surface. The air temperature at standard height is far less variable. In the soil, the daily cycle becomes gradually less pronounced with depth, until we reach a point where daily temperature variations on the surface cause no change at all.

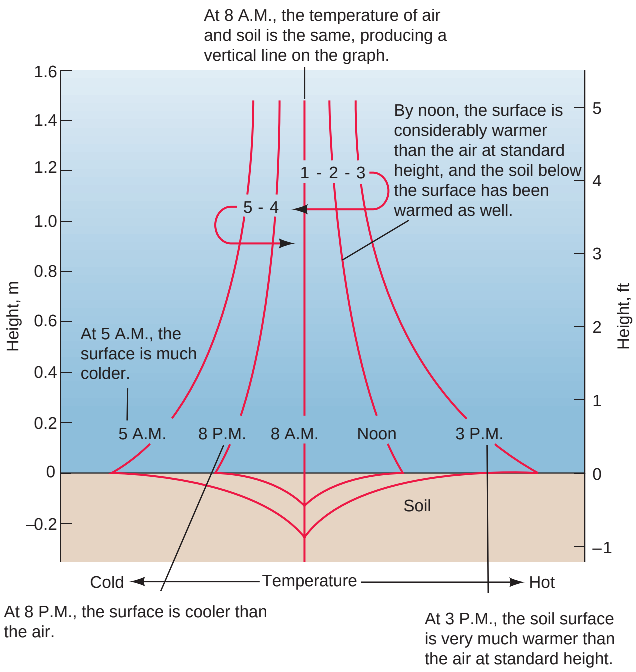
ENVIRONMENTAL CONTRASTS: URBAN AND RURAL TEMPERATURES

On a hot day, rural environments will feel cooler than urban environments (Figure 3.7). In rural areas, water is taken up by plant roots and moves to the leaves in a process called **transpiration**. This water evaporates, cooling leaf surfaces, which in turn cool nearby air. Soil surfaces are moist because water seeps into the soil during rainstorms. It is drawn upward and evaporates when sunlight warms the surface, again producing cooling. We refer to the combined effects of transpiration and evaporation as **evapotranspiration**.

There are other reasons why urban surfaces are hotter than rural ones. Many city surfaces are dark and absorb rather than reflect solar energy. In fact, asphalt paving absorbs more than twice as much solar energy as vegetation. Rain runs off the roofs, sidewalks, and streets into storm sewer systems. Because the city surfaces are dry, there is little evaporation to help lower temperatures.

Another important factor is waste heat. In summer, city air temperatures are raised by air conditioning, which pumps heat out of buildings and releases it to the air. In winter, heat from buildings and structures is conducted directly to the urban environment.

Urban surfaces lack moisture and so are warmer than rural surfaces during the day. At night, urban materials conduct stored heat to the surface, also keeping temperatures warmer.



3.6 Daily temperature profiles close to the ground

The red curves in the figure show a set of temperature profiles for a bare, dry soil surface from about 30 cm (12 in.) below the surface to 1.5 m (4.9 ft) above it at five times of day curves (1–5).

THE URBAN HEAT ISLAND

As a result of these effects, air temperatures in the central region of a city are typically several degrees warmer than those of the surrounding suburbs and countryside, as shown in Figure 3.8. The sketch of a temperature profile across an urban area in the late afternoon shows this effect. We call the central area an **urban heat island**, because it has a significantly elevated temperature. Such a large quantity of heat is stored in the ground during the daytime hours that the heat island remains warmer than its surroundings during the night, too. The thermal infrared image of the Atlanta central business district at night demonstrates the heat island effect.

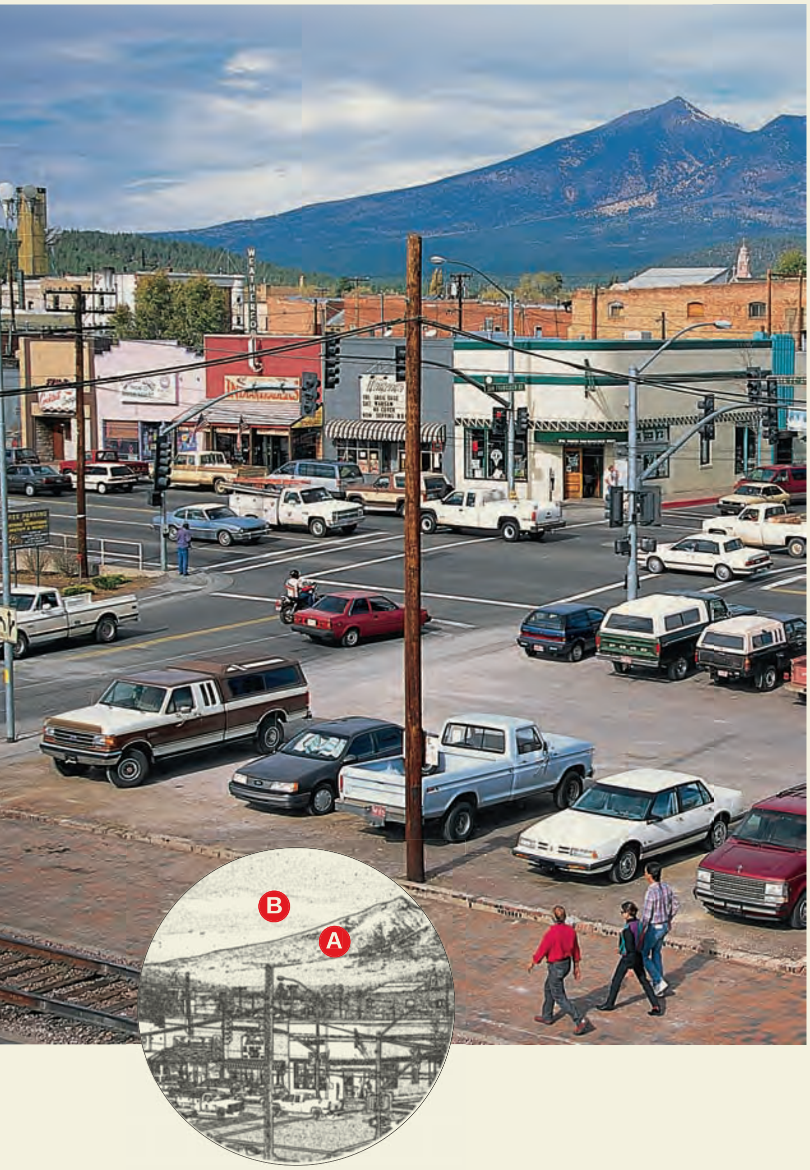
The urban heat island effect has important economic consequences. Higher temperatures demand more air conditioning and more electric power in the summer. The fossil fuel burned to generate this power contributes CO_2 and air pollutants to the air. The increased temperatures can lead to smog formation, which is unhealthy and damaging to materials. To reduce these effects, many cities are planting more vegetation and using more reflective surfaces, such as concrete or bright roofing materials, to reflect solar energy back to space.

The heat island effect does not necessarily apply to cities in desert climates. In the desert, the evapotranspiration of the irrigated vegetation of the city may actually keep the city cooler than the surrounding barren region.

HIGH-MOUNTAIN ENVIRONMENTS

We have seen that the ground surface affects the temperature of the air directly above it. But what happens as you travel to higher elevations (Figure 3.9)? For example, as you climb higher on a mountain, you may become short of breath and you might notice that you sunburn more easily. You also feel the temperature drop, as you ascend. If you camp out, you'll see that the nighttime temperature gets lower than you might

3.7 Rural and urban surfaces



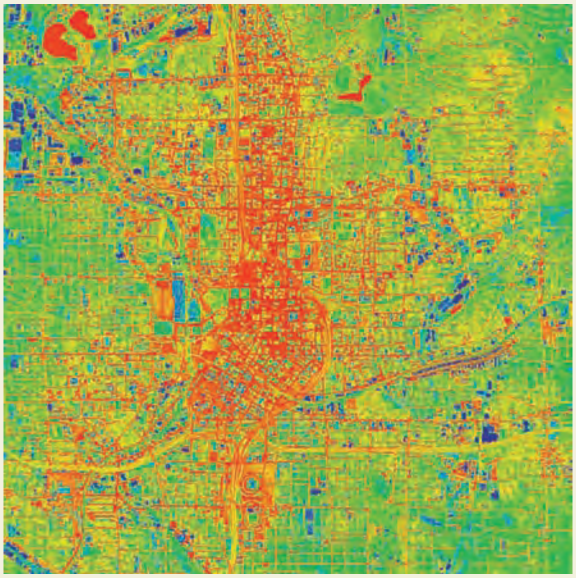
◀ **Urban surfaces** Urban surfaces are composed of asphalt, concrete, building stone, and similar materials. Sewers drain away rainwater, keeping urban surfaces dry. Because evapotranspiration is limited, surface and air temperatures are hotter.

EYE ON THE LANDSCAPE **What else would the geographer see?** Beyond the urban surfaces in the foreground is a distant view of semiarid landscape in the western United States (A). The sparse vegetation cover reflects the semiarid climate (see Chapters 7 and 9 for semiarid climate and vegetation). Note also the smooth profile of the land surface from the mountain peak to the base of the slope (B). This shape indicates long-continued erosion by running water (fluvial erosion), which we describe in Chapter 16.

▶ **Rural surfaces** Rural surfaces are composed of moist soil, covered largely by vegetation. Evapotranspiration keeps these surfaces cooler.

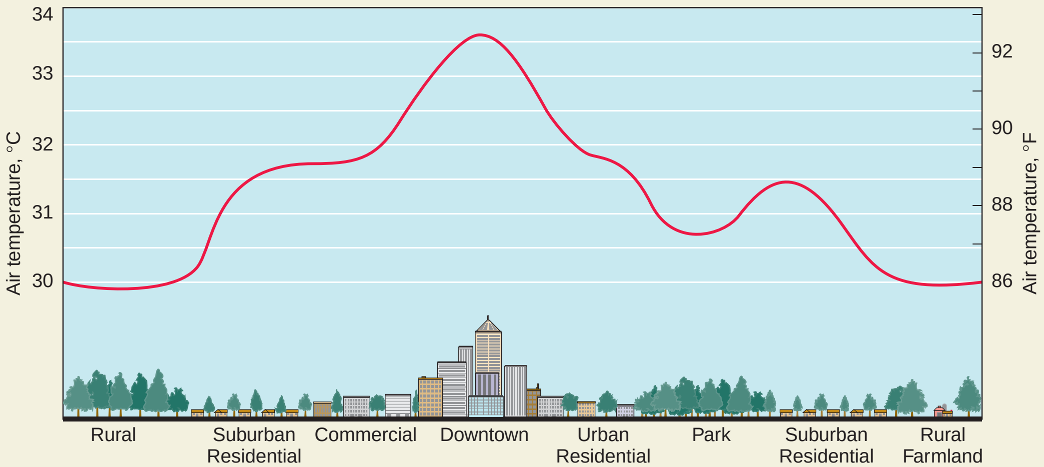
EYE ON THE LANDSCAPE **What else would the geographer see?** The human influence on this agricultural landscape is strong. A dam has created a small fire pond (A), providing water for both livestock and fire-fighting. The fields are mowed for hay, providing a groomed look. The young trees dotting the landscape appear to be planted and pruned to pleasing shapes. The split-rail fencing is attractively rustic but too expensive for most farm applications. In short, this is the spread of a gentleman farmer.

3.8 Urban heat island effect



◀ **Atlanta, Georgia** This image, taken at night in May, over downtown Atlanta, Georgia, shows the urban heat island. The main city area, in tones of red and yellow, is clearly warmer than the suburban area, in blue and green. The street pattern of asphalt pavement is shown very clearly as a red grid, with many of the downtown squares filled with red.

▶ **Temperature diagram** This diagram shows how air temperatures might vary across the urban and rural areas during the late afternoon. Downtown and commercial areas are warmest, while rural farmland is coolest.



expect, even given that temperatures are generally cooler the farther up you go.

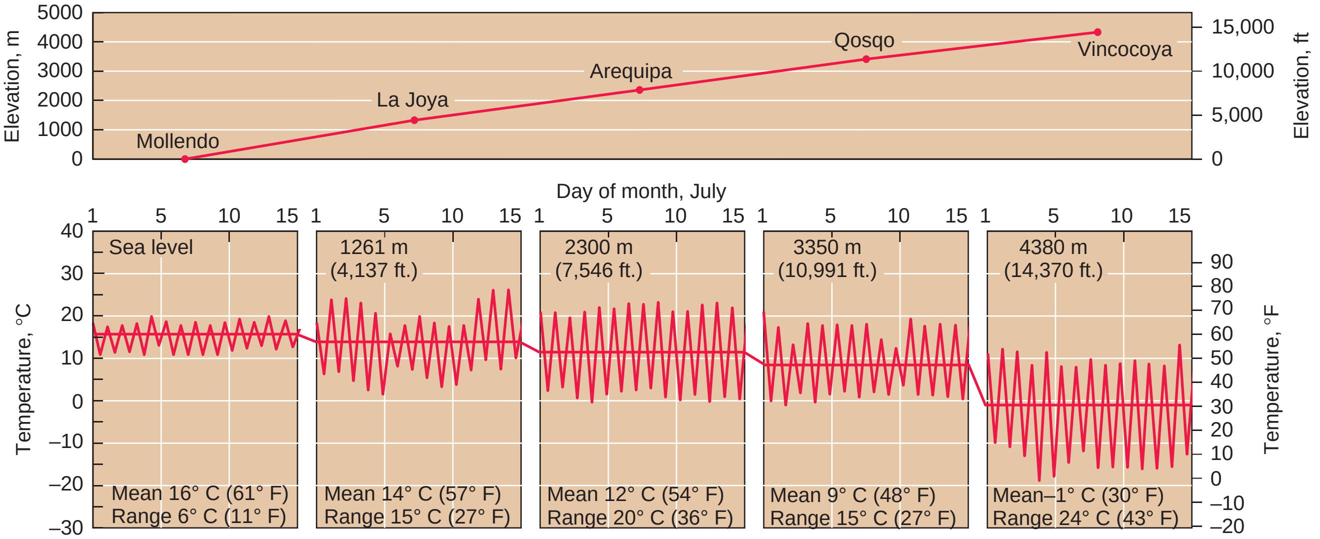
What causes these effects? At high elevations there is significantly less air above you, so air pressure is low. It becomes harder to catch your breath simply because of the reduced oxygen pressure in your lungs. And with fewer molecules to scatter and absorb the Sun's light, the Sun's rays will feel stronger. There is less carbon dioxide and water vapor, and so the greenhouse effect is reduced. With less warming, temperatures will tend to drop even lower at night. Later in this chapter, we will see how this pattern of decreasing air temperature extends high up into the atmosphere.

At high elevations, air temperatures are generally cooler and show a greater day-to-night range. Both effects occur because the thickness and density of the air column above decrease with elevation, and therefore the greenhouse effect is weaker at high elevations.

Figure 3.10 shows temperature graphs for five stations at different heights in the Andes Mountain Range in Peru. Mean temperatures clearly decrease with elevation, from 16°C (61°F) at sea level to −1°C (30°F) at 4380 m (14,370 ft). The range between maximum and minimum temperatures also increases with elevation, except for Qosqo. Temperatures in this large city do not dip as low as you might expect because of its urban heat island.

3.9 High elevation

The peaks of this mountain range climb to about 3500 m (about 12,000 ft). At higher elevation, there is less air to absorb solar radiation. The sky is deep blue and temperatures are cooler. Wind River Range, Wyoming (National Geographic Image Collection).



3.10 The effect of elevation on air temperature cycles

The graph shows the mean air temperature for mountain stations in Peru, lat. 15° S, during the same 15 days in July. As elevation increases, the mean daily temperature decreases and the temperature range increases.

TEMPERATURE INVERSION

So far, air temperatures seem to decrease with height. But is this always true? Think about what happens on a clear, calm night. The ground surface radiates longwave energy to the sky, and net radiation becomes negative. The surface cools. This means that air near the surface also cools, as we saw in Figure 3.6. If the surface stays cold, a layer of cooler air above the ground will build up under a layer of warmer air, as shown in Figure 3.11. This is a **temperature inversion**.

In a temperature inversion, the temperature of the air near the ground can fall below the freezing point. This temperature condition is called a *killing frost*—even though actual frost may not form—because of its effect on sensitive plants during the growing season.

Growers of fruit trees or other crops use several methods to break up an inversion. Large fans can be used to mix the cool air at the surface with the warmer air above, and oil-burning heaters are sometimes used to warm the surface air layer.

> **A temperature inversion is a reversal of a normal temperature pattern so that air temperature increases with height. Temperature inversions commonly appear on clear, calm nights.**

TEMPERATURE INDEXES

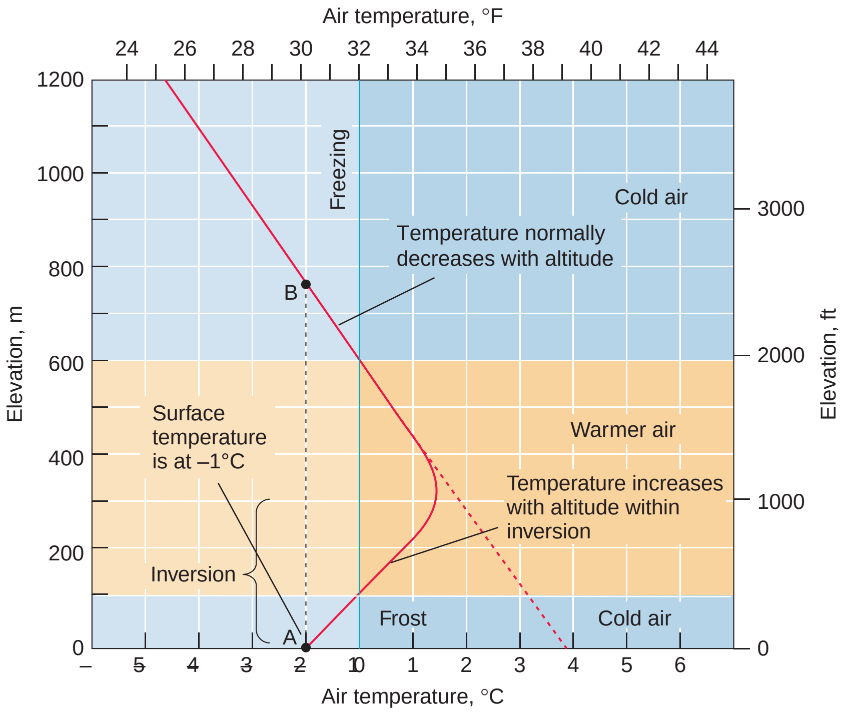
Temperature can also be used with other weather and climate data to produce *temperature indexes*—indicators of the temperature's impact upon environmental and human conditions. Two of the more familiar indexes are the wind chill index and the heat index.

The *wind chill index* is used to determine how cold temperatures feel to us, based on not only the actual temperature but also the wind speed. Air is actually a very good insulator, so when the air is still, our skin temperature can be very different from the temperature of the surrounding environment. However, as air moves across our skin, it removes sensible and latent heat and transports it away from our bodies. During the summer, this process keeps us cool as sweat is evaporated away, lowering our skin temperature. During the winter, it removes heat necessary to keep our bodies warm, thereby cooling our skin and making conditions feel much colder than the actual measured temperature.

The wind chill index, which is used in the United States and measured in °F, can be very different from the actual temperature (Figure 3.12). For example, an actual temperature of 30°F (–1°C) and a wind speed of 30 mi/hr (13.45 m/s) produce a wind chill of 15°F (–26°C).

The *heat index* gives an indication of how hot we feel based on the actual temperature and the *relative humidity*. Relative humidity is the humidity given in most weather reports and indicates how much water vapor is in the atmosphere as a percentage of the maximum amount possible. Low relative humidity indicates relatively dry atmospheric conditions, while high relative humidity indicates relatively humid atmospheric conditions.

Why does relative humidity influence how hot the temperature feels? One of the ways our bodies remove



3.11 Temperature inversion

While air temperature normally decreases with altitude (dashed line), in an inversion temperature increases with altitude. Air temperature is the same at the surface (A) as at 760 m (2500 ft) aloft (B).

Temperature, °F

Wind speed, mph	40	35	30	25	20	15	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45
5	36	31	25	19	13	7	1	–5	–11	–16	–22	–28	–34	–40	–46	–52	–57	–63
10	34	27	21	15	9	3	–4	–10	–16	–22	–28	–35	–41	–47	–53	–59	–66	–72
15	32	25	19	13	6	0	–7	–13	–19	–26	–32	–39	–45	–51	–58	–64	–71	–77
20	30	24	17	11	4	–2	–9	–15	–22	–29	–35	–42	–48	–55	–61	–68	–74	–81
25	29	23	16	9	3	–4	–11	–17	–24	–31	–37	–44	–51	–58	–64	–71	–78	–84
30	28	22	15	8	1	–5	–12	–19	–26	–33	–39	–46	–53	–60	–67	–73	–80	–87
35	28	21	14	7	0	–7	–14	–21	–27	–34	–41	–48	–55	–62	–69	–76	–82	–89
40	27	20	13	6	–1	–8	–15	–22	–29	–36	–43	–50	–57	–64	–71	–78	–84	–91
45	26	19	12	5	–2	–9	–16	–23	–30	–37	–44	–51	–58	–65	–72	–79	–86	–93
50	26	19	12	4	–3	–10	–17	–24	–31	–38	–45	–52	–60	–67	–74	–81	–88	–95
55	25	18	11	4	–3	–11	–18	–25	–32	–39	–46	–54	–61	–68	–75	–82	–89	–97
60	25	17	10	3	–4	–11	–19	–26	–33	–40	–48	–55	–62	–69	–76	–84	–91	–98

Frostbite times: 30 minutes / 10 minutes / 5 minutes

To convert the wind chill index from °F to °C, use the following equation: °C = (°F – 32) × 5/9

3.12 Wind chill conversion

The wind chill index provides an indicator of how cold temperatures feel based on the actual temperature and the wind speed.

excess heat is through the evaporation of sweat from our skin. This evaporation removes latent heat, which cools our bodies. However, when the relative humidity is high, less evaporation occurs because the surrounding atmosphere is already relatively moist, and the cooling effect is reduced.

The heat index is given in °F, and, like the wind chill, it can be very different from the actual temperature (Figure 3.13). For example, if the actual temperature is 90°F (32°C) and the relative humidity is 90 percent, the heat index indicates that the temperature will feel like 122°F (50°C)—a difference of 32°F (18°C)!

Temperature Structure of the Atmosphere

In general, the air is cooler at higher altitudes. Remember from Chapter 2 that most incoming solar radiation passes through the atmosphere and is absorbed by the Earth's surface. The atmosphere is then warmed at the surface by latent and sensible heat flows. So it makes sense that, in general, air farther from the Earth's surface will be cooler.

We call the decrease in air temperature with increasing altitude the **lapse rate**. We measure the temperature

Relative humidity, percent — Heat index (Apparent temperature)

Air temperature, °F	40	45	50	55	60	65	70	75	80	85	90	95	100
110	136												
108	130	137											
106	124	130	137										
104	119	124	131	137									
102	114	119	124	130	137								
100	109	114	118	124	129	136							
98	105	109	113	117	123	128	134						
96	101	104	108	112	116	121	126	132					
94	97	100	103	106	110	114	119	124	129	135			
92	94	96	99	101	105	108	112	116	121	126	131		
90	91	93	95	97	100	103	106	109	113	117	122	127	132
88	88	89	91	93	95	98	100	103	106	110	113	117	121
86	85	87	88	89	91	93	95	97	100	102	105	108	112
84	83	84	85	86	88	89	90	92	94	96	98	100	103
82	81	82	83	84	84	85	86	88	89	90	91	93	95
80	80	80	81	81	82	82	83	84	84	85	86	86	87

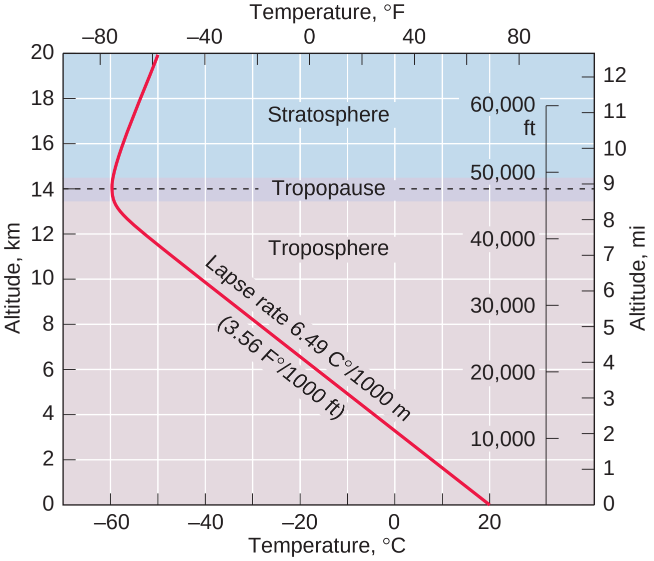
With prolonged exposure and/or physical activity

With prolonged exposure and/or physical activity	
Extreme danger	Heat stroke or sunstroke highly likely
Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely
Extreme caution	Sunstroke, muscle cramps, and/or heat exhaustion possible
Caution	Fatigue possible

To convert the heat index from °F to °C, use the following equation: °C = (°F – 32) × 5/9

3.13 Heat index conversion

The heat index provides an indicator of how hot temperatures feel based on the actual temperature and relative humidity.



3.14 A typical atmospheric temperature curve for a summer day in the midlatitudes

Temperature decreases with altitude in the troposphere. The rate of temperature decrease with elevation, or lapse rate, is shown at the average value of 6.49°C/1000 m (3.56°F/1000 ft), which is known as the environmental temperature lapse rate. At the tropopause, the decreasing trend stops. In the stratosphere above, temperature is constant or increases slightly with altitude.

drop in degrees C per 1000 m (or degrees F per 1000 ft). Figure 3.14 shows how temperature varies with altitude on a typical summer day in the midlatitudes. Temperature drops at an average rate of 6.49°C/1000 m (3.56°F/1000 ft). This average value is known as the **environmental temperature lapse rate**. Looking at the graph, we see that when the air temperature near the surface is a pleasant 21°C (70°F), the air at an altitude of 12 km (40,000 ft) will be a bone-chilling –55°C (–67°F). Keep in mind that the environmental temperature lapse rate is an average value and that on any given day the observed lapse rate might be quite different.

In the lower atmosphere, air temperatures decrease with increasing altitude. The average rate of temperature decrease with height is termed the environmental temperature lapse rate and is 6.49°C/1000 m (3.56°F/1000 ft).

Figure 3.14 shows another important feature. For the first 12 km (7 mi) or so, temperature falls with increasing elevation. But between 12 and 15 km (7 and 9 mi), the temperature stops decreasing. In fact, above that height, temperature slowly rises with elevation. Atmospheric scientists use this feature to define two different layers in the lower atmosphere—the troposphere and the stratosphere.

TROPOSPHERE

The **troposphere** is the lowest atmospheric layer. All human activity takes place here. Everyday weather phenomena, such as clouds and storms, mainly happen in the troposphere. Here temperature decreases with increasing elevation. The troposphere is thickest in the equatorial and tropical regions, where it stretches from sea level to about 16 km (10 mi). It thins toward the poles, where it is only about 6 km (4 mi) thick.

The troposphere contains significant amounts of water vapor. When the water vapor content is high, vapor can condense into water droplets, forming low clouds and fog, or the vapor can be deposited as ice crystals, forming high clouds. Rain, snow, hail, or sleet—collectively termed precipitation—are produced when these condensation or deposition processes happen rapidly. Places where water vapor content is high throughout the year have moist climates. In desert regions water vapor is low, so there is little precipitation.

When water vapor absorbs and reradiates heat emitted by the Earth's surface, it helps to create the greenhouse effect—a natural phenomenon that is responsible for warming the Earth to temperatures that allow life to exist.

The troposphere contains countless tiny particles that are so small and light that the slightest movements of the air keep them aloft. These are called **aerosols**. They are swept into the air from dry desert plains, lakebeds, and beaches, or, as we saw in the chapter opener, they are released by exploding volcanoes. Oceans are also a source of aerosols. Strong winds blowing over the ocean lift droplets of spray into the air. These droplets of spray lose most of their moisture by evaporation, leaving tiny particles of watery salt that are carried high into the air. Forest fires and brushfires also generate particles of soot as smoke. And as meteors vaporize as they hit the atmosphere, they leave behind dust particles in the upper layers of air. Closer to the ground, industrial processes that incompletely burn coal or fuel oil release aerosols into the air as well.

Aerosols are important because water vapor can condense on them to form tiny droplets. When these droplets grow large and occur in high concentration, they are visible as clouds or fog. Aerosol particles scatter sunlight, brightening the whole sky while slightly reducing the intensity of the solar beam.

The troposphere gives way to the stratosphere at the *tropopause*. Here, temperatures stop decreasing with altitude and start to increase. The altitude of the tropopause varies somewhat with season, so the troposphere is not uniformly thick at any location.

STRATOSPHERE AND UPPER LAYERS

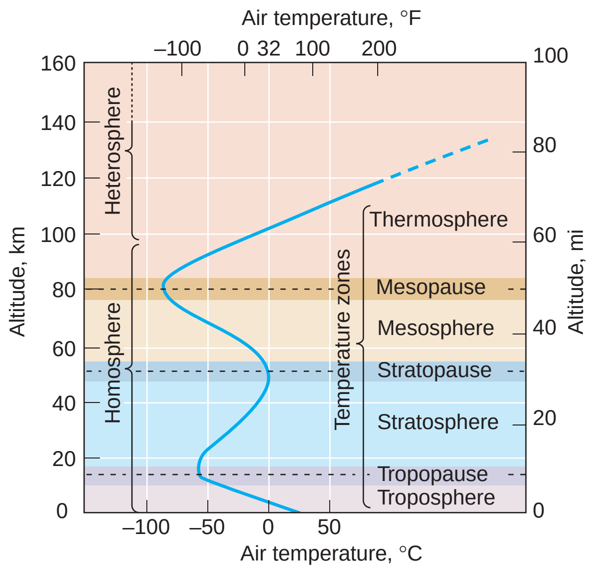
The **stratosphere** lies above the tropopause. Air in the stratosphere becomes slightly warmer as altitude increases. The stratosphere reaches up to roughly 50 km (about 30 mi) above the Earth's surface. It is the home of strong, persistent winds that blow from west to east. Air doesn't really mix between the troposphere and stratosphere, so the stratosphere normally holds very little water vapor or dust.

The troposphere and stratosphere are the two lowermost atmospheric layers. Clouds and weather phenomena occur in the troposphere. The stratosphere is the home of strong, persistent winds that flow from west to east.

The stratosphere contains the *ozone layer*, which shields Earthly life from intense, harmful ultraviolet energy. It is the ozone molecules that warm the stratosphere, causing temperature to increase with altitude, as they absorb solar energy.

Temperatures stop increasing with altitude at the stratopause. Above the stratopause we find the *mesosphere*, shown in Figure 3.15. In the mesosphere, temperature falls with elevation. This layer ends at the mesopause, the level at which temperature stops falling with altitude. The next layer is the *thermosphere*. Here, temperature increases with altitude again, but because the density of air is very thin in this layer, the air holds little heat.

The gas composition of the atmosphere is uniform for about the first 100 km of altitude, which includes the troposphere, stratosphere, mesosphere, and the lower portion of the thermosphere. We call this region the *homosphere*. Above 100 km, gas molecules tend to be sorted into layers by molecular weight and electric charge. This region is called the *heterosphere*.



3.15 Temperature structure of the upper atmosphere

Above the troposphere and stratosphere are the mesosphere and thermosphere. The homosphere, in which the air's molecules are well mixed, ranges from the surface to nearly 100 km altitude.

Daily and Annual Cycles of Air Temperature

Let's turn to how, and why, air temperatures vary around the world. Insolation from the Sun varies across the globe, depending on latitude and season. Net radiation at a given place is positive during the day, as the surface gains heat from the Sun's rays. At night, the flow of incoming shortwave radiation stops, but the Earth continues to radiate longwave radiation. As a result, net radiation becomes negative. Because the air next to the surface is warmed or cooled as well, we get a daily cycle of air temperatures (Figure 3.16).

Why does the temperature peak in the midafternoon? We might expect it to continue rising as long as the net radiation is positive. But on sunny days in the early afternoon, large convection currents develop within several hundred meters of the surface, complicating the pattern. They carry hot air near the surface upwards, and they bring cooler air downwards. So the temperature typically peaks between 2 and 4 P.M. By sunset, air temperature is falling rapidly. It continues to fall more slowly throughout the night.

The height of the temperature curves varies with the seasons. In the summer, temperatures are warm and the daily curve is high. In winter, the temperatures are colder. The September equinox is considerably warmer than the March equinox even though net radiation is the same. This is because the temperature curves lag behind net radiation, reflecting earlier conditions.

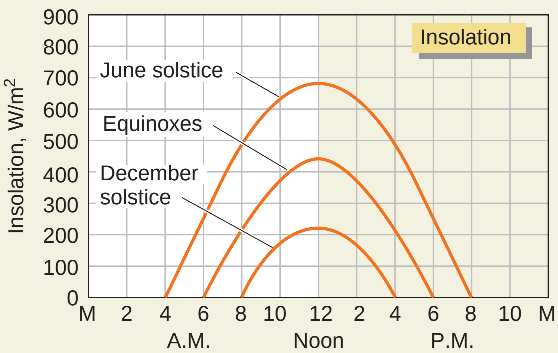
LAND AND WATER CONTRASTS

There is another factor that influences the annual temperature cycle. If you have visited San Francisco, you probably noticed that this magnificent city has a unique climate. It's often foggy and cool, and the weather is damp for most of the year. Its cool climate is due to its location on the tip of a peninsula, with the Pacific Ocean on one side and San Francisco Bay on the other. A southward-flowing ocean current sweeps cold water from Alaska down along the northern California coast, and winds from the west move cool, moist ocean air, as well as clouds and fog, across the peninsula. This air flow keeps summer temperatures low and winter temperatures above freezing.

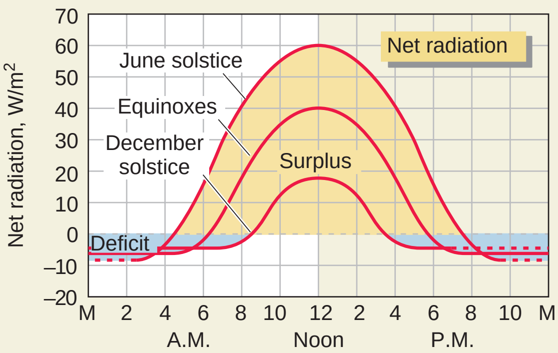
Figure 3.17 shows a typical temperature record for San Francisco for a week in the summer. Temperatures hover around 13°C (55°F) and change only a little from day to night. The story is very different at locations far from the water, like Yuma, in Arizona. Yuma is in the Sonoran Desert, and average air temperatures here are

3.16 Daily cycles of insolation, net radiation, and air temperature

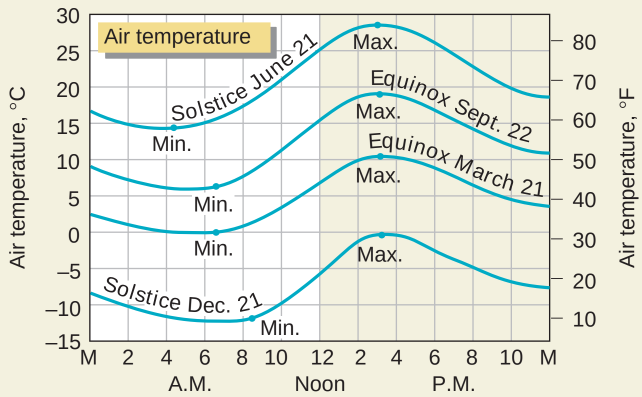
These three graphs show idealized daily cycles for a midlatitude station at a continental interior location and illustrate how insolation, net radiation, and air temperature are linked.



◀ **Insolation** At the equinox (middle curve), insolation begins at about sunrise (6 a.m.), peaks at noon, and falls to zero at sunset (6 p.m.). At the June solstice, insolation begins about two hours earlier (4 a.m.) and ends about two hours later (8 p.m.). The June peak is much greater than at equinox, and there is much more total insolation. At the December solstice, insolation begins about two hours later than at equinox (8 a.m.) and ends about two hours earlier (4 p.m.). The daily total insolation is greatly reduced in December.



▲ **Net radiation** Net radiation curves strongly follow the insolation curves in (a). At midnight, net radiation is negative. Shortly after sunrise, it becomes positive, rising sharply to a peak at noon. In the afternoon, net radiation decreases as insolation decreases. Shortly before sunset, net radiation is zero—incoming and outgoing radiation are balanced. Net radiation then becomes negative.



▲ **Air temperatures** All three curves show that the minimum daily temperature occurs about a half hour after sunrise. Since net radiation has been negative during the night, heat has flowed from the ground surface, and the ground has cooled the surface air layer to its lowest temperature. As net radiation becomes positive, the surface warms quickly and transfers heat to the air above. Air temperature rises sharply in the morning hours and continues to rise long after the noon peak of net radiation.

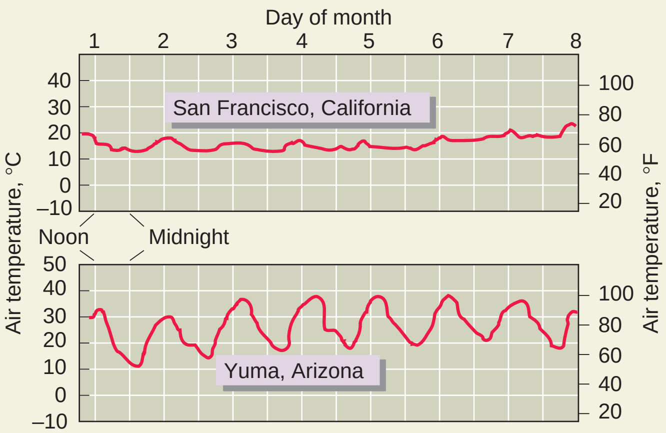
much warmer on the average—about 28°C (82°F). Clearly, no ocean cooling is felt in Yuma! The daily range is also much greater—the hot desert drops by nearly 20°C (36°F) from its daytime temperature, producing cool desert nights. The clear, dry air also helps the ground lose heat rapidly.

Air temperatures at coastal locations tend to be more constant than at interior continental locations because water bodies heat and cool more slowly than the land surface.

What is behind these differences? The important principle is this: the surface layer of any extensive, deep body of water heats more slowly and cools more slowly than the surface layer of a large body of land when both are subjected to the same intensity of insolation. Because of this principle, daily and annual air temperature cycles will be quite different at coastal locations than at interior locations. Together they make air temperatures above water less variable than those over land. Places located well inland and far from oceans will tend to have stronger temperature contrasts from winter to summer and night to day (Figure 3.18).

How does the land–water contrast affect the annual air temperature cycle? Let's look in detail at the annual cycle of another pair of stations—Winnipeg, Manitoba, located in the interior of the North American continent, and the Scilly Islands, off the southwestern tip of England, which are surrounded by the waters of the Atlantic Ocean

3.17 Maritime and continental temperatures



▲ A recording thermometer made these continuous records of the rise and fall of air temperature for a week in summer at San Francisco, California, and at Yuma, Arizona.

▲ At San Francisco, on the Pacific Ocean, the daily air temperature cycle is very weak (National Geographic Image Collection).

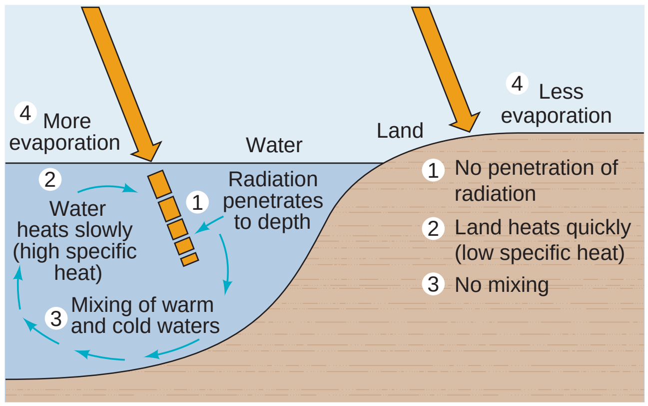
▼ At Yuma, a station in the desert, the daily cycle is strongly developed (National Geographic Image Collection).

(Figure 3.19). Because these two stations have the same latitude, 50° N, they have the same insolation cycle and receive the same potential amount of solar energy for surface warming.

The temperature graphs for the Scilly Islands and Winnipeg show that the annual range in temperature is much larger for the interior station (39°C, 70°F) than for the coastal station (8°C, 14°F). The nearby ocean waters keep the air temperature at the Scilly Islands well above freezing in the winter, while January temperatures at Winnipeg fall to near –20°C (–4°F).

Another important effect of the land–water contrast concerns the timing of maximum and minimum temperatures. Insolation reaches a maximum at the summer solstice, but it is still strong for a long period afterward, so that net radiation is positive well after the solstice. Therefore, the hottest month of the year for interior regions is July, the month following the summer solstice. The coldest month is January, the month after the winter solstice. The continued cooling after the winter solstice takes place because the net radiation is still negative even though the insolation has begun to increase.

Over the oceans and at coastal locations, maximum and minimum air temperatures are reached a month



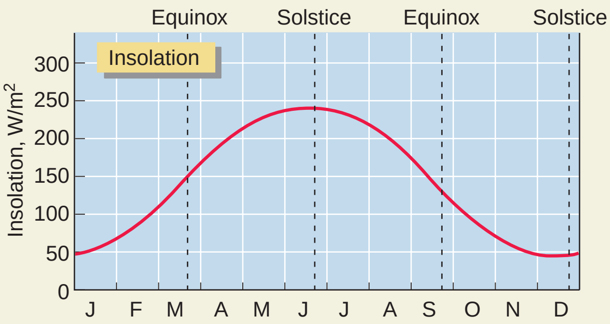
3.18 Land-water contrasts

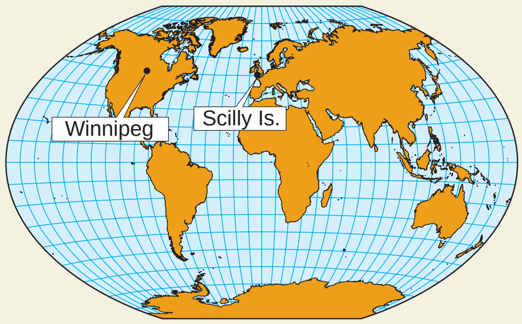
These four differences illustrate why a land surface heats more rapidly and more intensely then the surface of a deep water body. As a result, locations near the ocean have more uniform air temperatures—cooler in summer and warmer in winter.

3.19 Maritime and continental annual air temperature cycles

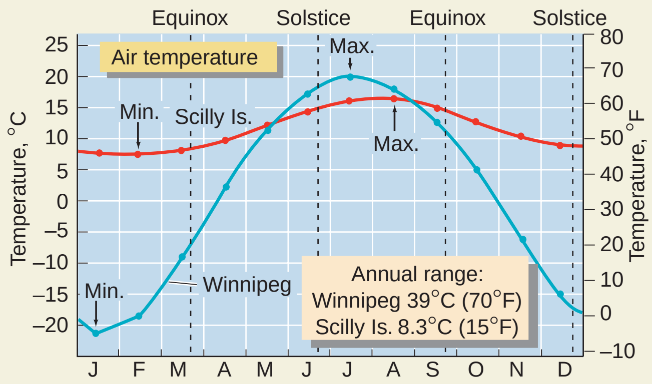
Annual cycles of insolation and mean monthly air temperature for two stations at latitude 50° N: Winnipeg, Canada and Scilly Islands, England.

▼ Insolation is identical for the two stations.





▶ Winnipeg temperatures clearly show the large annual range and earlier maximum and minimum that are characteristic of its continental location. Scilly Islands temperatures show a maritime location with a small annual range and delayed maximum and minimum.



later than on land—in August and February, respectively. Because water bodies heat or cool more slowly than land areas, the air temperature changes more slowly. This effect is clearly seen in the Scilly Islands graph, which shows that February is slightly colder than January.

ANNUAL NET RADIATION AND TEMPERATURE CYCLES

We have seen that location—maritime or continental—has an important influence on annual temperature cycles. But the largest effect is caused by the annual cycle of net radiation. Daily insolation varies over the seasons of the year, owing to the Earth's motion around the Sun and the tilt of the Earth's axis. That rhythm produces a net radiation cycle, which, in turn, causes an annual cycle in mean monthly air temperatures. Figure 3.20 examines the cycles of net radiation and temperature at four sites ranging from the Equator to the Arctic Circle.

> **The annual cycle of net radiation, which results from the variation of insolation with the seasons, drives the annual cycle of air temperatures. Where net radiation varies strongly with the seasons, so does surface air temperature.**

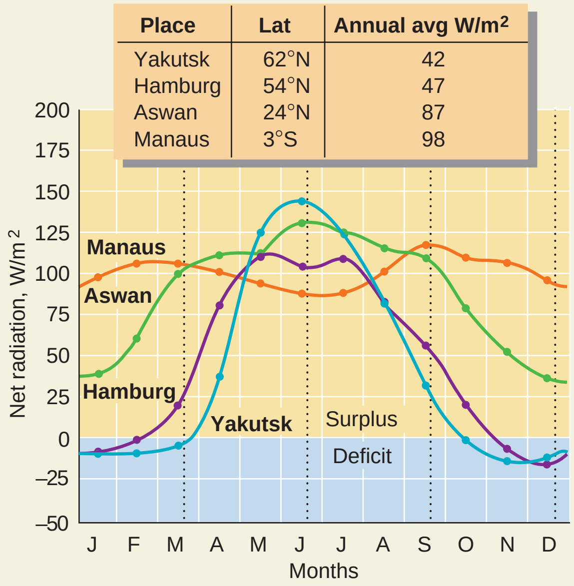
World Patterns of Air Temperature

We have learned some important principles about air temperatures in this chapter. Surface type (urban or rural), elevation, latitude, daily and annual insolation cycles, and location (maritime or continental) can all influence air temperatures. Now let's put all these together and see how they affect world air temperature patterns.

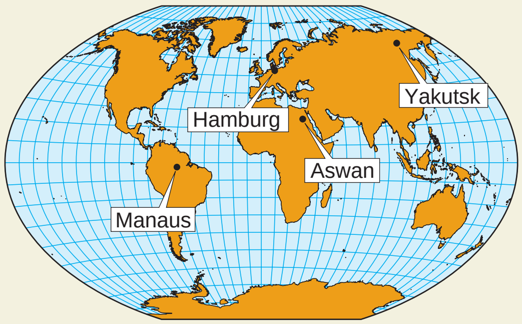
> **Isotherms are lines of equal temperature drawn on a map. Maps of isotherms show centers of high and low temperatures as well as temperature gradients.**

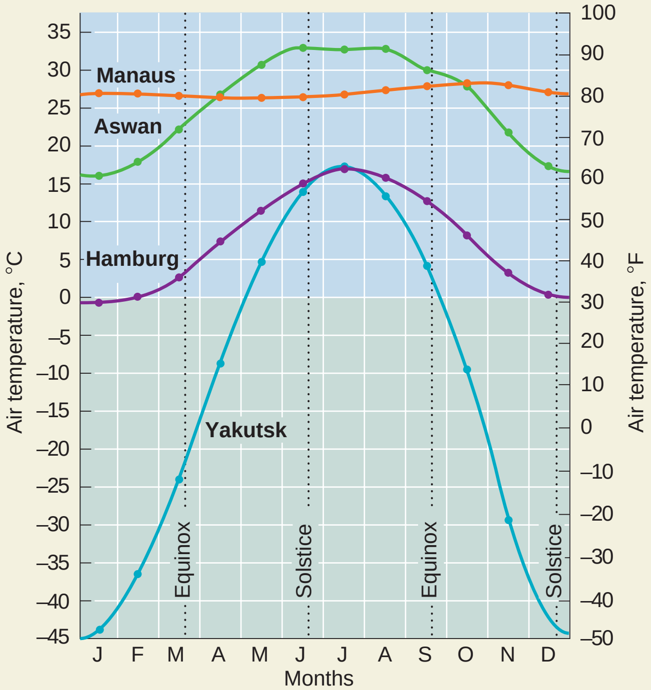
First, we need a quick explanation of air temperature maps. Figure 3.21 shows a set of **isotherms**—lines connecting locations that have the same temperature. Usually, we choose isotherms that are separated by 5 or 10 degrees, but they can be drawn at any convenient temperature interval.

3.20 The relationship between net radiation and temperature

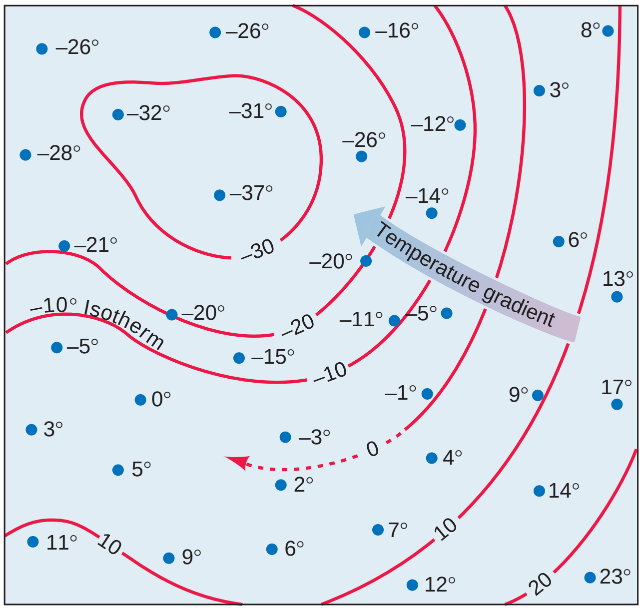


▶ **Net radiation** At Manaus, the average net radiation rate is strongly positive every month. But there are two minor peaks, coinciding roughly with the equinoxes, when the Sun is nearly straight overhead at noon. The curve for Aswan shows a large surplus of positive net radiation every month. The net radiation rate curve has a strong annual cycle—values for June and July that are triple those of December and January. The net radiation rate cycle for Hamburg, Germany is also strongly developed. There is a radiation surplus for nine months, and a deficit for three winter months. During the long, dark winters in Yakutsk, Siberia, the net radiation rate is negative, and there is a radiation deficit that lasts about six months.





◀ **Monthly mean air temperature** Manaus has uniform air temperatures, averaging about 27°C (81°F) for the year. Mean monthly temperature has only a small range—about 1.7°C (3.0°F). There are no temperature seasons. The Aswan data for temperature follows the cycle of the net radiation rate curve very well, and shows an annual range in monthly temperatures of about 17°C (31°F). June, July, and August are terribly hot, averaging over 32°C (90°F). Hamburg's temperature cycle reflects the reduced total insolation at this latitude. Summer months reach a maximum of just over 16°C (61°F), while winter months reach a minimum of just about freezing (0°C or 32°F). The annual range is about 17°C (31°F), the same as at Aswan. In Yakutsk, Siberia, monthly mean temperatures for three winter months are between –35 and –45°C (about –30 and –50°F). In summer, when daylight lasts most of a 24-hour day, the net radiation rate rises to a strong peak. Air temperatures rise phenomenally in the spring to summer. Because of Yakutsk's high latitude and continental interior location, its annual temperature range is enormous—over 60°C (108°F).



3.21 Isotherms

Isotherms are used to make temperature maps. Each line connects points having the same temperature. Where temperature changes along one direction, a temperature gradient exists. Where isotherms close in a tight circle, a center exists. This example shows a center of low temperature.

Isothermal maps clearly show centers of high or low temperatures. They also illustrate the directions along which temperature changes, which are known as *temperature gradients*. In the winter, isotherms dip equatorward while in the summer, they arch poleward (Figure 3.22). Figure 3.23 provides a map of the annual range of temperature, which is greatest in northern latitudes between 60 and 70 degrees.

FACTORS CONTROLLING AIR TEMPERATURE PATTERNS

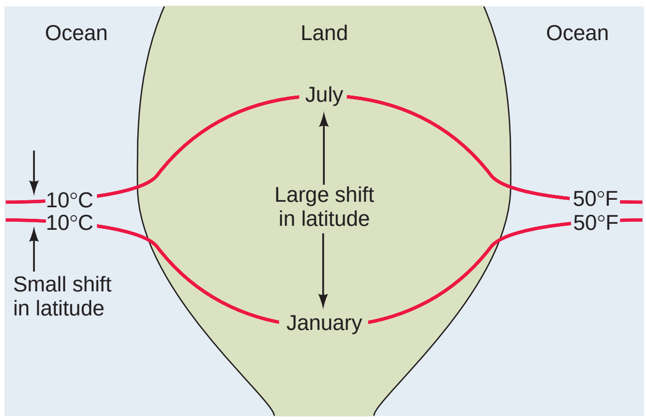
We have already met the three main factors that explain world isotherm patterns. The first is latitude. As latitude increases, average annual insolation decreases, and so temperatures decrease as well, making the poles colder than the Equator. Latitude also affects seasonal temperature variation. For example, the poles receive more solar energy at the summer solstice than the Equator. So we must remember to note the time of year and the latitude when looking at temperature maps.

The second factor is the maritime-continental contrast. As we've noted, coastal stations have more uniform temperatures, and are cooler in summer and warmer in winter. Interior stations, on the other hand, have much larger annual temperature variations. Ocean currents can also have an effect because they can keep coastal waters warmer or cooler than you might expect.

Elevation is the third important factor. At higher elevations, temperatures will be cooler, so we expect to see lower temperatures near mountain ranges.

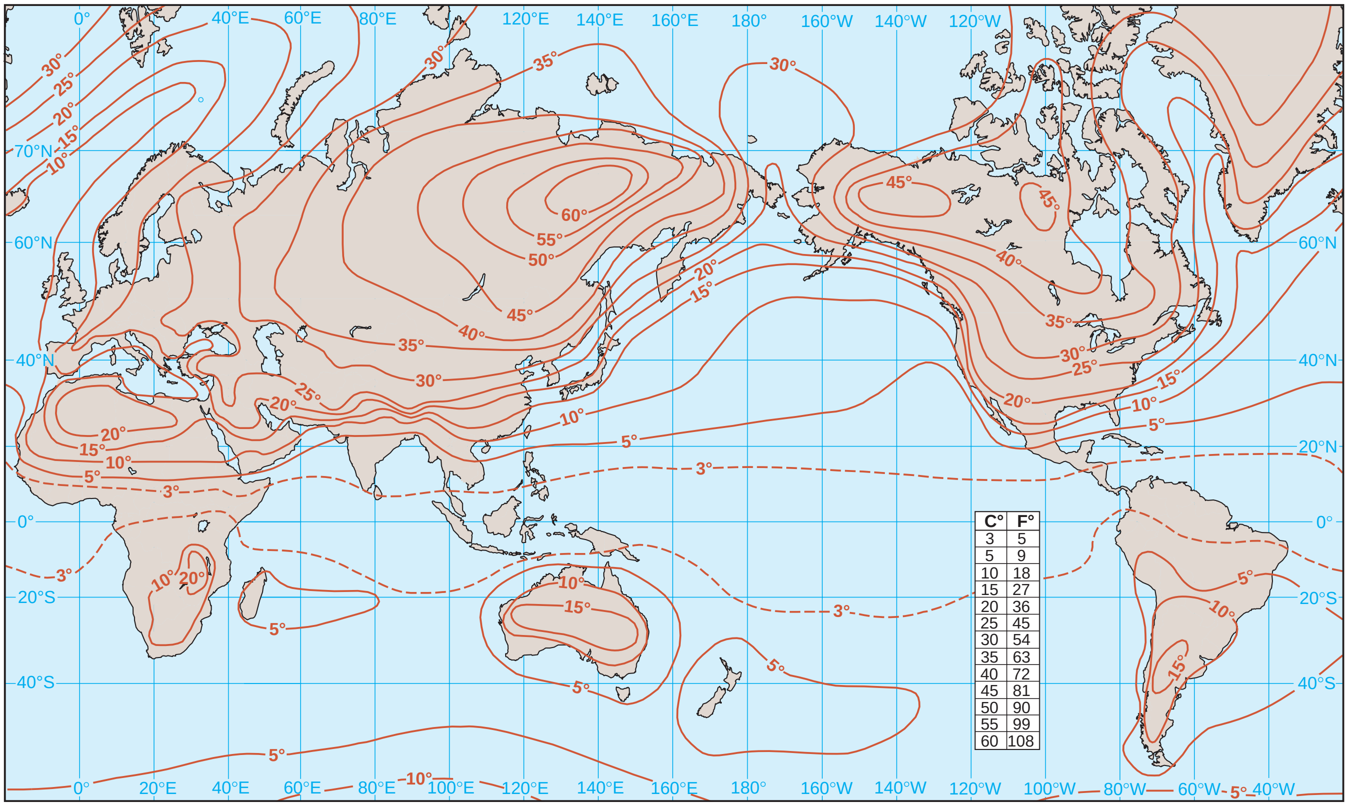
WORLD AIR TEMPERATURE PATTERNS FOR JANUARY AND JULY

World air temperatures for the months of January and July are shown in Figures 3.24 and 3.25. The polar maps (Figure 3.24) show higher latitudes well, while the Mercator maps (Figure 3.25) are best for illustrating trends from the Equator to the midlatitude zones. Using the principles of how air temperatures are related to



3.22 Seasonal migration of isotherms

Continental air temperature isotherms shift over a much wider latitude range from summer to winter than do oceanic air temperature isotherms. This difference occurs because oceans heat and cool much more slowly than continents.



3.23 Annual range of air temperature in Celsius degrees

The annual range of air temperature is defined as the difference between January and July means. Near the Equator, the annual range is quite small. In continental interiors, however, the range is much larger—as large as 60°C (108°F) in eastern Siberia.

latitude, maritime-continental contrast, and elevation, it is easy to explain the six important features that are described in the figures.

Global Warming and the Greenhouse Effect

The Earth is getting warmer. In February 2007, the Intergovernmental Panel on Climate Change (IPCC), a United Nations-sponsored group of more than 2000 scientists, issued a report saying that global warming is "unequivocal."

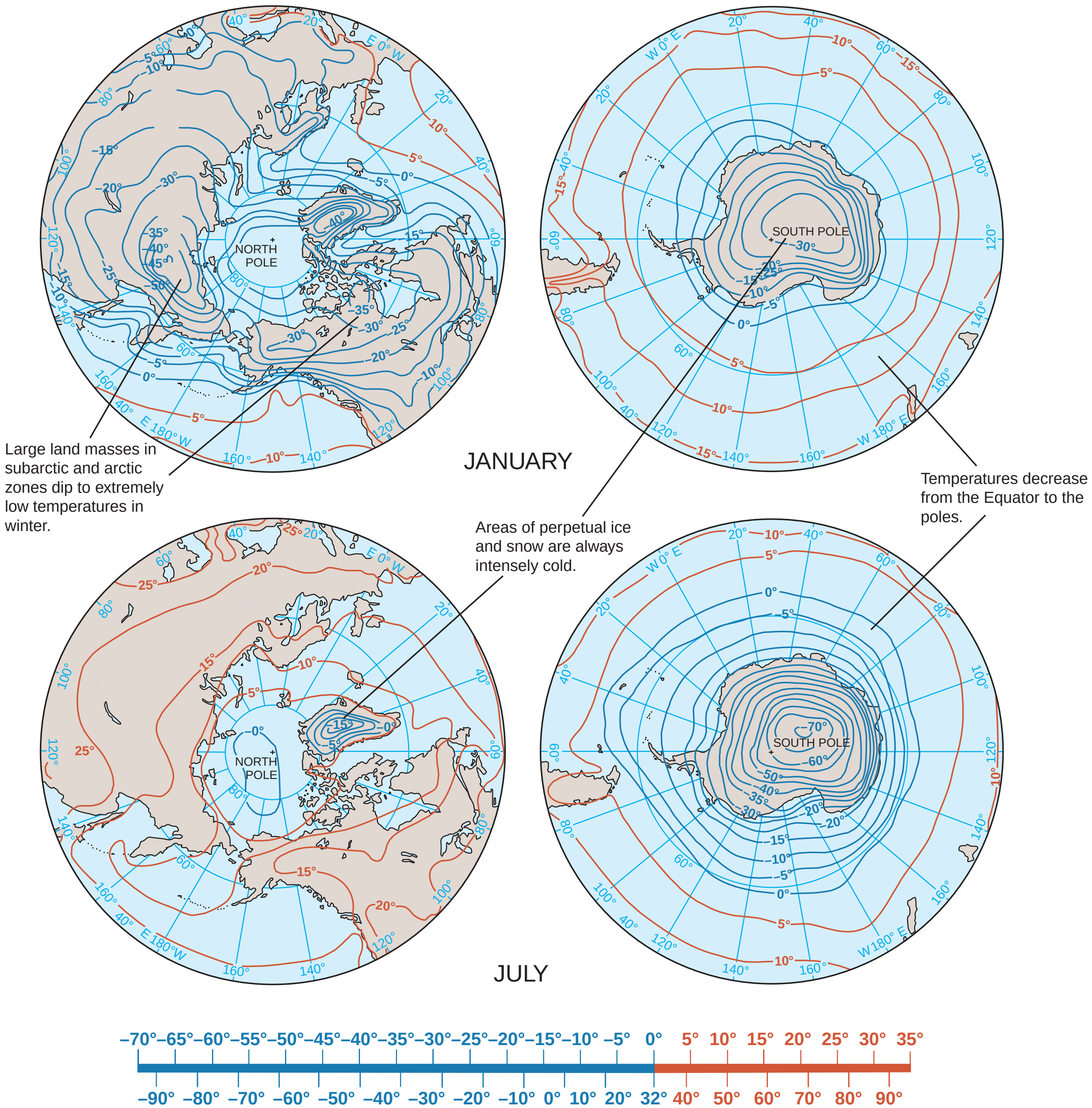
Is this recent warming an effect of human activity? In 1995 the IPCC concluded that human activity has probably caused climatic warming by increasing the concentration of **greenhouse gases** in the atmosphere. This judgment, which was upgraded to "likely" in 2001 and "very likely" in 2007, was based largely on computer simulations that showed that the release of CO_2, CH_4, and other gases from fossil fuel burning and human activity over the last century has accounted for the pattern of warming we have seen.

FACTORS INFLUENCING CLIMATIC WARMING AND COOLING

Greenhouse gases act to warm the atmosphere and enhance the greenhouse effect. CO_2 is the most important greenhouse gas, but methane (CH_4), chlorofluorocarbons, tropospheric ozone, and nitrous oxide (N_2O), when taken together, are as important as CO_2.

Carbon dioxide (CO_2) is a major cause of concern because of its role in the greenhouse effect. Burning fossil fuels releases large amounts of the CO_2 into the atmosphere. As human energy consumption increases, so does atmospheric CO_2. Other gases that are normally present in much smaller concentrations—methane (CH_4), the chlorofluorocarbons, tropospheric ozone (O_3), and nitrous oxide (N_2O)—are also of concern. Taken together with CO_2, they are known as greenhouse gases.

Figure 3.26 shows how a number of important factors have influenced global warming since about 1850. Taken together, the total enhanced energy flow to the surface produced by added greenhouse gases is about

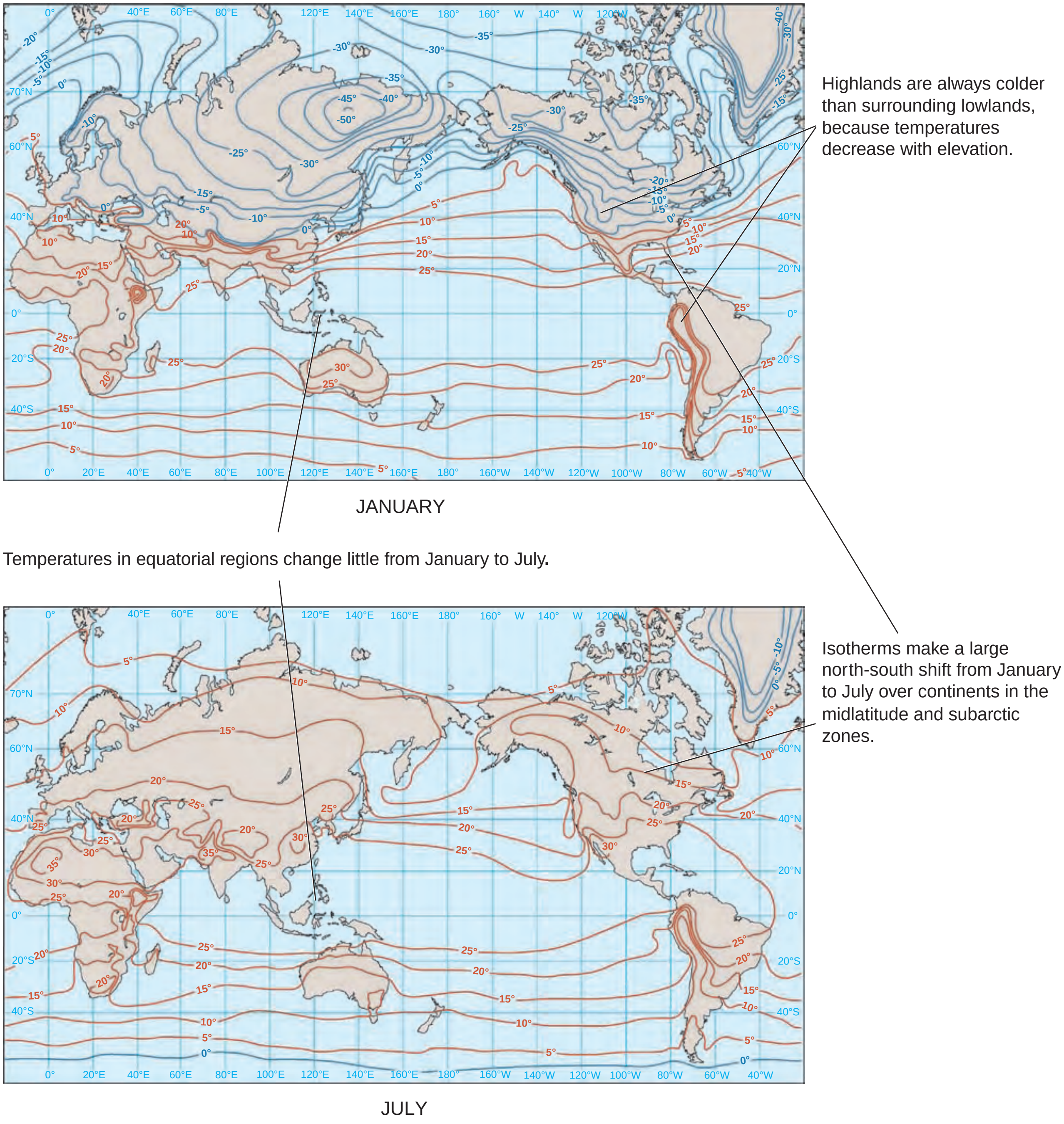


3.24 Mean monthly air temperatures for January and July, polar projections

Large land masses located in the subarctic and arctic zones dip to extremely low temperatures in winter. Look at North America and Eurasia on the January north polar map. These low-temperature centers are very clear. The cold center in Siberia, reaches –50°C (–58°F), while northern Canada is also quite cold (–35°C, –32°F). The high albedo of the snow helps keep winter temperatures low by reflecting much of the winter insolation back to space.

Temperatures decrease from the Equator to the poles. This is shown on the polar maps by the general pattern of the isotherms as nested circles, with the coldest temperatures at the center, near the poles. The temperature decrease is driven by the difference in annual insolation from the Equator to the poles.

Areas of perpetual ice and snow are always intensely cold. Our planet's two great ice sheets are contained in Greenland and Antarctica. Notice how they stand out on the polar maps as cold centers in both January and July. They are cold for two reasons. First, their surfaces are high in elevation, rising to over 3000 m (about 10,000 ft) in their centers. Second, their white snow surfaces reflect most of the incoming solar radiation.

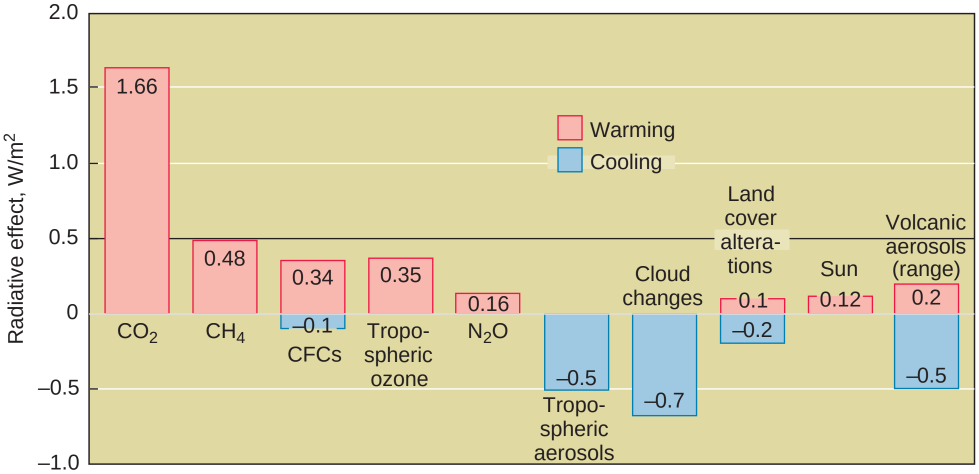


3.25 Mean monthly air temperatures for January and July, Mercator projections

Highlands are always colder than surrounding lowlands because temperatures decrease with elevation. Look at the pattern of isotherms around the Rocky Mountain chain in western North America. In both summer and winter, the isotherms dip down around the mountains. The Andes Mountains in South America show the effect even more strongly.

Temperatures in equatorial regions change little from January to July. This is because insolation at the Equator doesn't vary greatly with the seasons. Look at the broad space between 25°C (77°F) isotherms on both January and July Mercator maps. In this region, the temperature is greater than 25°C (77°F) but less than 30°C (86°F). Although the two isotherms move a bit from winter to summer, the equator always falls between them, showing how uniform the temperature is over the year.

Isotherms make a large north-south shift from January to July over continents in the midlatitude and subarctic zones. The 15°C (59°F) isotherm lies over central Florida in January, but by July it has moved far north, cutting the southern shore of Hudson Bay and then looping far up into northwestern Canada. In contrast, isotherms over oceans shift much less. This is because continents heat and cool more rapidly than oceans.



3.26 Factors affecting global warming and cooling

Greenhouse gases act primarily to enhance global warming, while aerosols, cloud changes, and land-cover alterations caused by human activity act to retard global warming. Natural factors may be either positive or negative.

3 W/m^2. That is about 1.25 percent of the solar energy absorbed by the Earth and atmosphere.

Methane, CH_4, is naturally released from wetlands when organic matter decays. But human activity generates about double that amount in rice cultivation, farm animal wastes, bacterial decay in sewage and landfills, fossil fuel extraction and transportation, and biomass burning.

Chlorofluorocarbons (CFCs) have both a warming and cooling effect. The compounds are very good absorbers of longwave energy, providing a warming effect. But CFCs also destroy ozone in the stratosphere, and since ozone contributes to warming, the CFCs also have a cooling effect.

Air pollution also increases the amount of ozone in the troposphere, leading to further warming. *Nitrous oxide*, N_2O, is released by bacteria acting on nitrogen fertilizers in soils and runoff water. Motor vehicles also emit significant amounts of N_2O.

Human activity is also mostly responsible for the next three factors listed in Figure 3.26, which all tend to cool the Earth–atmosphere system. Fossil fuel burning produces tropospheric aerosols. They are a potent form of air pollution including sulfate particles, fine soot, and organic compounds. Aerosols scatter solar radiation back to space, reducing the flow of solar energy to the surface. They also enhance the formation of low, bright clouds that reflect solar radiation back to space. These, and other changes in cloud cover caused directly or indirectly by human activity, lead to a significant cooling effect. As we convert forests to croplands and pastures, which are brighter and reflect more solar energy, we induce further cooling.

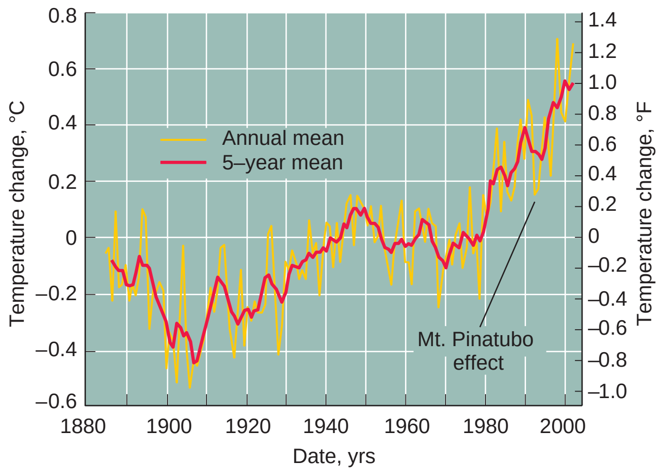
The last two factors in Figure 3.26 are natural. Solar output has increased slightly, causing warming. You can see that volcanic aerosols have both a warming and, at other times, a cooling effect.

THE TEMPERATURE RECORD

When we add all these factors together, the warming effects of the greenhouse gases outweigh the cooling effects. The result is a net warming effect of about 1.6 W/m^2, which is about two thirds of 1 percent of the total solar energy flow absorbed by the Earth and atmosphere. Has this made global temperatures rise? If not, will it warm the Earth in the near future? To understand the implications for the future, we must first look back at the Earth's surface temperature over the last few centuries.

The Earth's mean annual surface temperature from 1866 to 2006 is shown in Figure 3.27. We can see that temperature has increased, especially in the last 50 years. But there have also been wide swings in the mean annual surface temperature. Some of this variation is caused by volcanic eruptions. As we noted above, volcanic activity propels particles and gases—especially sulfur dioxide, SO_2—into the stratosphere, forming stratospheric aerosols. Strong winds spread the aerosols quickly throughout the entire layer, where they reflect incoming solar radiation, having a cooling effect.

The eruption of Mount Pinatubo in the Philippines lofted 15 to 20 million tons of sulfuric acid aerosols into the stratosphere in the spring of 1991. The aerosol layer produced by the eruption reduced solar radiation reaching the Earth's surface between 2 and 3 percent for the year or so following the blast. In response, global temperatures fell about 0.3°C (0.5°F) in 1992 and 1993, which we can see caused a dip in the temperature record in Figure 3.27.



3.27 Mean annual surface temperature of the Earth, 1866–2007

The vertical scale shows departures in degrees from a zero line of reference representing the average for the years 1951–1980. The yellow line shows the mean for each year. The red line shows a running five-year average. Note the effect of Mount Pinatubo in 1992–1993.

TEMPERATURE RECONSTRUCTION

We have direct records of air temperature measurements dating to the middle of the nineteenth century. If we want to know about temperatures at earlier times, we need to use indirect methods, such as tree-ring, coral, and ice core analysis (Figure 3.28).

In climates with distinct seasons, trees grow annual rings. For trees along the timberline in North America, the ring width is related to temperature—the trees grow better when temperatures are warmer. Since only one ring is formed each year, we can work out the date of each ring by counting backward from the present. Because these trees live a long time, we can extend the temperature record back several centuries.

Corals, which survive for hundreds of years, are another living record of past temperatures. As they grow, coral skeletons take up trace elements and atomic isotopes that depend on the temperature of the water.

Ice cores from glaciers and polar regions show annual layers that are related to the precipitation cycles over the years. The crystalline structure of the ice, the concentrations of salts and acids, dust and pollen trapped in the layers, and amounts of trapped gases such as carbon dioxide and methane, all reveal information about long-term climate change.

All direct and indirect methods of recording temperatures show a striking upward turn in temperature over the last century, which nearly all scientists attribute to human activity.

FUTURE SCENARIOS

The year 2005 was the warmest year on record since the middle of the nineteenth century, according to data compiled by NASA scientists at New York's Goddard Institute for Space Studies. It was also the warmest year of the past thousand, according to reconstructions of past temperatures using tree rings and glacial ice cores by University of Massachusetts scientists. In fact, 2005, 2007, 1998, 2002, and 2003, ranked in order as the five warmest years since 1400. In the past 30 years, the Earth has warmed by 0.6°C (1.1°F). In the last century, it has warmed by 0.8°C (1.4°F).

What will be the future effect of this greenhouse warming? Using computer climate models, the scientists of the IPCC projected that global temperatures will warm between 1.8°C (3.2°F) and 4.0°C (7.2°F) by the year 2100.

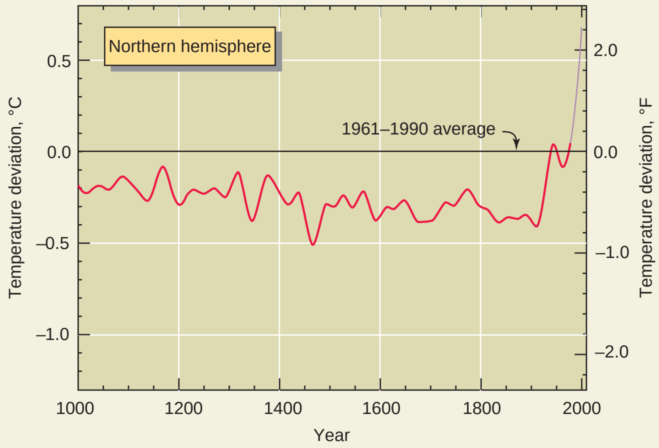
That may not sound like very much, but the problem is that many other changes may accompany a rise in temperature. One of these changes is a rise in sea level, as glaciers and sea ice melt in response to the warming. Current predictions call for a rise of 28 to 43 cm (11.0 to 16.9 in.) in sea level by the year 2100. This would place as many as 92 million people within the risk of annual flooding.

Climate change could also promote the spread of insect-borne diseases such as malaria. Climate boundaries may shift their positions, making some regions wetter and others drier. A shift in agricultural patterns could displace large human populations as well as natural ecosystems.

Our climate could also become more variable. Very high 24-hour precipitation—extreme snowstorms, rainstorms, sleet and ice storms—have become more frequent since 1980. These more frequent and more intense spells of hot and cold weather may be related to climatic warming.

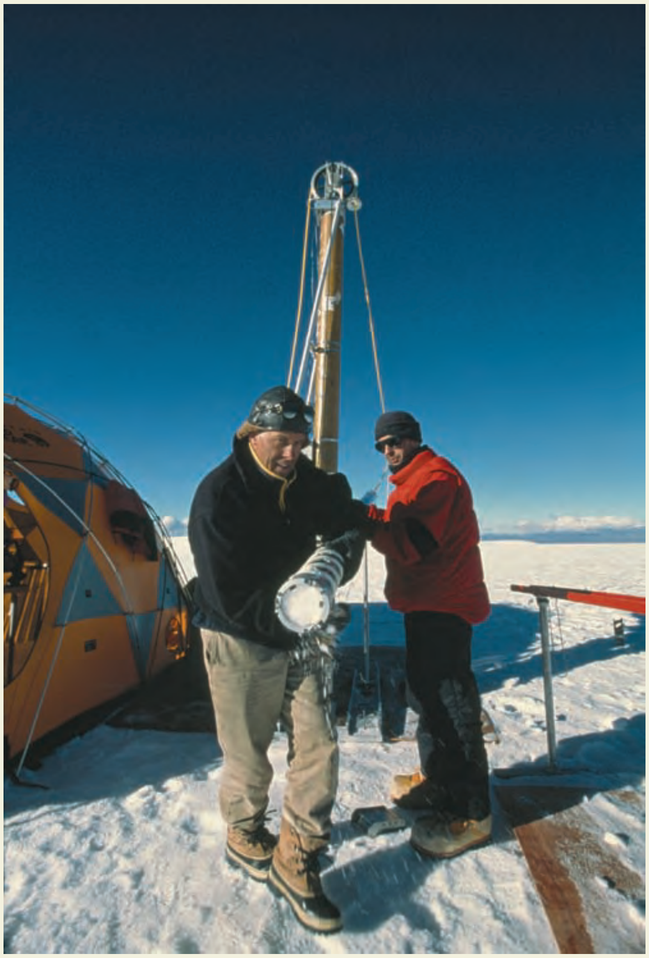
The world has become widely aware of these problems, and at the Rio de Janeiro Earth Summit in 1992, nearly 150 nations signed a treaty limiting emissions of greenhouse gases. Many details were ironed out at a subsequent meeting in Kyoto, Japan, in 1997. The Kyoto protocol called on 38 industrial nations to reduce their greenhouse gas emissions in 2008–2012 to about 8 percent below 1990 levels. By 2004, the European Union group of 23 nations had reduced their emissions by 5 percent, while the United States increased its emissions by 16 percent.

3.28 Reconstructing temperature records



◀ **Temperature variation over the last thousand years** As compared to the reference temperature of the 1961–1990 average, northern hemisphere temperatures trended slightly downward until the beginning of the twentieth century. The line shown is a 40-year moving average obtained from thermometers, historical data, tree rings, corals, and ice cores. Annual data are shown after 1965.

▼ **Ice cores** Chemical analysis of ice cores taken from glaciers and ice caps can provide a record of temperature at the time of ice formation (National Geographic Image Collection).



▲ **Tree rings** The width of annual tree rings varies with growing conditions and in some locations can indicate air temperature (National Geographic Image Collection).

▼ **Coral growth** The constant growth of some corals provides structures similar to annual rings in trees. Sampling the chemical composition of the coral from ring to ring can provide a temperature record. Black lines drawn on the lower section mark years, and red and blue lines mark quarters.

China and India increased their emissions by about 50 percent, while emissions from Russia dropped by 32 percent. A recent United Nations report indicates that the 36 nations signing the Kyoto protocol, when taken together, will most likely have reduced their emissions by 5 percent between 1990 and 2012, largely as a result of the economic decline of Eastern European countries in the 1990s.

The last decade has brought a succession of very warm years, including the warmest year of the last thousand years (2005). Human activity, primarily through the enhanced generation of greenhouse gases, is very likely responsible for the warming trend.

In the meantime, negotiations have begun to provide a successor to the Kyoto protocol. In 2007, a group of major CO_2-emitting nations, including the United States, agreed to develop a cap-and-trade system for CO_2 emissions that would apply to both industrialized nations and developing countries. If adopted, such a system could make a major contribution to reducing the rate of growth of carbon dioxide emissions in the future. While this system would not reduce atmospheric CO_2 concentrations to preindustrial levels, it could lessen the impact of increasing greenhouse gases on global climate change.

But it seems clear that the ultimate solution to reducing greenhouse gas concentrations and global climate change will inevitably involve harnessing solar, wind, geothermal, and even nuclear energy sources, which produce power without releasing CO_2. Energy conservation and development of new methods of utilizing fossil fuels that produce reduced CO_2 emissions will also be important.[CU2]

GEODISCOVERIES **Web Quiz**
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

In this chapter we have developed an understanding of both air temperatures and temperature cycles, along with the factors that influence them, including insolation, latitude, surface type, continental-maritime location, and elevation. Air temperatures are a very important part of climate, and looking ahead, we will study the climates of the Earth in Chapter 7.

The other key ingredient of climate is precipitation—the subject covered in the next chapter. Here temperature plays a very important role, since moist air must cool before condensation forms water droplets and, eventually, precipitation.

GEODISCOVERIES **Web Links**
Visit a NASA site to see today's continental and global temperature maps. Check out global change sites to explore global warming and past climates. See how ice cores and tree rings are used to reconstruct climate. Explore the urban heat island effect.

IN REVIEW AIR TEMPERATURE

- Carbon dioxide is one of several greenhouse gases that trap heat radiation leaving the Earth. The amount of carbon dioxide has increased very significantly since global industrialization from fossil fuel burning, and will probably continue to increase for the next century.
- Future increases in carbon dioxide and other greenhouse gases will depend on economic growth, efficiency of energy use, and substitution of alternative sources of energy.
- **Air temperature**—is influenced by latitude, surface type, coastal or interior location, elevation, and air and ocean circulation patterns.
- Radiation flows into and out of the **surface** of a substance. The energy balance of the ground surface is determined by **net radiation, conduction** to the soil, and **latent heat transfer** and **convection** to and from the atmosphere.
- Air temperature is measured at 1.2 m (4 ft) above the surface. Weather stations make daily minimum and maximum temperature measurements.
- Temperatures of air and soil at or very close to the ground surface are more variable than air temperature as measured at standard height.
- Surface characteristics also affect temperatures. Rural surfaces are generally moist and slow to heat and cool, while urban surfaces are dry and absorb and give up heat readily.
- The difference between rural and urban surfaces creates an **urban heat island** effect that makes cities warmer than surrounding areas. Waste heat from urban activities also significantly warms cities.
- Air temperatures observed at mountain locations are lower with higher elevation, and day–night temperature differences increase with elevation.
- When air temperature increases with altitude, a **temperature inversion** is present. This can develop on clear nights when the surface loses longwave radiation to space.
- The wind chill index combines the effects of temperature and wind to show how cold the air feels to a person outdoors. The heat index couples temperature

and relative humidity to provide a measure of how hot the air feels.

- Air temperatures normally fall with altitude in the lower atmosphere. The decrease in air temperature with increasing altitude is called the **lapse rate**. The average value of decrease with altitude is the **environmental temperature lapse rate**, 6.48C/1000 m (3.58F/1000 ft).
- Temperatures decrease with increasing altitude in the lowest layer of the atmosphere, or **troposphere**. This layer includes abundant water vapor that condenses into clouds of water droplets with **aerosol** particles at their centers.
- Above the troposphere is the **stratosphere**, in which temperature stays uniform or slightly increases with elevation. Winds in the stratosphere are strong and persistent. The stratosphere contains the ozone layer, which absorbs harmful ultraviolet energy.
- The daily cycle of air temperature is driven largely by net radiation, which is positive during the day and negative at night. Net radiation depends on insolation, which is a function of latitude and season.
- Land and water contrasts affect both daily and annual temperature cycles. Water bodies heat and cool more slowly than land, so maritime locations have less extreme temperatures, while interior continental temperature cycles are more extreme.
- Global temperature patterns for January and July show the effects of latitude, maritime-continental location, and elevation. Equatorial temperatures vary little from season to season. Poleward, temperatures decrease with latitude, and continental surfaces at high latitudes can become very cold in winter. At higher elevations, temperatures are always colder.
- **Isotherms**—lines of equal temperature—over continents swing widely north and south with the seasons, while isotherms over oceans move through a much smaller range of latitude. The annual range in temperature increases with latitude and is greatest in northern hemisphere continental interiors.
- Within the last few decades, global temperatures have been increasing. CO_2 released by fossil fuel burning is important in causing warming, but so are the other **greenhouse gases**, CH_4, CFCs, O_3, and N_2O.
- Aerosols scatter sunlight back to space and induce more low clouds, so they tend to lower global temperatures. Solar output and volcanic activity also influence global temperatures.
- The global temperature record shows significant increases, especially in the last 50 years. Since 1998, we have encountered the five warmest years since 1400. By 2100, the latest projections show that global temperatures will warm between 1.8°C and 4.0°C (3.2°F–7.2°F). Also predicted are shifts of climate zones and increases in sea level.

KEY TERMS

air temperature, p. 85
surface, p. 86
net radiation, p. 86
conduction, p. 86
latent heat transfer, p. 86
convection, p. 86
transpiration, p. 88
evapotranspiration, p. 88
urban heat island, p. 88
temperature inversion, p. 92
lapse rate, p. 93
environmental temperature lapse rate, p. 94
troposphere, p. 94
aerosols, p. 94
stratosphere, p. 94
isotherms, p. 98
greenhouse gases, p. 101

REVIEW QUESTIONS

1. Apart from water vapor, which greenhouse gas plays the largest role in warming the atmosphere? Where does it come from? How will its concentration change in the future?
2. Identify five important factors in determining air temperature and air temperature cycles.
3. What factors influence the temperature of a surface?
4. How are mean daily air temperature and mean monthly air temperature determined?
5. How does the daily temperature cycle measured within a few centimeters or inches of the surface differ from the cycle at normal air temperature measurement height?
6. Compare the characteristics of urban and rural surfaces and describe how the differences affect urban and rural air temperatures. Include a discussion of the urban heat island.
7. How and why are the temperature cycles of high-mountain stations different from those of lower elevations?
8. Identify two temperature indexes and provide an example of each.
9. Explain how air temperature changes with elevation in the atmosphere, using the terms *lapse rate* and *environmental temperature lapse rate* in your answer.

10. What are the two layers of the lower atmosphere? How are they distinguished? Name the two upper layers.
11. Why do large water bodies heat and cool more slowly than land masses? What effect does this have on daily and annual temperature cycles for coastal and interior stations?
12. Explain how latitude affects the annual cycle of air temperature through net radiation by comparing Manaus, Aswan, Hamburg, and Yakutsk.
13. What three factors are most important in explaining the world pattern of isotherms? Explain how and why each factor is important, and what effect it has.
14. Turn to the January and July world temperature maps shown in Figures 3.24 and 3.25. Make six important observations about the patterns and explain why each occurs.
15. Identify the important greenhouse gases and rank them in terms of their warming effect. What human-influenced factors act to cool global temperature? How?
15. Describe how global air temperatures have changed in the recent past. Identify some factors or processes that influence global air temperatures on this time scale.
16. How are global temperatures predicted to change in the future? Identify some effects of this change on climate and human activity.

VISUALIZING EXERCISES

1. Sketch graphs showing how insolation, net radiation, and temperature might vary from midnight to midnight during a 24-hour cycle at a midlatitude station such as Chicago.
2. Sketch a graph of air temperature with height showing a low-level temperature inversion. Where and when is such an inversion likely to occur?

ESSAY QUESTIONS

1. Portland, Oregon, on the north Pacific coast, and Minneapolis, Minnesota, in the interior of the North American continent, are at about the same latitude. Sketch the annual temperature cycle you would expect for each location. How do they differ and why? Select one season, summer or winter, and sketch a daily temperature cycle for each location. Again, describe how they differ and why.
2. Many scientists have concluded that human activities are acting to raise global temperatures. What human processes are involved? How do they relate to natural processes? Are global temperatures increasing now? What other effects could be influencing global temperatures? What are the consequences of global warming?

Chapter 4
Atmospheric Moisture and Precipitation

A rainbow arcs over in the Amazon rainforest near Tefé, Amazonas, Brazil. In the equatorial rainforest, precipitation is largely in the form of convective showers.

The Earth's broad belt of equatorial rainforests plays a major role in the circulation of water and energy in the hydrologic cycle. The trees serve as water pumps, taking up rainwater from the soil and evaporating it using the energy of the Sun. Although much of the water vapor condenses locally as convective showers, a portion is carried to higher latitudes through the atmosphere's global circulation. When this water vapor condenses, its latent heat is released—far from the site of its original evaporation. In this way, solar energy is exported from the equatorial regions to the tropics and midlatitudes.

What will happen as the world's equatorial rainforests are cleared for timber and agriculture? With reduced evaporation, local air temperatures will rise and precipitation will be reduced. The export of solar energy and water vapor will be lessened, affecting tropical and midlatitude climates. Thus, the clearing of equatorial rainforests is a process that is changing the Earth's climates.

Rainbow over rainforest, Amazonas, Brazil

Atmospheric Moisture and Precipitation

Precipitation is a commonplace event for most people, and as part of our daily lives we don't tend to think too much about it. But without precipitation, our planet would be inhospitable. How does water flow between the atmosphere, land surface, and oceans? What factors affect the amount of water vapor present in the atmosphere? What causes water vapor in the atmosphere to condense, forming clouds of water droplets and ice crystals? How do mountains induce precipitation and create rain shadows? How do thunderstorms form, and why are they sometimes severe? What causes tornadoes to form? These are questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Acid Deposition

Perhaps you've heard about *acid rain* killing fish and poisoning trees. Acid rain is part of the phenomenon of acid deposition (Figure 4.1). It's made up of raindrops that have been acidified by air pollutants. Fossil fuel burning releases sulfur dioxide (SO_2) and nitric oxide (NO_2) into the air. The SO_2 and NO_2 readily combine with oxygen and water in the presence of sunlight and dust particles to form sulfuric and nitric acid aerosols, which then act as condensation nuclei. The tiny water droplets created around these nuclei are acidic, and when the droplets coalesce in precipitation, the resulting raindrops or ice crystals are also acidic. Sulfuric and nitric acids can also be formed on dust particles, creating dry acid particles. These can be as damaging to plants, soils, and aquatic life as acid rain.

What are the effects of acid deposition? In Europe and in North America, acid deposition has had a severe impact on some ecosystems. In Norway, acidification of stream water has virtually eliminated many salmon runs by inhibiting salmon egg development. In 1990, American scientists estimated that 14 percent of Adirondack lakes were heavily acidic, along with 12 to 14 percent of the streams in the Mid-Atlantic states. Forests, too, have been damaged by acid deposition. In western Germany, the impact has been especially severe in the Harz Mountains and the Black Forest.

Since 1990, the United States has significantly reduced the release of sulfur oxides, nitrogen oxides, and volatile organic compounds, largely by improving industrial emission controls. But acid deposition is still a very important problem in many parts of the world—especially Eastern Europe and the states of the former Soviet Union. There, air pollution controls have been virtually nonexistent for decades. Reducing pollution levels and cleaning up polluted areas will be a major task for these nations over the next decades.

Water in the Environment

In this chapter, we focus on water in the air, both as vapor and as liquid and solid water. **Precipitation** is the fall of liquid or solid water from the atmosphere that reaches the Earth's land or ocean surface. It forms when moist air is cooled, causing water vapor to form liquid droplets or solid ice particles. If cooling is sufficient, liquid and solid water particles will grow to a size too large to be held aloft by the motion of the atmosphere. They can then fall to the Earth. Before we begin our study of atmospheric moisture and precipitation, however, we will briefly review the three states of water and the conversion of one state to another.

THREE STATES OF WATER

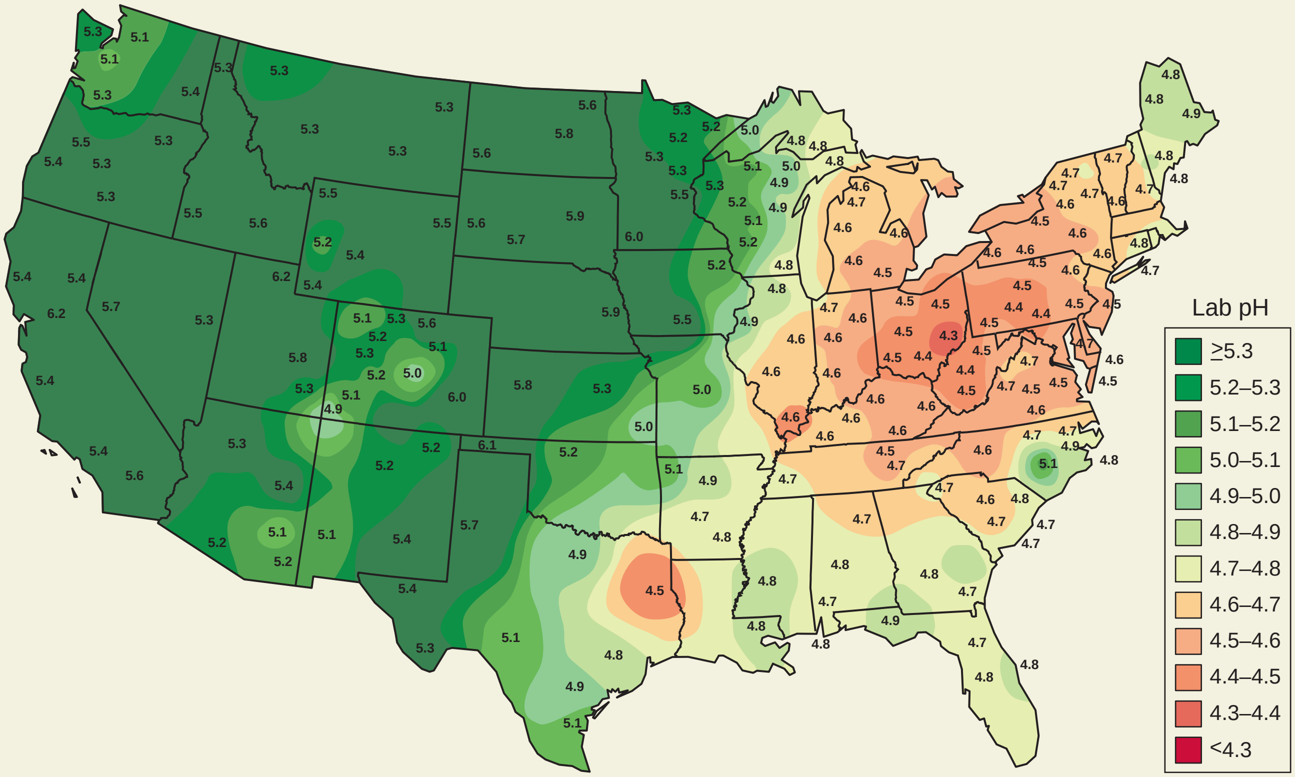
Water can exist in three states—as a solid (ice), as a liquid (water), or as an invisible gas (water vapor), as shown in Figure 4.2. If we want to change the state of water from solid to liquid, liquid to gas, or solid to gas, we must put

4.1 Acid deposition

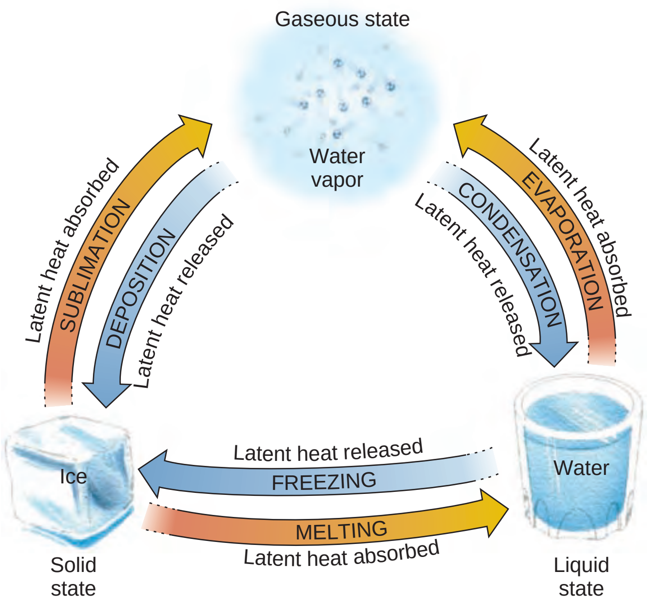
Deposition of acid droplets and dry particles, formed in the atmosphere from gases released by fossil fuel burning, can have severe environmental effects.

▲ **Forests** Acid fallout from a nearby nickel smelter killed this lush forest in Monchegorsk, Russia, which then burned (National Geographic Image Collection).

▲ **Buildings** Acid rain has eroded and eaten away the face of this stone angel in London, England (National Geographic Image Collection).



▲ **Acidity of rainwater for the United States in 2005** Values are pH units, which indicate acidity. The eastern United States, notably Ohio, Pennsylvania, and West Virginia, shows the lowest, most acid values.



4.2 Three states of water

Arrows show the ways that any one state of water can change into either of the other two states. Heat energy is absorbed or released, depending on the direction of change.

in heat energy. This energy, which is drawn in from the surroundings and stored within the water molecules, is called *latent heat*. When the change goes the other way, from liquid to solid, gas to liquid, or gas to solid, this latent heat is released to the surroundings.

Sublimation is the direct transition from solid to vapor. Perhaps you have noticed that old ice cubes left in the freezer shrink away from the sides of the ice cube tray and get smaller. They shrink through sublimation—never melting, but losing mass directly as vapor. In this book, we use the term **deposition** to describe the reverse process, when water vapor crystallizes directly as ice. Frost forming on a cold winter night is a common example of deposition.

Water exists in solid, liquid, and gaseous states as ice, water, and water vapor. Latent heat energy is released or absorbed as water changes from one state to another.

THE HYDROSPHERE

The realm of water in all its forms, and the flows of water among ocean, land, and atmosphere, are known as the **hydrosphere**, shown in Figure 4.3. About 97.2 percent of the hydrosphere consists of ocean salt water. The remaining 2.8 percent is fresh water. The next largest reservoir is fresh water stored as ice in the world's ice sheets and mountain glaciers, which accounts for 2.15 percent of total global water.

Fresh liquid water is found above and below the Earth's land surfaces. Subsurface water lurks in openings in soil and rock. Most of it is held in deep storage as ground water, where plant roots cannot reach. Ground water makes up 0.63 percent of the hydrosphere.

The small remaining proportion of the Earth's water includes the water available for plants, animals, and human use. Plant roots can access soil water. Surface water is held in streams, lakes, marshes, and swamps. Most of this surface water is about evenly divided between freshwater lakes and saline (salty) lakes. An extremely small proportion makes up the streams and rivers that flow toward the sea or inland lakes.

Only a very small quantity of water is held as vapor and cloud water droplets in the atmosphere—just 0.001 percent of the hydrosphere. However, this small reservoir of water is enormously important. Through precipitation, it supplies water and ice to replenish all freshwater stocks on land. In addition, this water, and its conversion from one form to another in the atmosphere, is an essential part of weather events across the globe. Finally, the flow of water vapor from warm tropical oceans to cooler regions provides a global flow of heat from low to high latitudes.

THE HYDROLOGIC CYCLE

The **hydrologic cycle**, or water cycle, moves water from land and ocean to the atmosphere (Figure 4.4). Water from the oceans and from land surfaces evaporates, changing state from liquid to vapor and entering the atmosphere. Total evaporation is about six times greater over oceans than land because oceans cover most of the planet and because land surfaces are not always wet enough to yield much water.

The hydrologic cycle describes the global flow of water to and from oceans, land, and atmosphere. Water moves by evaporation, precipitation, and runoff.

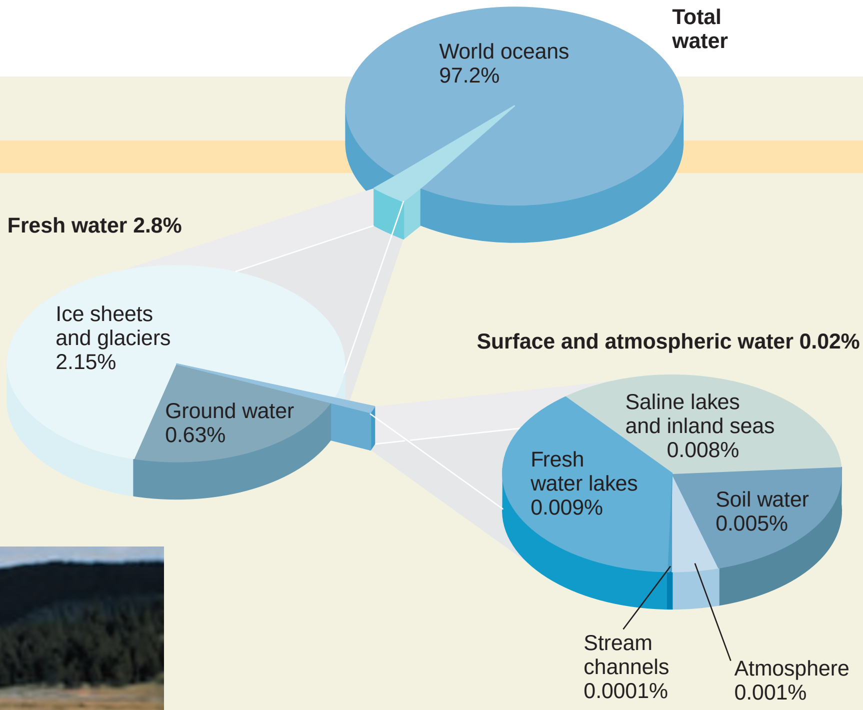
Water vapor in the atmosphere can condense or deposit to form clouds and precipitation, which falls to Earth as rain, snow, or hail. There is nearly four times as much precipitation over oceans than precipitation over land.

When it hits land, precipitation has three fates. First, it can evaporate and return to the atmosphere as water vapor. Second, it can sink into the soil and then into the surface rock layers below. As we will see in later chapters, this subsurface water emerges from below to feed rivers, lakes, and even ocean margins. Third, precipitation can run off the land, concentrating in streams and rivers that eventually carry it to the ocean or to lakes. This flow is known as *runoff*.

Because our planet contains only a fixed amount of water, a global balance must be maintained among flows

4.3 Water reservoirs of the hydrosphere

▶ **Distribution of water** Nearly all the Earth's water is contained in the world's oceans. Fresh surface and soil water make up only a small fraction of the total volume of global water.

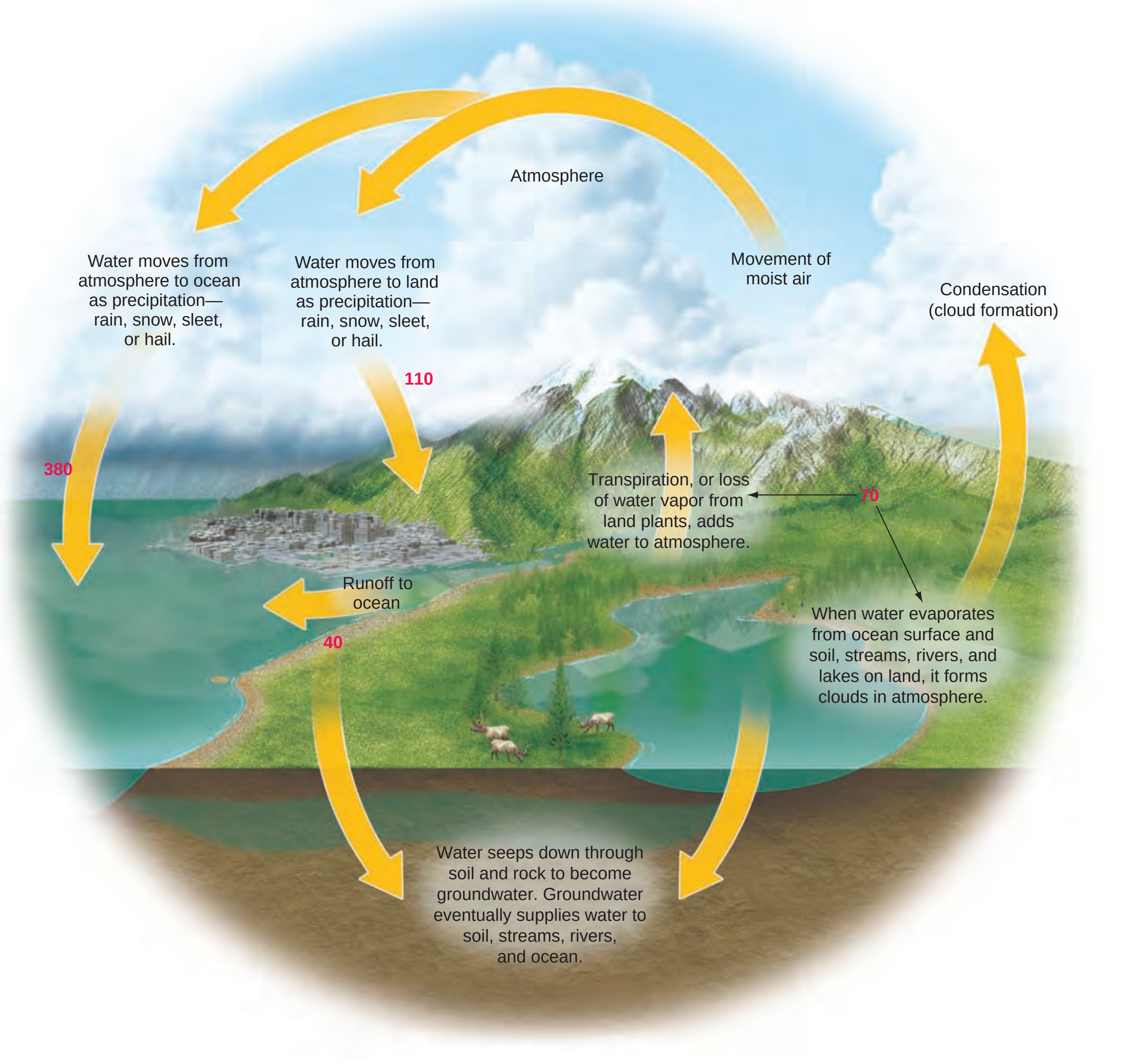


▲ **Surface water** Surface water, including lakes, is only a very tiny fraction of Earth's water volume. Here a bull moose wades along the margin of lake in search of tasty aquatic plants (National Geographic Image Collection).

▲ **Atmosphere** Atmospheric water, although only 0.001 percent of total water, is a vital driver of weather and climate and sustains life on Earth (National Geographic Image Collection).

▲ **Oceans** Most of the Earth's water is held by its vast ocean. Here, a southern stingray swims along a shallow ocean bottom near Grand Cayman Island (National Geographic Image Collection).

▼ **Ice** Ice sheets and glaciers are the second largest reservoir of water. Although glaciers are too cold and forbidding for most forms of animal life, sea ice provides a habitat for polar bears hunting seals and fish in arctic waters (National Geographic Image Collection).



Calculating the global hydrologic balance

The natural flow of water between the oceans, the land, and atmosphere is a system in balance. This table explains that balance as depicted in the figure.

Entering ocean	Leaving ocean	Entering land	Leaving land
380 × 1000 km^3/yr	**420** × 1000 km^3/yr	**110** × 1000 km^3/yr	**70** × 1000 km^3/yr
40 × 1000 km^3/yr			**40** × 1000 km^3/yr
Total: **420** × 1000 km^3/yr	Total: **420** × 1000 km^3/yr	Total: **110** × 1000 km^3/yr	Total: **110** × 1000 km^3/yr

4.4 The hydrologic cycle

As the Sun warms the surface of the Earth, water evaporates from lakes, rivers, oceans, plants, the ground, and other sources. The vapor rises into the atmosphere, providing the moisture that forms clouds. It then returns to the Earth in the form of rain, snow, sleet, and hail. It fills lakes and wetlands, flows into rivers and oceans, and recharges underground water reserves. The process endlessly recycles the Earth's water.

of water to and from the lands, oceans, and atmosphere. For the ocean, evaporation leaving the ocean is approximately 420 km^3/yr (101 mi^3/yr), while the amount entering the ocean via precipitation is 380 km^3/yr (91 mi^3/yr). There is an imbalance between the amount of water lost to evaporation and the amount gained through precipitation. This imbalance is made up by the 40 km^3/yr (10 mi^3/yr) that flows from the land back to the ocean.

Similarly, for the land surfaces of the world, there is a balance. Of the 110 km^3/yr (27 mi^3/yr) of water that falls on the land surfaces, 70 km^3/yr (17 mi^3/yr) is re-evaporated back into the atmosphere. The remaining 40 km^3/yr (10 mi^3/yr) stays in the form of liquid water and eventually flows back into the ocean.

Of all these pathways, we will be most concerned with one aspect of the hydrologic cycle—the flow of water from the atmosphere to the surface in the form of precipitation. To understand this process, we first need to examine how water vapor in the atmosphere is converted into clouds and subsequently into precipitation.

Humidity

Blistering summer heat waves can be deadly, with the elderly and the ill at most risk. However, even healthy young people need to be careful, especially in hot, humid weather. High humidity slows the evaporation of perspiration from our bodies, reducing its cooling effect. Clearly, it is not only the temperature of the air that controls how hot weather affects us—the amount of water vapor in the air is important as well.

> **Humidity refers to the amount of water vapor present in the air. Warm air can hold much more water vapor than cold air.**

The amount of water vapor present in air, referred to as **humidity**, varies widely from place to place and time to time. In the cold, dry air of arctic regions in winter, the humidity is almost zero, while it can reach up to as much as 3 to 4 percent of a given volume of air in the warm wet regions near the Equator.

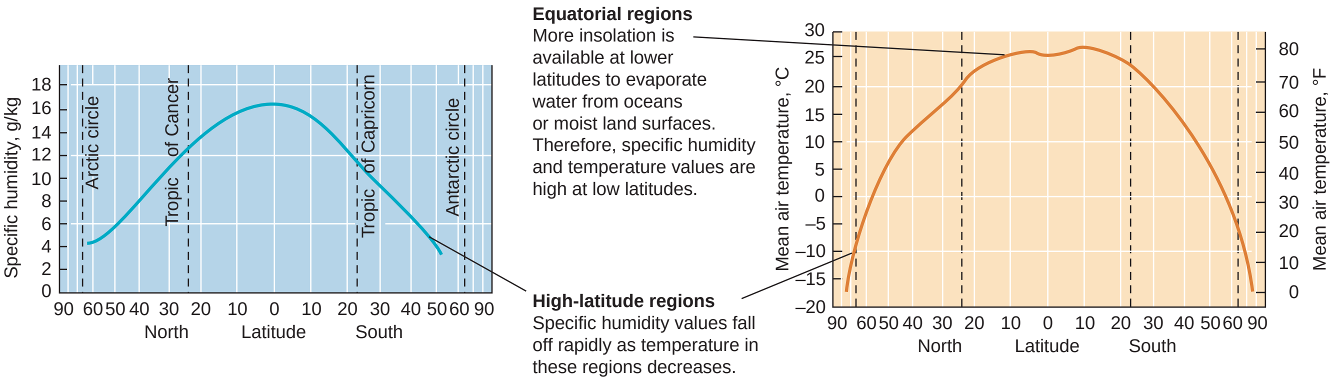
An important principle concerning humidity states that the maximum quantity of water vapor an air parcel can contain is dependent on the air temperature itself. Warm air can contain more water vapor than cold air—a lot more. Air at room temperature (20°C, 68°F) can contain about three times as much water vapor as freezing air (0°C, 32°F).

SPECIFIC HUMIDITY

The actual quantity of water vapor contained within a parcel of air is known as its **specific humidity** and is expressed as grams of water vapor per kilogram of air (g/kg). The equation for specific humidity is given as:

$$\text{specific humidity} = \frac{\text{mass of water vapor}}{\text{mass of total air}}$$

Specific humidity is often used to describe the amount of water vapor in a large mass of air. Both humidity and temperature are measured at the same locations in standard thermometer shelters the world over and also on ships at sea. Specific humidity is largest at the warm, equatorial zones, and falls off rapidly toward the colder poles (Figure 4.5). Extremely cold, dry air over arctic regions in winter may have a specific humidity as low as 0.2 g/kg, while the extremely warm, moist air of equatorial regions often contains as much as 18 g/kg. The total natural range on a worldwide basis is very wide. In fact, the largest values of specific humidity observed are from 100 to 200 times as great as the smallest values.



4.5 Global specific humidity and temperature

Pole-to-pole profiles of specific humidity (left) and temperature (right) show similar trends because the ability of air to hold water vapor (measured by specific humidity) is limited by temperature.

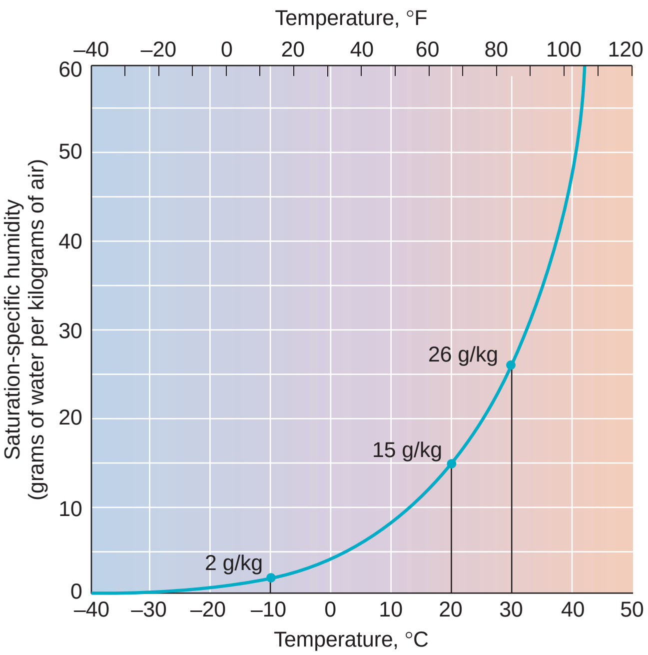
DEW-POINT TEMPERATURE

Although the actual amount of water in a given volume of air is called the specific humidity, this is not the same as the maximum quantity of moisture that a given volume of air can contain at any time. This maximum specific humidity, referred to as the *saturation-specific* humidity, is dependent on the air's temperature.

The dew-point temperature of a mass of air is the temperature at which saturation will occur. The more water vapor in the air, the higher is the dew-point temperature.

In Figure 4.6 we see, for example, that at 20°C (68°F), the maximum amount of water vapor that the air can contain—the saturation-specific humidity—is about 15 g/kg. At 30°C (86°F), it is nearly doubled—about 26 g/kg. For cold air, the values are quite small. At –10°C (14°F), the maximum is only about 2 g/kg.

Another way of describing the water vapor content of air is by its **dew-point temperature**, also called simply the *dew point*. If air is slowly chilled, its saturation-specific humidity decreases. This can continue until the saturation-specific humidity is equal to the specific humidity. When this condition is reached, the air has reached *saturation*, because the air contains the maximum amount of water vapor possible. If further cooling continues, condensation begins. The temperature at which saturation occurs is therefore known as the *dew-point temperature*—that is, the temperature at which dew forms by condensation.



4.6 Saturation-specific humidity and temperature

The maximum specific humidity a mass of air can have—the saturation-specific humidity—increases sharply with rising temperature.

RELATIVE HUMIDITY

When weather forecasters speak of humidity, they are usually referring to **relative humidity**. This measure compares the amount of water vapor present to the maximum amount that the air can contain at its given temperature. The relative humidity is expressed as a percentage given by:

$$\text{relative humidity} = \frac{100 \times \text{specific humidity}}{\text{saturation-specific humidity}}$$

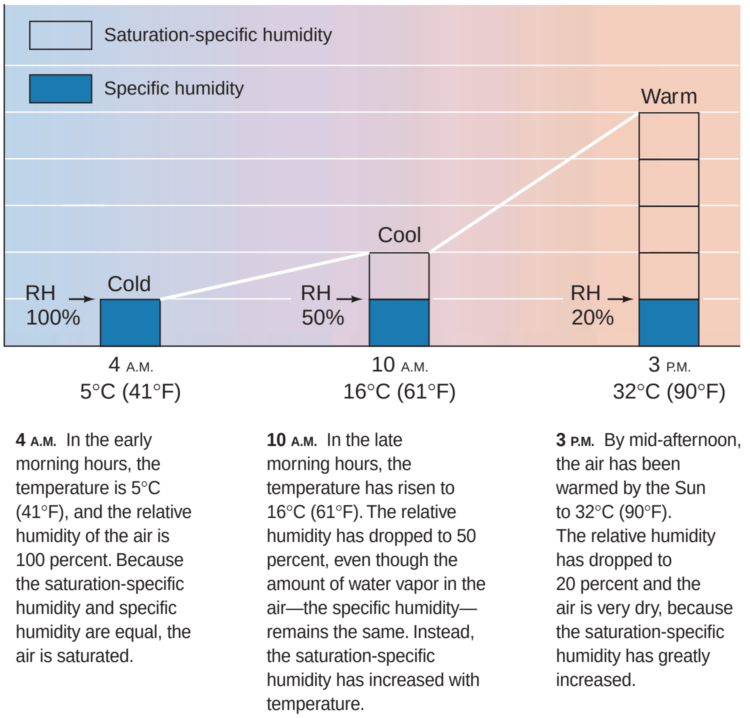
For example, if the air currently contains half the moisture possible at the present temperature, then the relative humidity is 50 percent. When the humidity is 100 percent, the air contains the maximum amount of moisture possible. The air is saturated, and its temperature is at the dew point. When the specific humidity and saturation-specific humidity are not the same, the air is unsaturated. Generally, when the difference between the two is large, the relative humidity is small and vice versa.

The relative humidity of the atmosphere can change in one of two ways. First, the atmosphere can directly gain or lose water vapor, thereby changing the specific humidity of the air mass. For example, additional water vapor can enter the air from an exposed water surface or from wet soil. This process is slow because the water vapor molecules must diffuse upward from the surface into the air layer above.

Relative humidity depends on both the water vapor content and the temperature of air. It compares the amount of water held by air to the maximum amount that can be held at that temperature.

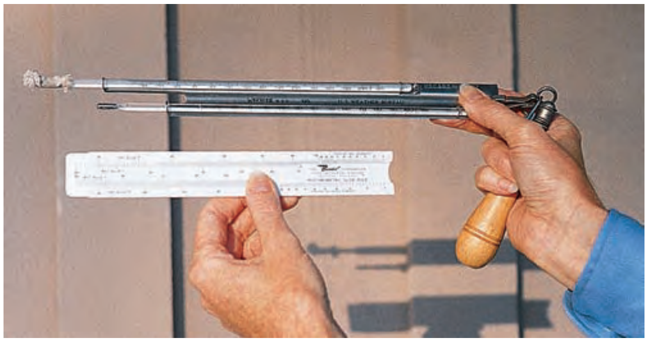
The second way relative humidity changes is through a change of temperature. Even though no water vapor is added, an increase of temperature results in a decrease of relative humidity (Figure 4.7). Recall that the saturation-specific humidity of air is dependent on temperature. When the air is warmed, the saturation-specific humidity increases. The existing amount of water vapor, given by the specific humidity, then represents a smaller fraction of the saturation-specific humidity.

A simple method of measuring relative humidity uses two thermometers mounted together side by side in an instrument called a *sling psychrometer* (see Figure 4.8). After whirling the psychrometer in the air, the temperature difference between the wet-bulb thermometer and the dry-bulb thermometer can be used to derive the relative humidity. Direct-reading electronic instruments are also available for measuring humidity.



4.7 Relative humidity and air temperature

Relative humidity changes with temperature because warm air can contain more water vapor than cold air. In this example, the amount of water vapor stays the same, and only the saturation-specific humidity of the air mass changes.



4.8 Sling psychrometer

The sling psychrometer measures relative humidity using paired wet- and dry-bulb thermometers. The wet-bulb thermometer is wetted with water, and the thermometers are whirled overhead. As the water evaporates from the wet-bulb, its temperature drops in proportion to the relative humidity of the air. The difference in temperature between the dry- and wet-bulb thermometers gives the relative humidity, which is read using the special scale held below the psychrometer.

GEODISCOVERIES Weather Station Interactivity

Test your skill at forecasting fog or frost at five locations across the continent based on weather station data. Issue pollution alerts, frostbite and heat index warnings.

The Adiabatic Process

What makes the water vapor in the air turn into liquid or solid particles that can fall to the Earth? The answer is that the air is naturally cooled. When air cools to the dew point, the air is saturated with water. Think about extracting water from a moist sponge. To release the water, you have to squeeze the sponge—that is, reduce its ability to hold water. In the atmosphere, chilling the air beyond the dew point is like squeezing the sponge—it reduces the amount of water vapor the air can contain, forcing some water vapor molecules to change state to form water droplets or ice crystals.

One mechanism for chilling air is nighttime cooling. On a clear night, the ground surface can become quite cold as it loses longwave radiation. If the air is moist, frost can be deposited as water vapor forms ice crystals. However, this cooling is not enough to form precipitation. Precipitation only forms when a substantial mass of air experiences a steady drop in temperature below the dew point. This happens when an air parcel is lifted to higher and higher levels in the atmosphere.

GEODISCOVERIES The Adiabatic Process

Watch an animation that demonstrates how an air parcel cools as it rises and warms as it descends. The animation shows both dry and moist adiabatic motion.

DRY ADIABATIC RATE

If you have ever pumped up a bicycle tire using a hand pump, you might have noticed that the pump gets hot. If so, you have observed the **adiabatic principle**. This important law states that if no energy is added to a gas, its temperature will increase as it is compressed. As you pump vigorously, compressing the air, the metal bicycle pump gets warm. Conversely, when a gas expands, its temperature drops by the same principle. Physicists use the term *adiabatic process* to refer to a heating or cooling process that occurs solely as a result of pressure change, with no heat flowing into or away from a volume of air.

How does the adiabatic principle relate to the uplift of air and to precipitation? The missing link is simply that atmospheric pressure decreases as altitude increases. As a parcel of air is uplifted, atmospheric pressure on the parcel becomes lower, and the air expands and cools, as shown in Figure 4.9. As a parcel of air descends, atmospheric pressure becomes higher, and the air is compressed and warmed.

We describe this behavior in the atmosphere using the **dry adiabatic lapse rate**, as shown in the lower portion of Figure 4.10. It applies to a rising air parcel that has not yet been cooled to saturation. The dry adiabatic lapse rate has a value of about 10°C per 1000 m (5.5°F per 1000 ft) of vertical rise. That is, if a parcel of air is raised 1 km, its temperature will drop by 10°C. Conversely, an air parcel that descends will warm by 10°C per 1000 m. This is the *dry* rate because no condensation occurs during this process.

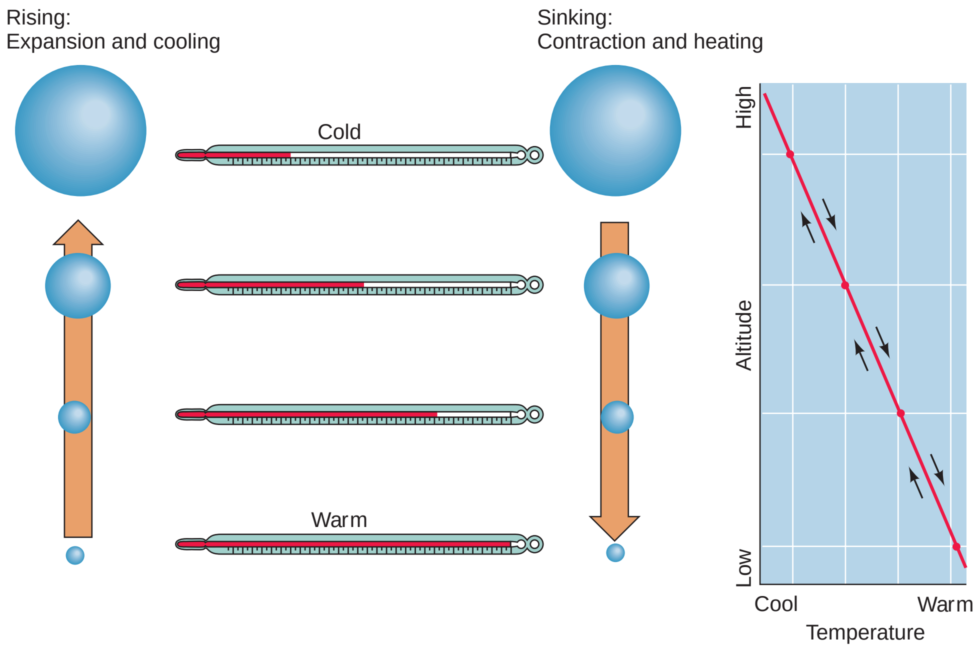
There is an important difference to note between the dry adiabatic lapse rate and the environmental temperature lapse rate. The environmental lapse rate is simply an expression of how the temperature of still air varies with altitude. This rate will vary from time to time and from place to place, depending on the state of the atmosphere. It is quite different from the dry adiabatic lapse rate. The dry adiabatic lapse rate applies to a mass of air moving vertically. It does not vary with time and place, and it is determined by physical laws, not the local atmospheric state.

MOIST ADIABATIC RATE

Let's continue examining the fate of a parcel of air that is moving upward in the atmosphere (Figure 4.10). As the parcel moves upward, its temperature drops at the dry adiabatic rate, 10°C/1000 m (5.5°F/1000 ft). Note, however, that the dew-point temperature changes slightly with elevation. Instead of remaining constant, it falls at the *dew-point lapse rate* of 1.8°C/1000 m (1.0°F/1000 ft). As the rising process continues, the air is eventually cooled to its dew-point temperature, and condensation starts to occur. This is shown in Figure 4.10 as the **lifting condensation level**. The lifting condensation level is thus determined by the initial temperature of the air and its initial dew point and can differ from the example shown here.

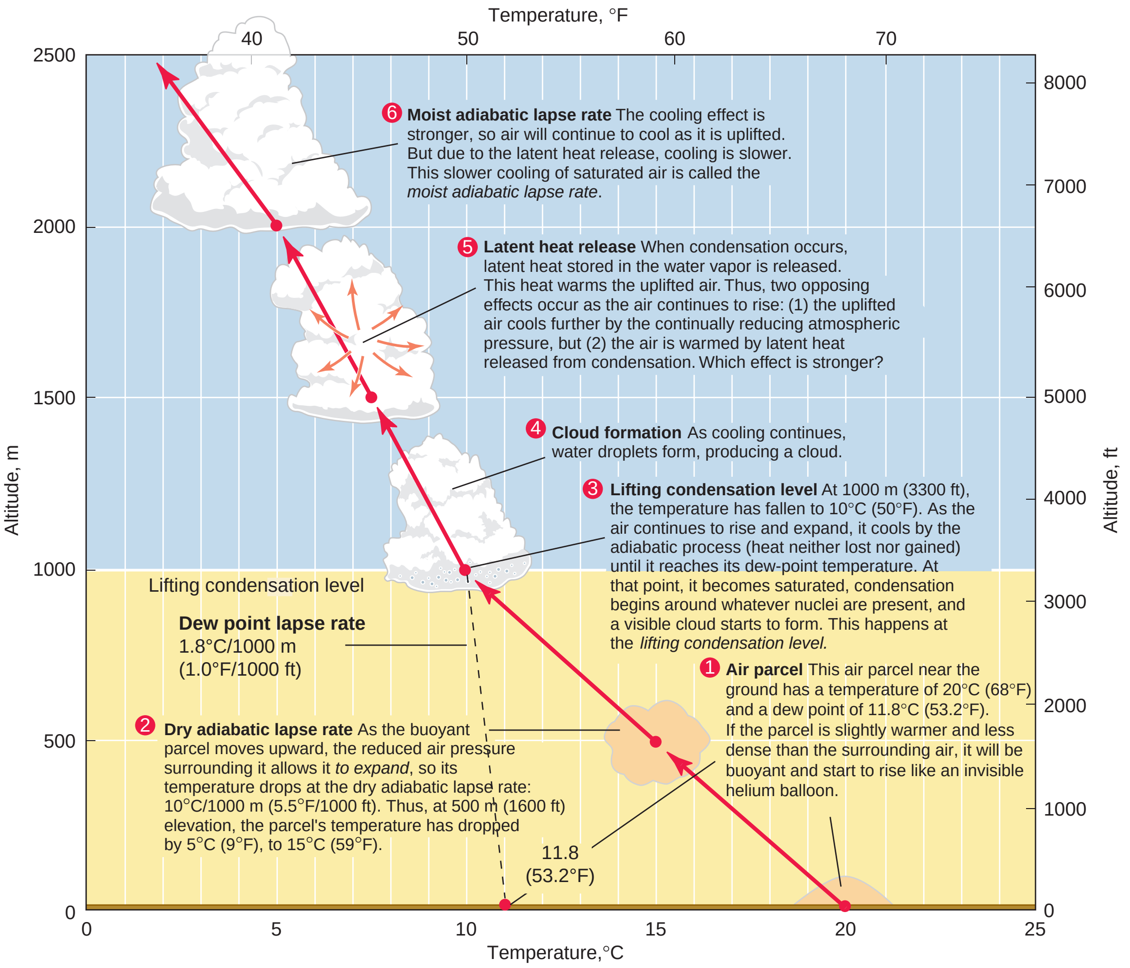
Rising air cools less rapidly when condensation is occurring, owing to the release of latent heat. This explains why the moist adiabatic cooling rate has a lesser value than the dry adiabatic cooling rate.

If the parcel of saturated air continues to rise, a new principle comes into effect—latent heat release. That is, when condensation occurs, latent heat is released by the condensing water molecules and warms the surrounding air molecules. In other words, two



4.9 Adiabatic cooling and heating

When air is forced to rise, it expands and its temperature decreases. When air is forced to descend, its temperature increases.



4.10 Adiabatic cooling in a rising parcel of air

Adiabatic decrease of temperature in a rising parcel of air leads to cooling, then to condensation of water vapor into water droplets and the formation of a cloud.

effects are occurring at once. First, the uplifted air is being cooled by the reduction in atmospheric pressure. Second, it is being warmed by the release of latent heat from condensation.

Which effect is stronger? As it turns out, the cooling effect is stronger, so the air will continue to cool as it is uplifted. However, because of the release of latent heat, the cooling will occur at a lesser rate. This cooling rate for saturated air is called the **moist adiabatic lapse rate** and ranges between 4 and 9°C per 1000 m (2.2–4.9°F per 1000 ft). Unlike the dry adiabatic lapse rate, which remains constant, the moist adiabatic lapse rate is variable because it depends on the temperature and pressure of the air and its moisture content. For most situations, however, we can use a value of 5°C/1000 m (2.7°F/1000 ft). In Figure 4.10, the moist adiabatic rate is shown as a slightly curving line to indicate that its value changes with altitude.

Keep in mind that as the air parcel becomes saturated and continues to rise, condensation is occurring. This condensation produces liquid droplets and solid ice particles that form clouds and eventually precipitation.

Clouds

Clouds are frequent features of the atmosphere. Views of the Earth from space show that clouds cover about half of the Earth at any given time. Low clouds reflect solar energy, thus cooling the Earth–atmosphere system, while high clouds absorb outgoing longwave radiation, thus warming the Earth–atmosphere system. One of the most familiar roles of clouds, however, is in producing precipitation.

A cloud consists of water droplets, ice particles, or a mixture of both. These form on tiny condensation nuclei, which are normally minute specks of sea salt or dust.

Clouds are made up of water droplets, ice particles, or a mixture of both, suspended in air. These particles are between 20 and 50 μm (0.0008–0.002 in.) in diameter. Cloud particles do not form in empty space. They need a tiny center of solid matter to grow around. This speck of matter is called a *condensation nucleus* and typically has a diameter of 0.1–1 μm (0.000004–0.00004 in.).

The surface of the sea is an important source of condensation nuclei. Droplets of spray from the crests of the waves are carried upward by turbulent air, shown in Figure 4.11. When these droplets evaporate, they leave behind a tiny residue of crystalline salt suspended in the air. This aerosol strongly attracts water molecules, helping to initiate cloud formation. Nuclei are also thrown into the atmosphere as dust in polluted air over cities, aiding condensation and the formation of clouds and fog.

If you ask, "What is the freezing point of water?" most people will reply that liquid water turns to ice at 0°C (32°F). This is true in everyday life, but when water is dispersed as tiny droplets in clouds, it behaves differently. Water in clouds can remain in the liquid state at temperatures far below freezing. In that case, we say the water is *supercooled*. In fact, clouds consist entirely of water droplets at temperatures down to about −12°C (10°F). As cloud temperatures drop below that value, ice crystals begin to appear. The coldest clouds, with temperatures below −60°C (−76°F), occur at altitudes above 12 km (40,000 ft) and are made up entirely of ice particles.

4.11 Cloud condensation nuclei

Cloud drops condense on small particulates called cloud *condensation nuclei*. Breaking or spilling waves in the open ocean, shown here from the deck of a ship, are an important source of condensation nuclei.

CLOUD FORMS

Anyone who has looked up at the sky knows that clouds come in many shapes and sizes (Figure 4.12). They range from the small, white, puffy clouds often seen in summer to the gray layers that produce a typical rainy day. Meteorologists name clouds by their vertical structure and the altitudes at which they occur. *Stratiform* clouds are blanket-like and cover large areas. A common type is *stratus*, a low cloud layer that covers the entire sky. Dense, thick stratus clouds can produce large amounts of rain or snow. Higher stratus clouds are referred to as *altostratus*. *Cirrus* clouds are high, thin clouds that often have a wispy or patchy appearance. When they cover the sky evenly, they form *cirrostratus*.

There are two major classes of clouds—stratiform (layered) and cumuliform (globular). Cumulonimbus clouds are dense, tall clouds that produce rain or thundershowers.

Cumuliform clouds are clouds with vertical development. The most common cloud of this type is the *cumulus* cloud, which is a globular cloud mass associated with small to large parcels of rising air starting near the surface. However, there are also *altocumulus*—individual, rounded clouds in the middle layers of the troposphere—and *cirrocumulus*—cloud rolls or ripples in the upper portions of the troposphere.

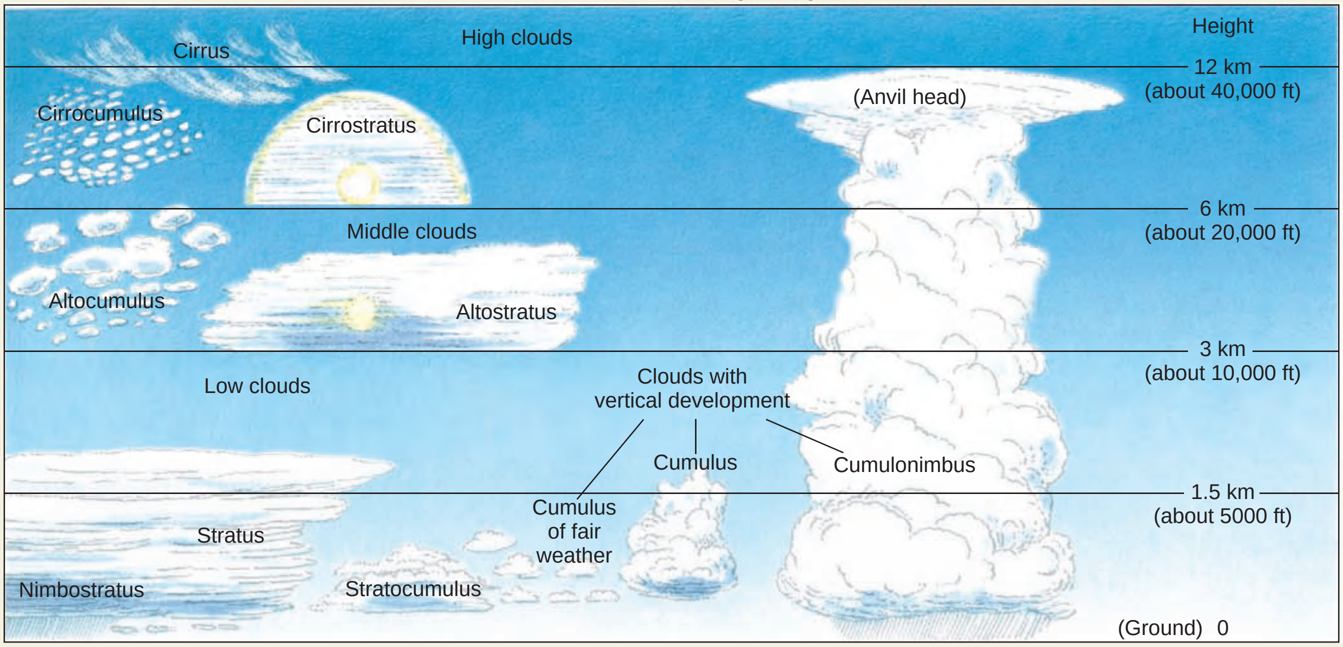
Nimbus clouds are clouds that produce rainfall. Thus, *nimbostratus* is a thick, flat, rain cloud, and *cumulonimbus* is a cumulus rain cloud.

FOG

Fog is simply a cloud layer at or very close to the Earth's surface. For centuries, fog at sea has been a navigational hazard, increasing the danger of ship collisions and groundings. In our industrialized world, it can be a major environmental hazard. Dense fog on high-speed highways can cause chain-reaction accidents, sometimes involving dozens of vehicles. When flights are shut down or delayed by fog, it is inconvenient to passengers and costs airlines money. Polluted fogs, like London's "pea-soupers" in the early part of the twentieth century, can injure urban dwellers' lungs and take a heavy toll in lives.

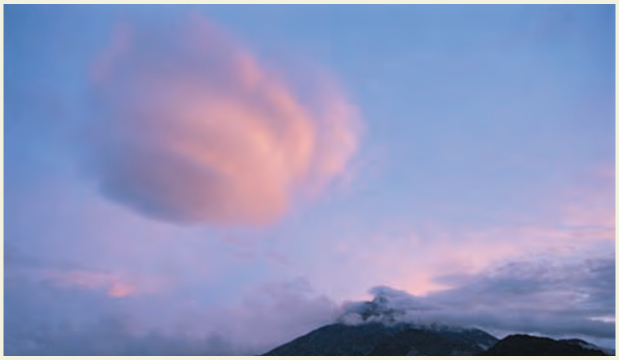
One type of fog, known as *radiation fog*, forms at night when the temperature of the air layer at the ground level falls below the dew point. This kind of fog forms in valleys and low-lying areas, particularly on clear winter nights when radiative cooling is very strong.

4.12 Cloud gallery



▲ **Cloud families and types** Clouds are grouped into families on the basis of height and vertical development. Individual cloud types are named according to their form. (Photos from National Geographic Image Collection.)

▲ **Cirrus** High, thin, wispy clouds drawn out into streaks are cirrus clouds. They are composed of ice crystals and form when moisture is present high in the air.



▲ **Lenticular cloud** A lenticular, or lens-shaped, cloud forms as moist air flows up and over a mountain peak or range.

▼ **Cumulus** Puffy, fair-weather cumulus clouds fill the sky above a prairie.

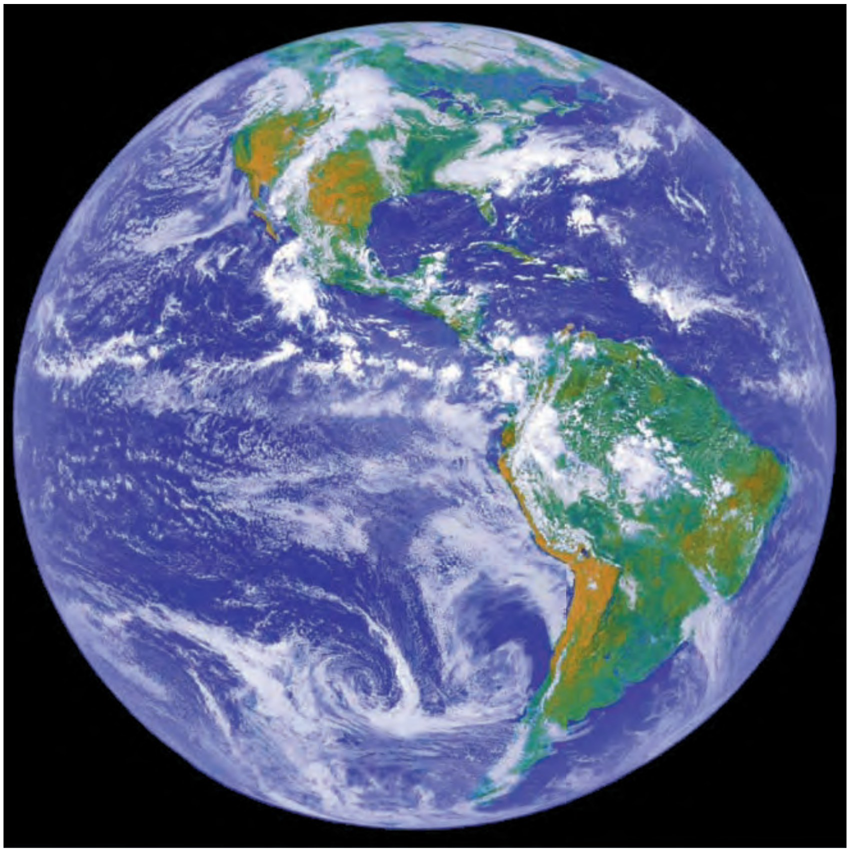
▼ **Altocumulus** High cumulus clouds, as photographed near sunset in Boston.

FOCUS ON REMOTE SENSING

Observing Clouds from GOES

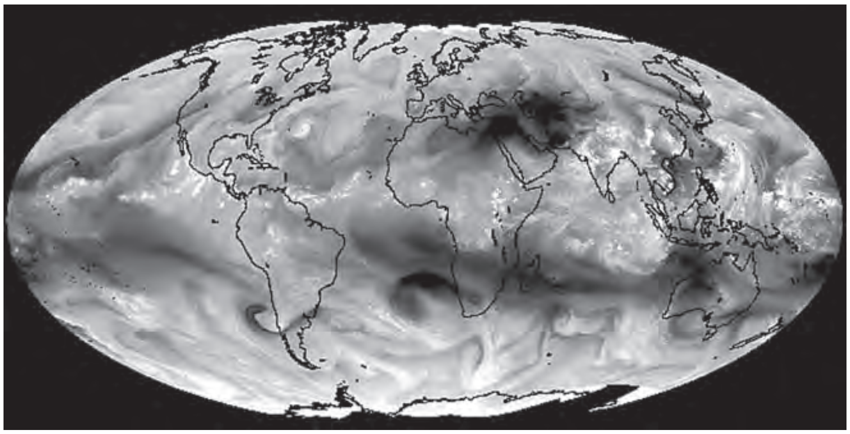
Some of the most familiar images of Earth acquired by satellite instruments are those of the *Geostationary Operational Environmental Satellite (GOES)* system. Images from the GOES series of satellites have been in constant use since 1974. The primary mission of the GOES series is to view cloud patterns and track weather systems by providing frequent images of the Earth from a consistent viewpoint in space provided by its geostationary orbit.

Altogether, 12 GOES satellites in three major generations have been placed in orbit since 1975. They have maintained a nearly continuous stream of images from two points on the Equator that bracket North America at latitudes 75° W and 135° W. From 135° W (GOES-West), Pacific storm systems can be tracked as they approach the continent and move across the western states and provinces. From 75° W (GOES-East), weather systems are observed in the eastern part of the continent as they move in from the west. GOES-East also observes the tropical Atlantic, allowing identification of tropical storms and hurricanes as they form and move eastward toward the Caribbean Sea and southeastern United States.



4.13 Earth from GOES-8

In this near-noon image from GOES-8 on September 2, 1994 the entire side of the globe nearest to the satellite is illuminated. Vegetated areas appear green, while semiarid and desert landscape appear yellow-brown. Clouds are white and ocean waters are lavender blue.



4.14 Water vapor composite image

Areas of high atmospheric water vapor content are bright in this global image, prepared by merging data from GOES and other geostationary satellites. The brightest areas show regions of active precipitation, while dark areas show low water vapor content. The bright patch in the Atlantic off the Carolina coast is Hurricane Alberto.

4.15 Fog

A layer of advection fog along the Big Sur coast of California, south of San Francisco. A patch of fog has burned off in the center embayment, revealing the water surface and a pocket beach.

EYE ON THE LANDSCAPE **What else would the geographer see?** The gently sloping terrace surfaces (A), used as hay fields, were formed by wave abrasion in the near-shore zone and have now been uplifted well above present sea level. The uplift is the result of tectonic activity just off the coast, where the Pacific crustal plate and the American plate are moving in different directions. Note also the gullying and rapid erosion of the cliff (B). The coast ranges of Big Sur receive abundant precipitation, as moist, eastward-moving air is raised over the mountain barrier. The soft sediments are easily eroded by heavy rains, keeping vegetation from stabilizing the slope. Loose sediment falls to the shoreline and is carried offshore by coastal currents.

Another fog type—*advection fog*—results when a warm, moist air layer moves over a cold surface. As the warm air layer loses heat to the surface, its temperature drops below the dew point, and condensation sets in. Advection fog commonly occurs over oceans where warm and cold currents occur side by side. When warm, moist air above the warm current moves over the cold current, condensation occurs. Fogs form in this way off the Grand Banks of Newfoundland because here the cold Labrador current comes in contact with the warmer waters of the Gulf Stream.

Advection fog is also frequently found along the California coast, as seen in Figure 4.15. It forms within a cool marine air layer in direct contact with the colder water of the California current, and it is frequently carried ashore by westerly winds. Similar fogs are also found on continental west coasts in the tropical latitude zones, where cool, equatorward currents lie parallel to the shoreline.

Precipitation

FORMATION OF PRECIPITATION

Clouds are the source of precipitation—the process that provides the fresh water essential for most forms of terrestrial life. Precipitation can form in two ways. In warm clouds, fine water droplets condense, collide, and coalesce into larger and larger droplets that can fall as rain. In colder clouds, ice crystals form and grow in a cloud that contains a mixture of both ice crystals and water droplets.

Raindrops form in warm clouds by collision and coalescence. Snow forms in cool clouds as water droplets evaporate and are deposited as ice crystals.

The first process occurs when saturated air rises rapidly and cooling forces additional condensation, as shown in Figure 4.16. For raindrops in a warm cloud, the updraft of rising air first lifts tiny suspended cloud droplets upward. By collisions with other droplets, some grow in volume. These larger droplets collide with other small droplets and continue to grow. Note that a droplet is kept aloft by the force of the updraft on its surface, and as the volume of each droplet increases, so does its weight. Eventually, the downward gravitational force on the drop exceeds the upward force, and the drop begins to fall. Now moving in the opposite direction to the fine cloud droplets, the drop sweeps them up and continues to grow. Collisions with smaller droplets can also split drops, creating more drops that can continue to grow in volume. Eventually, the drop falls out of the cloud, cutting off its source of growth. On its way to the Earth, it may suffer evaporation and decrease in size or even disappear.

Within cool clouds, snow is formed in a different way, known as the *Bergeron process* (Figure 4.17). Cool clouds are a mixture of ice crystals and supercooled water droplets. The ice crystals take up water vapor and grow by deposition. At the same time, the supercooled water droplets lose water vapor by evaporation and shrink. In addition, when an ice crystal collides with a droplet of supercooled water, it freezes the droplet. The ice crystals then coalesce to form ice particles, which can become heavy enough to fall from the cloud.

PRECIPITATION PROCESSES

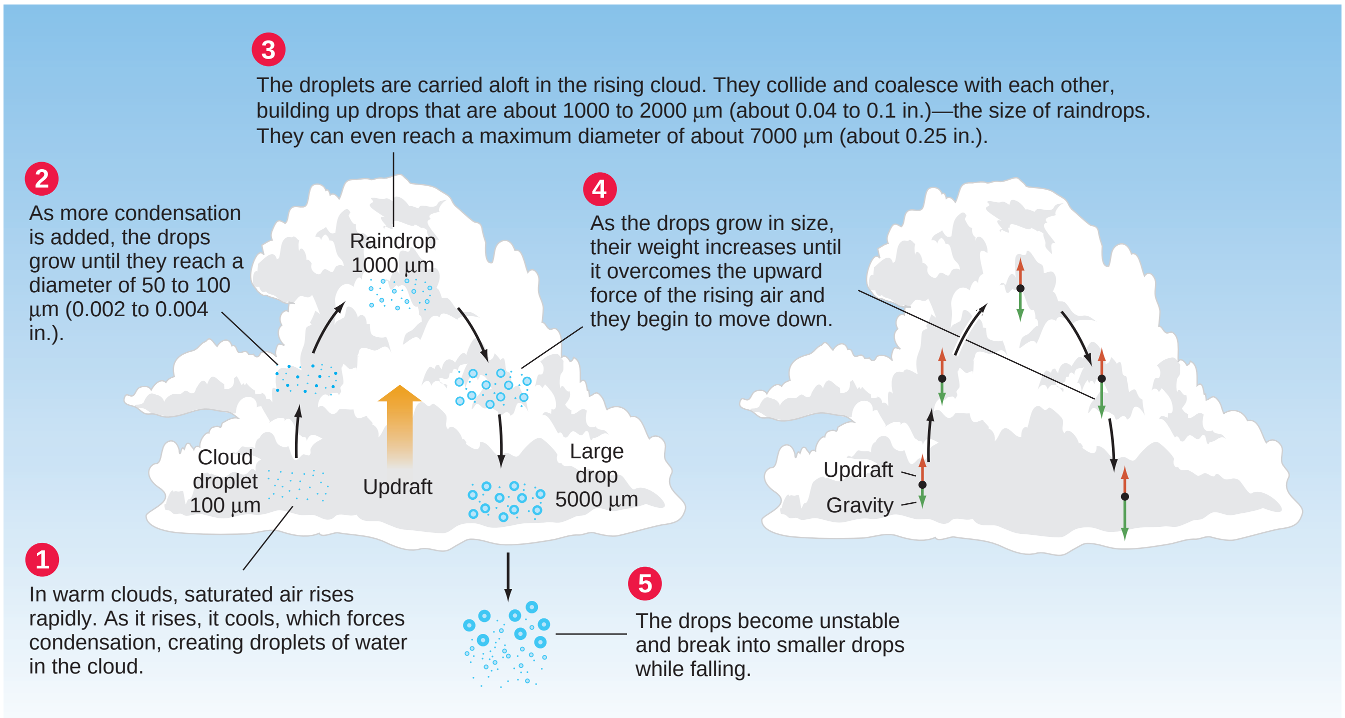
Air that is moving upward is chilled by the adiabatic process, which leads, eventually, to precipitation. However, one key piece of the precipitation puzzle is still missing—what causes air to move upward in the first place?

Air can move upward in four ways. In this chapter, we discuss the first two: *orographic precipitation* and *convective precipitation*. A third way for air to be forced upward is through the movement of air masses and their interaction with one another. This process occurs as spiral circulations of air, known as cyclones, leading to *cyclonic precipitation*. The fourth way is by *convergence*, in which air currents converge together at a location from different directions, forcing air at the surface upward. We will return to these last two types of motion in Chapters 5 and 6.

Four types of precipitation are orographic, convective, cyclonic, and convergent.

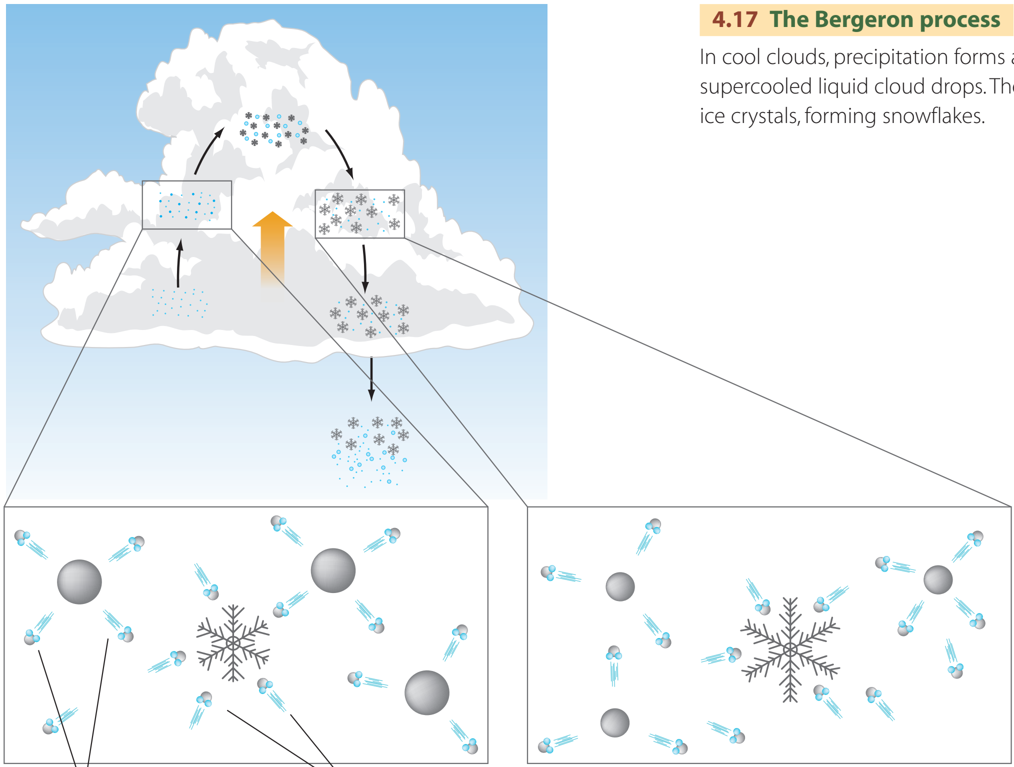
OROGRAPHIC PRECIPITATION

Orographic precipitation occurs when a through-flowing current of moist air is forced to move upward over a mountainous barrier. The term *orographic* means "related to mountains." To understand the orographic precipitation process, you can think of what happens



4.16 Rain formation in warm clouds

This type of precipitation formation occurs in convectional precipitation in warm clouds typical of the equatorial and tropical zones.



4.17 The Bergeron process

In cool clouds, precipitation forms as water vapor evaporates from supercooled liquid cloud drops. The water vapor is then deposited on ice crystals, forming snowflakes.

to a mass of air moving up and over a mountain range (Figure 4.18). As the moist air is lifted, it is cooled, and condensation and rainfall occur. Passing over the mountain summit, the air descends the leeward slopes of the range, where it is compressed and warmed. Because the air is much warmer and much drier than when it started, little precipitation occurs in these regions, producing a **rain shadow** on the far side of the mountain.

In orographic precipitation, moist air is forced up and over a mountain barrier, producing cooling, condensation, and precipitation.

California's rainfall patterns provide an excellent example of orographic precipitation and the rain shadow effect. Figure 4.19 contains maps of California's mean annual precipitation that use lines of equal precipitation called *isohyets*. These lines clearly show the orographic effect on air moving across the mountains of California into America's great interior desert zone, which extends from eastern California and across Nevada.

GEODISCOVERIES **Orographic Precipitation**

View this animation to see how moist air flows over a mountain barrier, creating precipitation and a rain shadow.

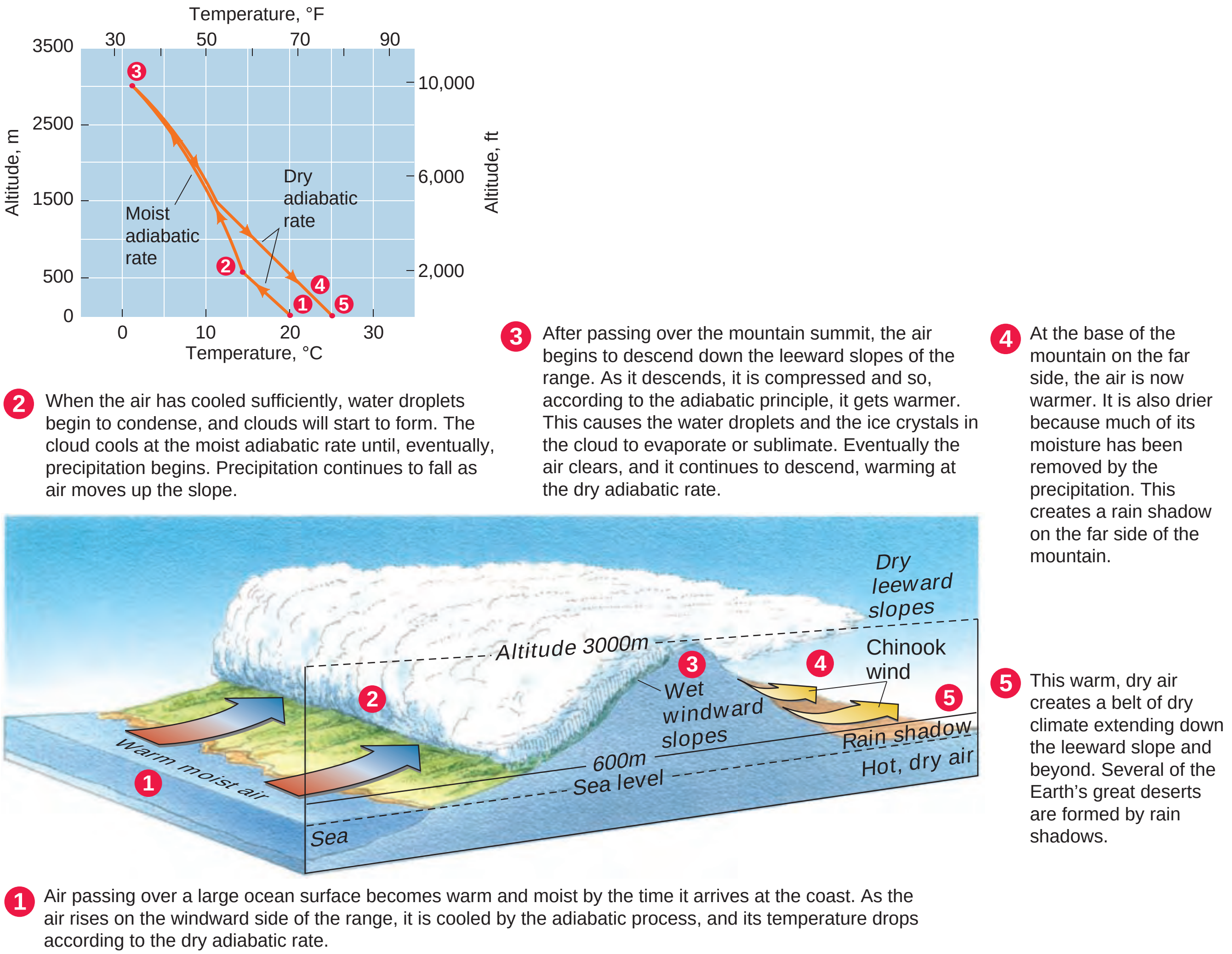
CONVECTIVE PRECIPITATION

Air can also be forced upward through convection, leading to **convective precipitation**. In this process, strong updrafts occur within convection cells—vertical columns of rising air that are often found above warm land surfaces. Air rises in a convection cell because it is warmer, and therefore less dense, than the surrounding air.

In convective precipitation, moist air is warmed at the surface, expands, becomes less dense than surrounding, cooler air, and is buoyed upward. At the lifting condensation level, clouds begin to form.

The convection process begins when a surface is heated unequally. Think of an agricultural field surrounded by a forest, for example. The field surface is largely made up of bare soil with only a low layer of vegetation, so under steady sunshine the field will be warmer than the adjacent forest. This means that as the day progresses, the air above the field will grow warmer than the air above the forest.

The density of air depends on its temperature—warm air is less dense than cooler air. The hot-air balloon operates on this principle. The balloon is open at the bottom,



4.18 Orographic precipitation

and in the basket below, a large gas burner forces heated air into the balloon. Because the heated air is less dense than the surrounding air, the balloon rises. The same principle will cause a bubble of air to form over the field, rise, and break free from the surface, as in Figure 4.20.

As the bubble of air rises, it is cooled adiabatically, and its temperature will decrease as it rises according to the dry or moist adiabatic lapse rate. The temperature of the surrounding air will normally decrease with altitude as well, but at the environmental lapse rate. For convection to occur, then, the temperature of the air bubble must always be warmer than the temperature of the surrounding atmosphere, even as it rises. This means that the environmental temperature must decrease more rapidly with altitude than the rising air parcel's temperature.

GEODISCOVERIES Convective Precipitation
This video lets you watch cumulus clouds form and grow into thunderheads as it explains the process of convective precipitation.

UNSTABLE AIR

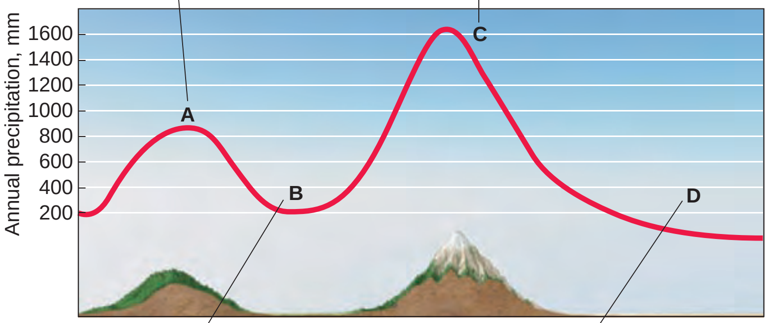
Another way to state this relationship is that the environmental lapse rate must be greater than the dry or moist adiabatic lapse rates. Air with this characteristic is referred to as **unstable air**. Figure 4.21 shows how to determine whether the atmosphere in a given region is able to support convection and precipitation. If the environmental lapse rate is greater than the dry adiabatic rate, the air is unstable. If it is less than the moist adiabatic rate, it is *stable*. Between those two values, the air is *conditionally stable*.

Figure 4.22 is a diagram of convection in unstable air. At first, the air parcel rises at the dry adiabatic rate. Above the

Unstable air—warm, moist, and heated by the surface—can produce abundant convective precipitation. It is typical of hot summer air masses in the central and southeastern United States.

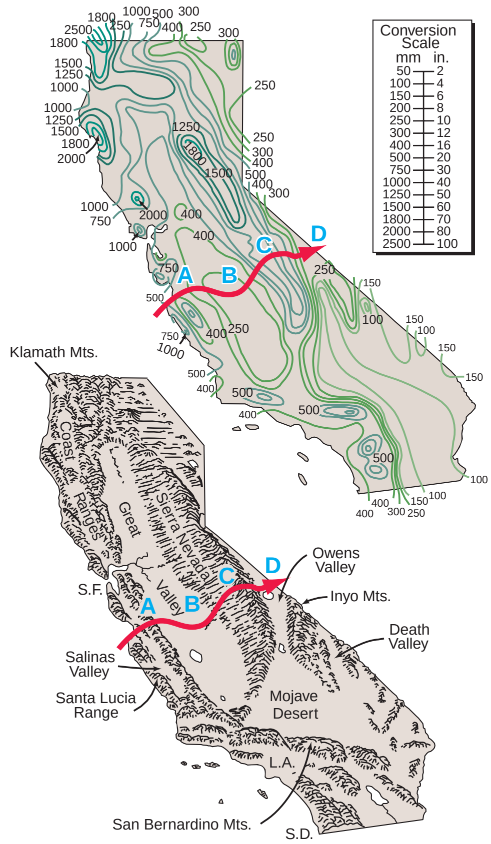
A Coastal ranges Prevailing westerly winds bring moist air in from the Pacific Ocean, first over the coast ranges of central and northern California, depositing rain on the ranges.

C Sierra Nevada The air continues up and over the great Sierra Nevada, whose summits rise to 4200 m (about 14,000 ft) above sea level. Heavy precipitation, largely in the form of winter snow, falls on the western slopes of these ranges and nourishes rich forests.



B Central valley After rain is deposited on the coast ranges, the air descends into the broad Great Valley. Precipitation is low here, averaging less than 250 mm (10 in.) per year.

D Interior desert Passing down the steep eastern face of the Sierra Nevada, the air descends quickly into the Owens Valley. Adiabatic heating warms and dries the air, creating a rain shadow desert. In the Owens Valley, annual precipitation is less than 100 mm (4 in.).

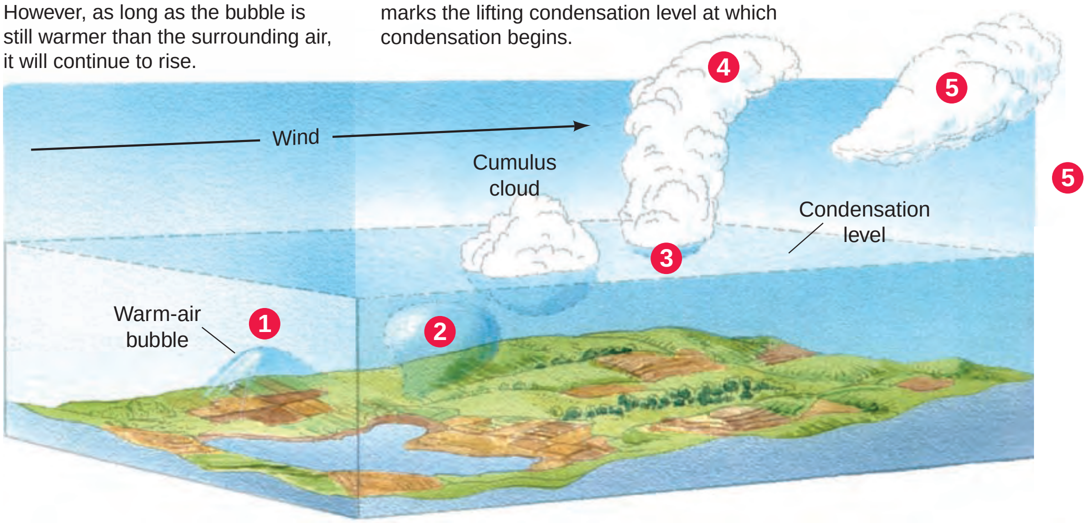


4.19 Orographic precipitation effects in California

3 Condensation If the bubble remains warmer than the surrounding air and uplift continues, adiabatic cooling chills the bubble to the dew point, and condensation sets in. The rising air column becomes a puffy cumulus cloud. The flat base of the cloud marks the lifting condensation level at which condensation begins.

2 Adiabatic cooling As the bubble of air rises, it is cooled adiabatically and its temperature decreases as it rises. However, as long as the bubble is still warmer than the surrounding air, it will continue to rise.

4 Continued convection The bulging "cauliflower" top of the cloud is the top of the rising warm-air column pushing into higher levels of the atmosphere.

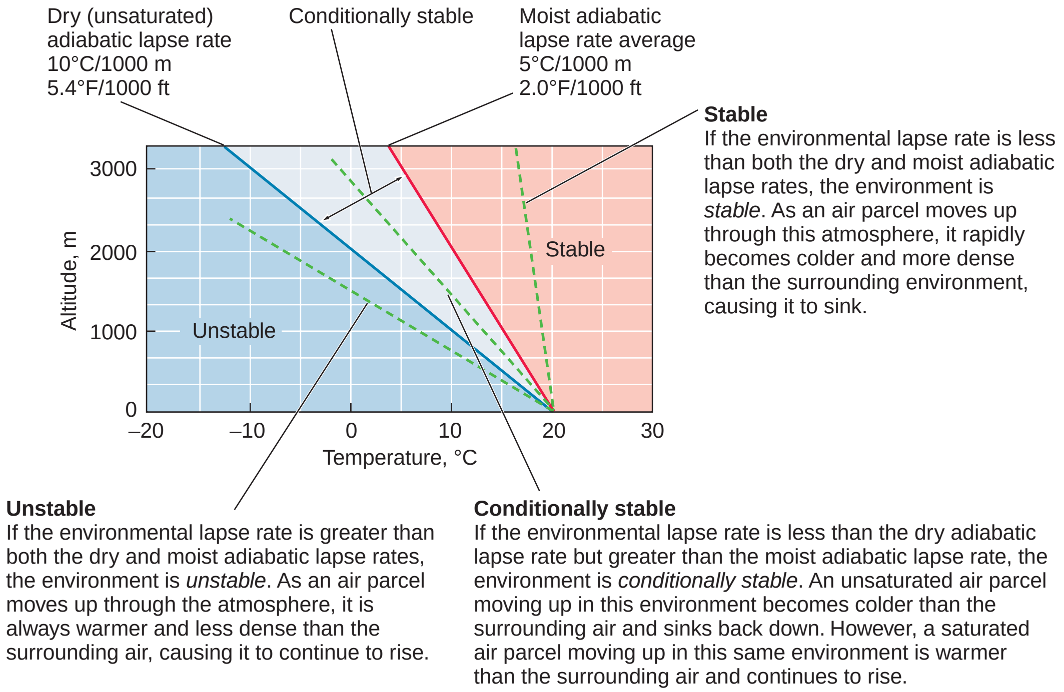


5 Dissipation A small cumulus cloud typically encounters winds aloft that mix it with the local air, reducing the temperature difference and slowing the uplift. After drifting some distance downwind, the cloud evaporates.

1 Surface heating Heated air is less dense than the surrounding air, causing a bubble of warm air to form over the field, then rise and break free from the surface.

4.20 Formation of a cumulus cloud

A bubble of heated air rises above the lifting condensation level to form a cumulus cloud.



4.21 Determining stability

lifting condensation level, the parcel cools at the moist adiabatic rate. But because the surrounding air is always cooler than the parcel, it rises high in the atmosphere, forming a tall cumulus cloud. If uplift and condensation persist, it may grow into a rain-producing cumulonimbus cloud.

The key to the convective precipitation process is latent heat release. When water vapor condenses into droplets or ice particles, it releases latent heat to the air parcel. This heat helps keep the parcel warmer than the surrounding air, fueling the convection process and driving the parcel ever higher.

When the parcel reaches a high altitude, most of its water will have condensed. As adiabatic cooling continues, less latent heat will be released, so the uplift weakens. Eventually, uplift stops because the energy source, latent heat, is gone. The cell dies and dissipates into the surrounding air.

Unstable air masses are often found over the central and southeastern United States in the summer. Summer weather patterns sweep warm, humid air from the Gulf of Mexico over this region, and the intense summer insolation strongly heats the air layer near the ground, producing a steep environmental lapse rate. Thunderstorms are very common in these moist and unstable air masses (Figure 4.23).

Unstable air is also commonly found in the equatorial and tropical zones. Here, convective showers and thundershowers are frequent. At these low latitudes, much of the orographic rainfall is in the form of heavy showers and thundershowers produced by convection. The forced ascent of unstable air up a mountain slope easily produces rapid condensation, which then triggers the convection process.

Types of Precipitation

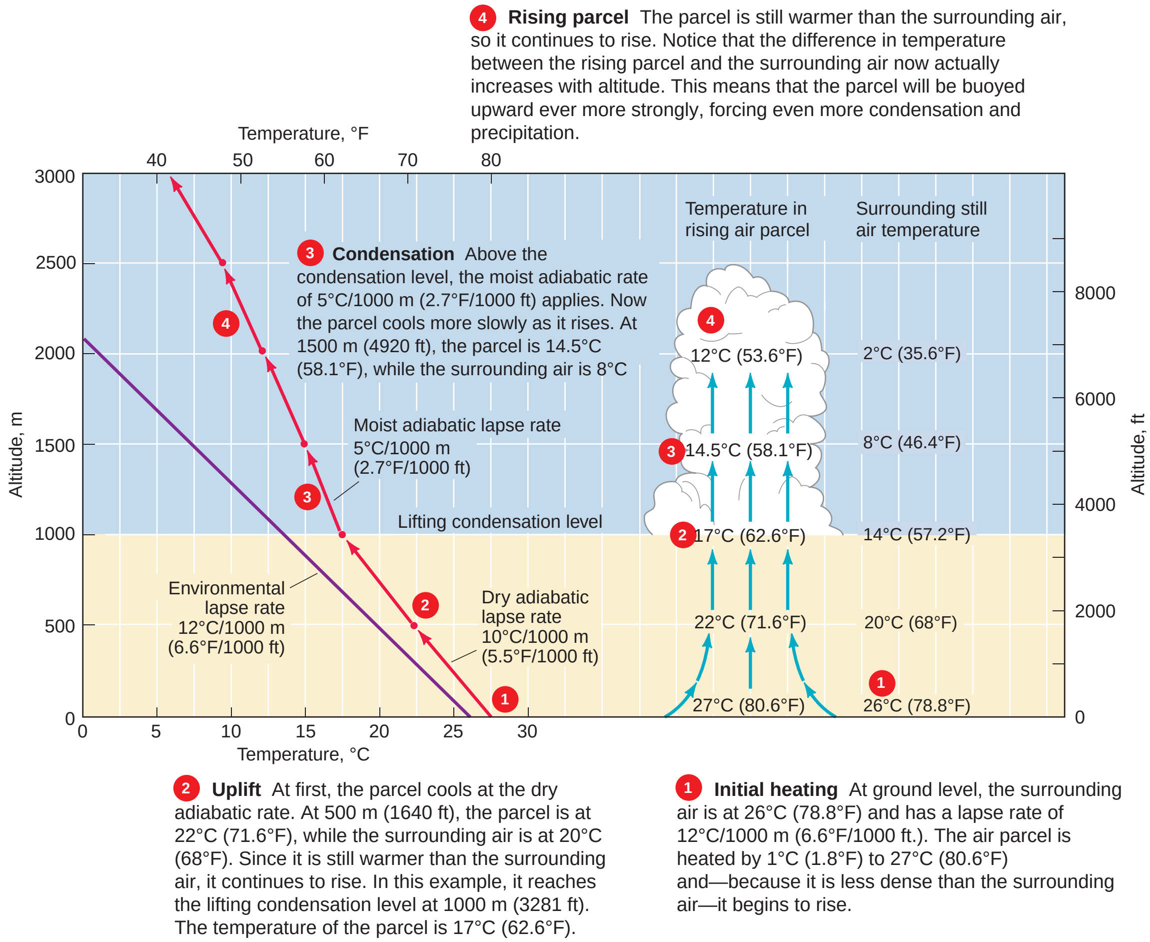
Precipitation consists of liquid water drops and solid crystals that fall from the atmosphere and reach the ground. This precipitation can take several different forms.

RAIN

Rain is precipitation that reaches the ground as liquid water. Raindrops can form in warm clouds as liquid water, which through collisions can coalesce with other drops and grow large enough to fall to Earth. They can form through other processes as well. For example, solid ice, in the form of snow or hail, can also produce rain by melting if it falls through a layer of warm air.

Types of precipitation include rain, snow, sleet and freezing rain, and hail.

To fall from the sky and reach the ground, raindrops usually have to grow larger than 0.2 mm (0.008 in.). At these sizes, we refer to the drops as *mist* or *drizzle*. Once the drops reach 0.5 mm (0.02 in.), they are termed



4.22 Convection in unstable air

When the air is unstable, a parcel of air that is heated enough to rise will continue to rise to great heights.

4.23 Cumulus clouds over South Dakota

A gathering of storm clouds forms over the Badlands region of South Dakota. Convection within these clouds gives them their vertical cumulus structure (National Geographic Image Collection).

raindrops. Typically, raindrops can only have a maximum size of 5–8 mm (0.2–0.3 in.); drops any larger than that become unstable and break into smaller drops as they fall through the atmosphere.

SNOW

Snow forms as individual water vapor molecules are deposited on existing ice crystals. If these ice crystals are formed entirely by deposition, they take the shape of snowflakes with their characteristic intricate crystal structure. However, most particles of snow have endured collisions and coalesce with each other and with supercooled water drops. As they do so, they lose their shape and can become simple lumps of ice.

Eventually, whether they are intricate snowflakes or accumulations of ice and supercooled water drops, these ice crystals become heavy enough to fall from the cloud. By the time this precipitation reaches the ground, it may have changed form. Snow produced in cold clouds reaches the ground as a solid form of precipitation if the underlying air layer is below freezing. Otherwise, the snow melts and arrives as rain.

SLEET AND FREEZING RAIN

Perhaps you have experienced an *ice storm*. Ice storms occur when the ground is frozen and the lowest air layer is also below freezing. Actually, ice storms are more accurately named "icing" storms because it is not ice that is falling but supercooled rain. Rain falling through the cold air layer is chilled and freezes onto ground surfaces as a clear, slippery glaze, making roads and sidewalks extremely hazardous. Ice storms cause great damage, especially to telephone and power lines and to tree limbs pulled down by the weight of the ice (Figure 4.24).

HAIL

Hailstones are formed by the accumulation of ice layers on ice pellets that are suspended in the strong updrafts of thunderstorms (Figure 4.25). As these ice pellets—called *graupel*—move through subfreezing regions of the atmosphere, they come into contact with supercooled liquid water droplets, which subsequently freeze to the pellets in a thin sheet. This process, called *accretion*, results in a buildup of concentric layers of ice around each pellet, giving it its typical ball-like shape.

With each new layer, the ball of ice—now called *hail*—gets larger and heavier. When it becomes too heavy for the updraft to support, it falls to Earth. When the updrafts are extremely strong, the hail remains aloft, slowly accumulating more mass and getting larger. In that case, hailstones can reach diameters of 3–5 cm (1.2–2.0 in.).

4.24 Ice storm

When rain falls into a surface layer of below-freezing air, clear ice coats the ground. The weight of the ice brings down power lines and tree limbs. Driving is particularly hazardous. In January of 1998, heavy rain fell into a layer of colder air causing ice accumulations of 10 cm (4 in.) or more over a large area of northern New England and Quebec. All outdoor surfaces, including trees and electric lines, were coated in ice. Watertown, New York, 1998.

MEASURING PRECIPITATION

Precipitation is recorded as a depth that falls during a certain time—for example, as millimeters or inches per hour or per day. A millimeter of rainfall would cover the ground to a depth of 1 mm if the water did not run off or sink into the soil.

Rainfall is measured with a *rain gauge* (Figure 4.26). This simple meteorological instrument is constructed from a narrow cylinder with a wide funnel at the top. The funnel gathers rain from a wider area than the mouth of the cylinder, so the cylinder fills more quickly. The water level gives the amount of precipitation, which is read on a graduated scale.

For meteorological records, snowfall is measured by the amount of liquid water it yields when melted. We can also measure snowfall by depth in millimeters or inches. Ordinarily, a 10-mm (or 10-in.) layer of snow is assumed to be equivalent to 1 mm (or 1 in.) of rainfall, but this ratio may range from 30 to 1 in very loose snow to 2 to 1 in old, partly melted snow.

Precipitation as water droplets or snow particles can be identified using *radar*, a technology in which a beam of radio waves is sent out from a transmitter, strikes the water particles, and then returns to a receiver. By measuring the intensity of the return beam and observing the time it takes for the beam to travel and return, it is possible to determine the intensity of precipitation and its location. Images obtained by scanning weather radars are widely used and familiar to anyone who routinely watches weather forecasts on television (Figure 4.27).

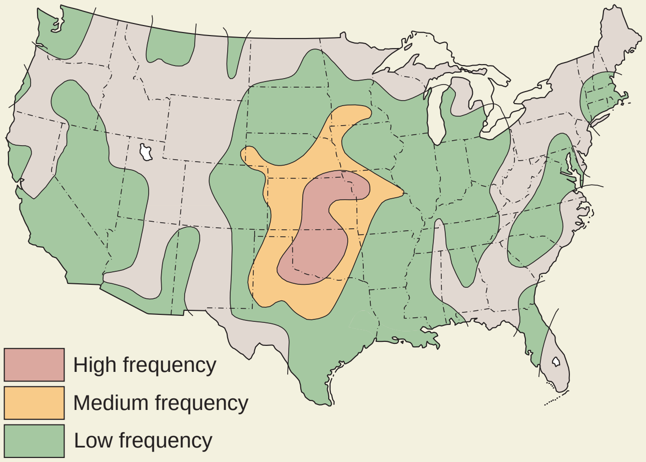
Thunderstorms

A **thunderstorm** is any storm that produces thunder and lightning. At the same time, thunderstorms can also produce high winds, hail, and tornadoes. They are typically associated with cumulus clouds that indicate the presence of rising, unstable air. It is this rising motion that produces the characteristic rainfall and lightning that accompany thunderstorms. Thunderstorms can range from fairly isolated, short-lived storms, sometimes called *air-mass thunderstorms*, to massive, well-organized complexes of storms, called *mesoscale convective systems*.

4.25 Hail

▲ **Hailstones** Fresh hailstones, up to about 1 cm (0.4 in.) in diameter.

▼ **Frequency of severe hailstorms** As shown in this map of the 48 contiguous United States, severe hailstorms are most frequent in the midwestern plains states of Oklahoma and Kansas. A severe hailstorm is defined as a local convective storm producing hailstones equal to or greater than 1.9 cm (0.75 in.) in diameter.



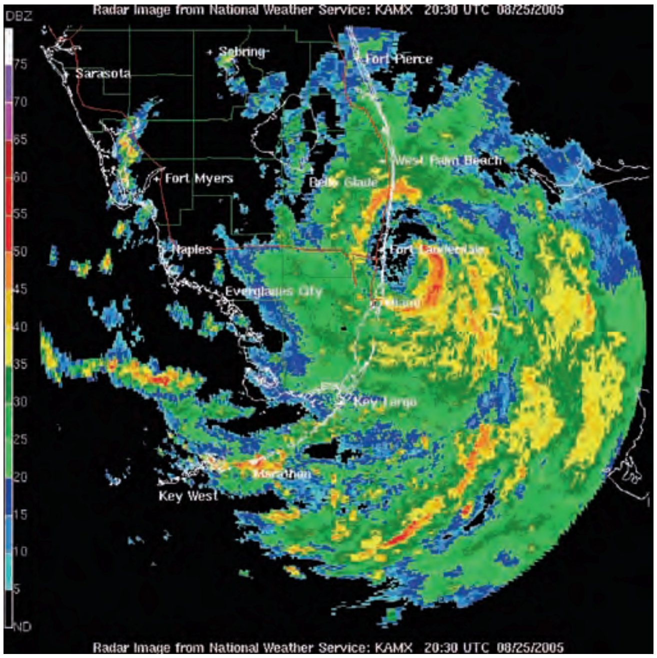
▲ **Hailstorm in progress, Santa Cruz County, Arizona** The white streaks in this photo are marble-sized hailstones. Although the hail is falling from a cloud directly overhead, the low afternoon Sun still illuminates the foreground scene.

EYE ON THE LANDSCAPE **What else would the geographer see?** This is the dry season in Arizona, judging from the dry, brown grass and the tough evergreen shrubs (A). The hailstorm is probably the result of the southwest monsoon, which brings moist air to the region in July and August after a nearly rainless spring and summer. Semiarid grasslands like this are called steppes.

4.26 Rain gauges

▶ This rain gauge consists of two clear plastic cylinders, here partly filled with red-tinted water. The inner cylinder receives rainwater from the funnel top. When it fills, the water overflows into the larger, outer cylinder.

▲ Shown here are five different types of rain gauges installed in Arvada, Colorado. By placing the gauges next to one another, it is possible to compare how their precipitation measurements differ.



4.27 Weather radar

In this weather radar image, the eye of Hurricane Katrina is about to pass over southern Florida on August 25, 2005. Weather radars scan the horizon in a circular pattern, sending out short pulses of radio waves that are reflected back by raindrops and ice crystals. By measuring the intensity of the return pulse and the delay between the time of sending the pulse and its return, the radar creates a map of precipitation within the radar's view. The radar can also detect the height of storm clouds by broadcasting a series of scans at progressively higher angles above the horizon, creating a three-dimensional picture of precipitation within the area. Using the principle of the Doppler effect, the weather radar can also measure cloud motion, which can be used to detect tornadoes.

Air-mass thunderstorms are isolated thunderstorms generated by daytime heating of the land surface. They occur in warm, moist air that is often of maritime origin. Triggered by solar heating of the land, they start, mature, and dissipate within an hour or two. Formation stops at night, since surface heating is no longer present.

A thunderstorm is an intense local storm associated with a tall cumulonimbus cloud in which there are strong updrafts of air. Thunderstorms can produce both hail and cloud-to-ground lightning.

The typical life cycle of an air-mass thunderstorm involves three stages of development (Figure 4.28). In the *cumulus stage*, unequal surface heating causes air parcels to rise. Isolated cumulus clouds form as the parcels reach and pass through the lifting condensation level. At first, these clouds dissipate as they mix with the surrounding dry air, which evaporates the cloud water droplets. However, this process cools the air aloft and raises its moisture content, creating instability.

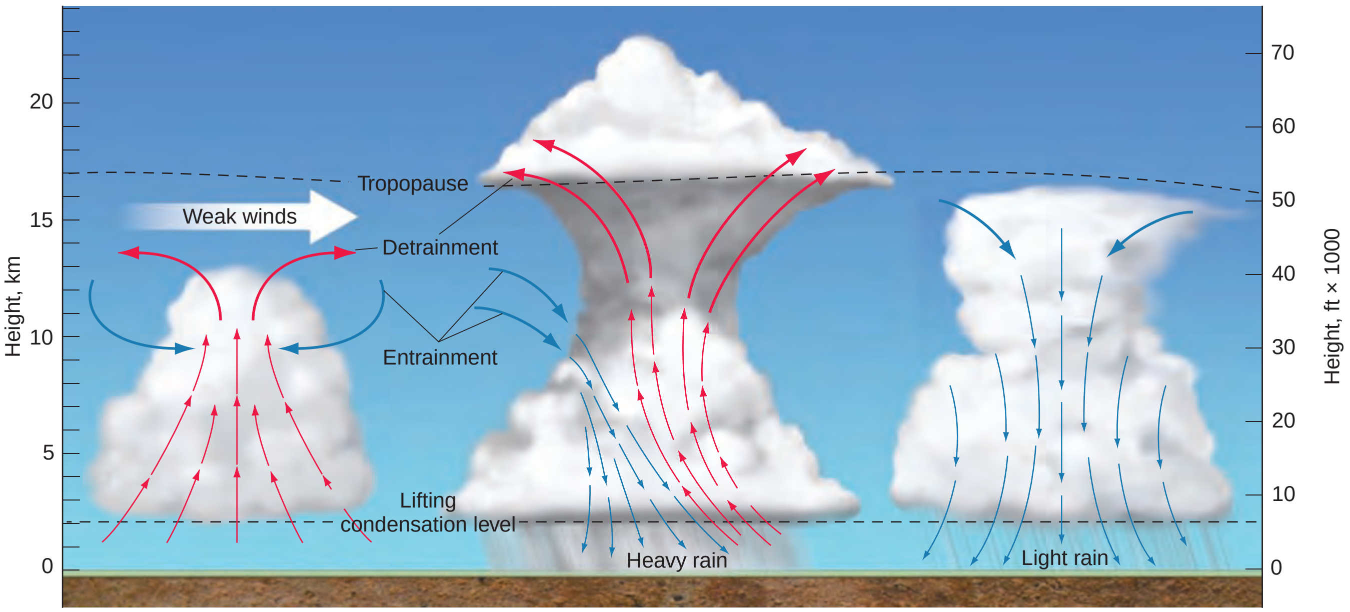
As instability increases, convection reaches greater heights and soon a thunderstorm develops. In this *mature stage*, there are both updrafts and downdrafts. The updrafts carry the cloud high into the atmosphere, where upper-level winds draw the cloud downwind to create a characteristic *anvil cloud*.

Downdrafts are created when water droplets become large enough to fall through the cloud and drag the surrounding air downward. Downdrafts can also be caused by the movement of cooler, drier surrounding air into the cloud from the upwind side. This cooler air tends to sink. It is further chilled by the evaporation of cloud water droplets, increasing the sinking motion. At ground level, the downdraft spreads forward, forcing more warm moist air up and into the cloud.

Eventually, the stabilizing effects of the movement of surrounding air into the cloud overcome the destabilizing effects of convection. Widespread downdrafts form that inhibit upward motion and suppress latent heat release, cutting off the power source of the storm. This is the *dissipating stage*.

Air-mass thunderstorms are initiated by surface heating during the day. They start, mature, and dissipate within an hour or two. Formation stops at night, since surface heating is no longer present.

Lightning is also generated by convection cell activity. It occurs when updrafts and downdrafts cause positive and negative static charges to build up within different



▲ **Cumulus stage** Vertical motions are limited by mixing with cool, dry environmental air aloft. But the mixing adds water droplets that evaporate and cool the surrounding air, creating instability.

▲ **Mature stage** In this stage, there are well-organized updrafts and downdrafts. Updrafts, which can reach as high as the tropopause, spread out to form an anvil cloud. Downdrafts are created by falling precipitation and entrainment of cooler, drier environmental air.

▲ **Dissipating stage** Dissipation occurs when cool, dry environmental air mixes into the cloud, inhibiting convection and latent heat release.

4.28 Stages in the development of an air-mass thunderstorm

The three development stages of an air-mass thunderstorm are the cumulus, mature, and dissipating stages. Each stage has characteristic vertical winds and precipitation.

regions of the cloud. Lightning is a great electric arc—a series of gigantic sparks—passing between differently charged parts of the cloud mass or between the cloud and the ground. The electric arc heats the atoms of the air along its path, causing an explosive expansion and producing the sound we hear as thunder.

SEVERE THUNDERSTORMS

Severe thunderstorms persist longer than air-mass thunderstorms and have higher winds. They often produce hail or even tornadoes. Although they may start as simple air-mass thunderstorms, they reach a mature stage and then intensify rather than dissipate. In the severe thunderstorm, large amounts of cooler, drier environmental air enter the cloud from the upwind side, creating a strong downdraft (Figure 4.29). As the downdraft spreads out in front of the storm, it creates a *gust front*. The advancing air pushes large volumes of moist surface air upward, feeding the convection. A distinctive *roll cloud* can form that is visible as the storm approaches.

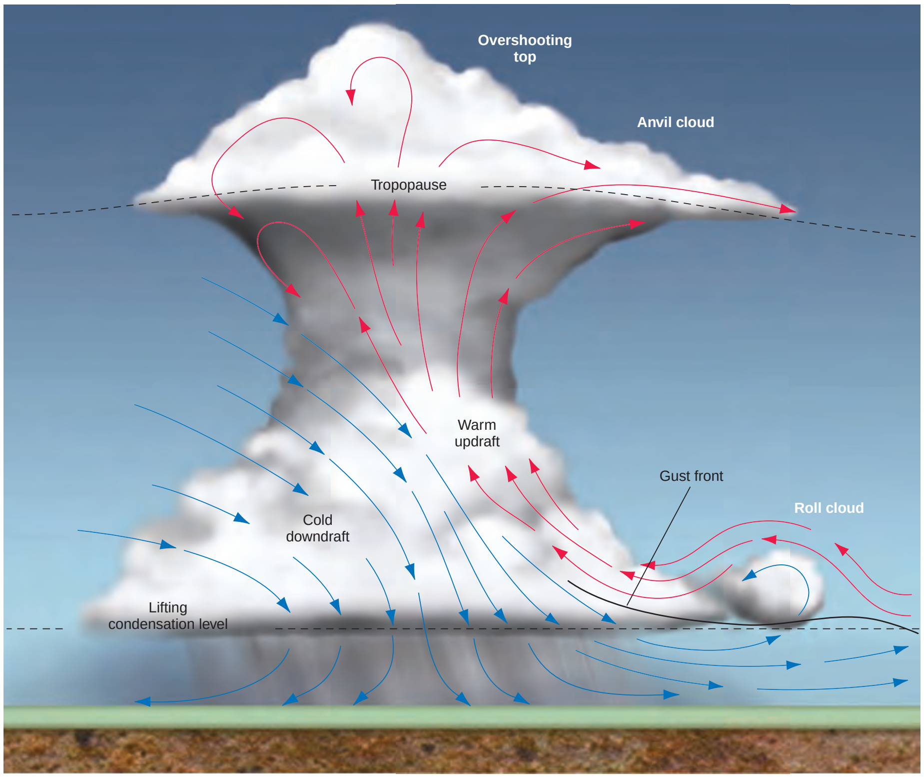
An essential component of the severe thunderstorm is *wind shear*—a change in wind velocity with height—that keeps cool, dry air entering from the upwind side while the warm, moist, rising air stays on the downwind side of the cell.

Under unusual circumstances involving a temperature inversion aloft, severe thunderstorms can become *supercell thunderstorms*—massive thunderstorms with a single circulation cell comprising very strong updrafts and downdrafts. Because of their vertical extent, which can be up to 25 km (16 mi), they are affected differently by winds at the surface and winds aloft. If the background wind shear not only involves a change in wind speed with height but also a change in direction—typically in a counterclockwise direction—a rotation of the storm can occur, which is a precursor to the formation of tornadoes.

MICROBURSTS

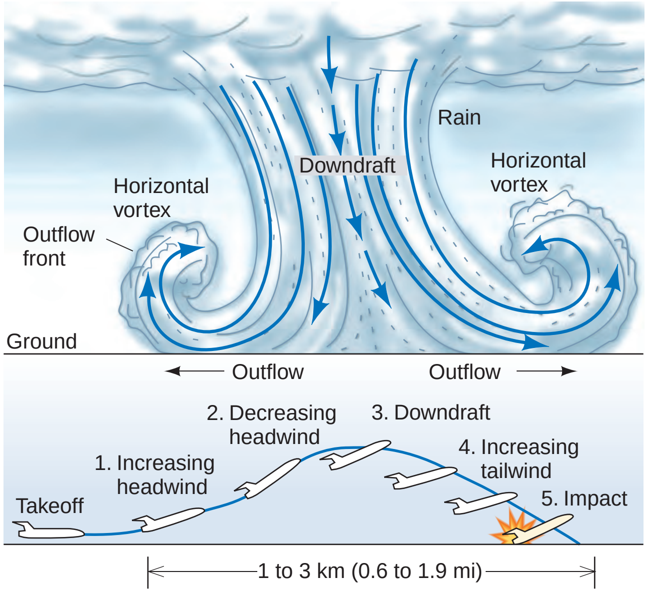
Another characteristic feature of many severe thunderstorms is the formation of a *microburst*—an intense downdraft or downburst that accompanies the gust front (Figure 4.30). Once the microburst hits the ground, it flows outward in all directions, producing intense, localized winds called *straight-line winds* or *plough winds*. A microburst is also often, but not always, accompanied by rain.

The microburst itself can be so intense that it is capable of causing low-flying aircraft to crash. An aircraft flying through the microburst first encounters strong headwinds, which may cause a bumpy ride but does not interfere with the airplane's ability to fly. However, as the



4.29 Anatomy of a severe thunderstorm

A severe thunderstorm can maintain convection and precipitation for long periods of time if it can continuously incorporate warm, moist air. Gust fronts associated with downdrafts extending ahead of the storm system force warm, moist surface air aloft and into the advancing storm.



4.30 Anatomy of a microburst

Passing through a microburst, an airplane first experiences a strong headwind, then a strong tailwind that can cause the aircraft to lose lift and crash.

airplane passes through the far side of the microburst, it encounters a strong tailwind. The lift of the airplane's wings depends on the speed of the air flowing across them, and the tailwind greatly reduces the air speed, which causes a loss of lift. If the tailwind is strong enough, the airplane cannot hold its altitude and may crash.

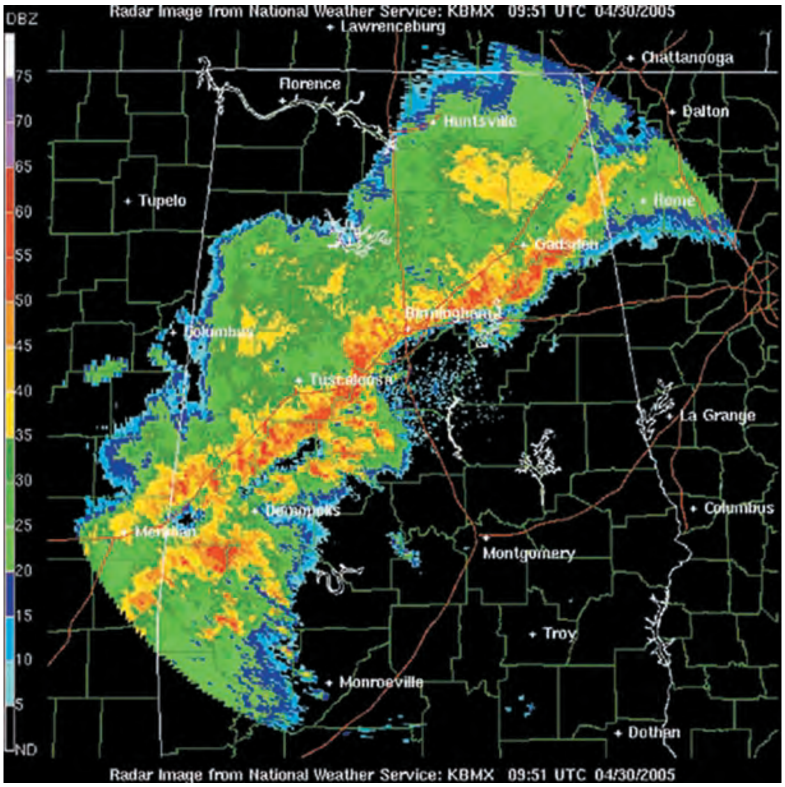
Microbursts can be detected by special radar instruments, now installed at many airports, that measure horizontal wind speeds. Training procedures for pilots have also reduced the incidence of aviation accidents in the United States attributed to microbursts and associated wind shear.

MESOSCALE CONVECTIVE SYSTEMS

Large, organized masses of severe and supercell thunderstorms sometimes occur under unusual conditions. These are called *mesoscale convective systems*. In one situation, upper-air wind flow patterns cause air to flow into a region and rise. The rising motion stimulates long-lasting clusters of severe and slowly-moving thunderstorms. In another situation, the change in wind direction with height caused by the approach of a cold front causes air to rise along a line ahead of the front. The resulting *squall line* of thunderstorms includes storms in different stages of development (Figure 4.31).

Tornadoes

A tornado is a small but intense vortex in which air spirals at tremendous speed. It is associated with thunderstorms spawned by fronts in the midlatitudes of North America. Tornadoes can also occur inside tropical cyclones (hurricanes).



4.31 Squall line

This radar image shows convective precipitation in reds and yellows associated with a line of thunderstorms extending across the state of Alabama on April 30, 2005. Gust fronts associated with these storms produced surface winds in excess of 27 m/s (60 mi/hr), knocking down trees and power lines.

TORNADO CHARACTERISTICS

A **tornado**, seen in Figure 4.32, appears as a dark funnel cloud hanging from the base of a dense cumulonimbus cloud. At its lower end, the funnel may be 100 to 450 m (about 300 to 1500 ft) in diameter. The base of the funnel appears dark because of the density of condensing moisture, dust, and debris swept up by the wind. Wind speeds in a tornado exceed speeds known in any other storm. Estimates of wind speed run as high as 100 m/s (about 225 mph), although generally they are closer to 50 m/s (about 110 mph). As the tornado moves across the countryside, the funnel writhes and twists. Where it touches the ground, it can cause complete destruction of almost anything in its path.

A tornado is a small but intense spiraling vortex of rising air associated with the strong updraft of an intense thunderstorm.

The center of a tornado is characterized by low pressure, which is typically 10–15 percent lower than the surrounding air pressure. The result is a very large pressure gradient force that generates high wind speeds as the air rushes into the low-pressure center of the tornado. Most tornadoes rotate in a counterclockwise direction, but a few rotate the opposite way.

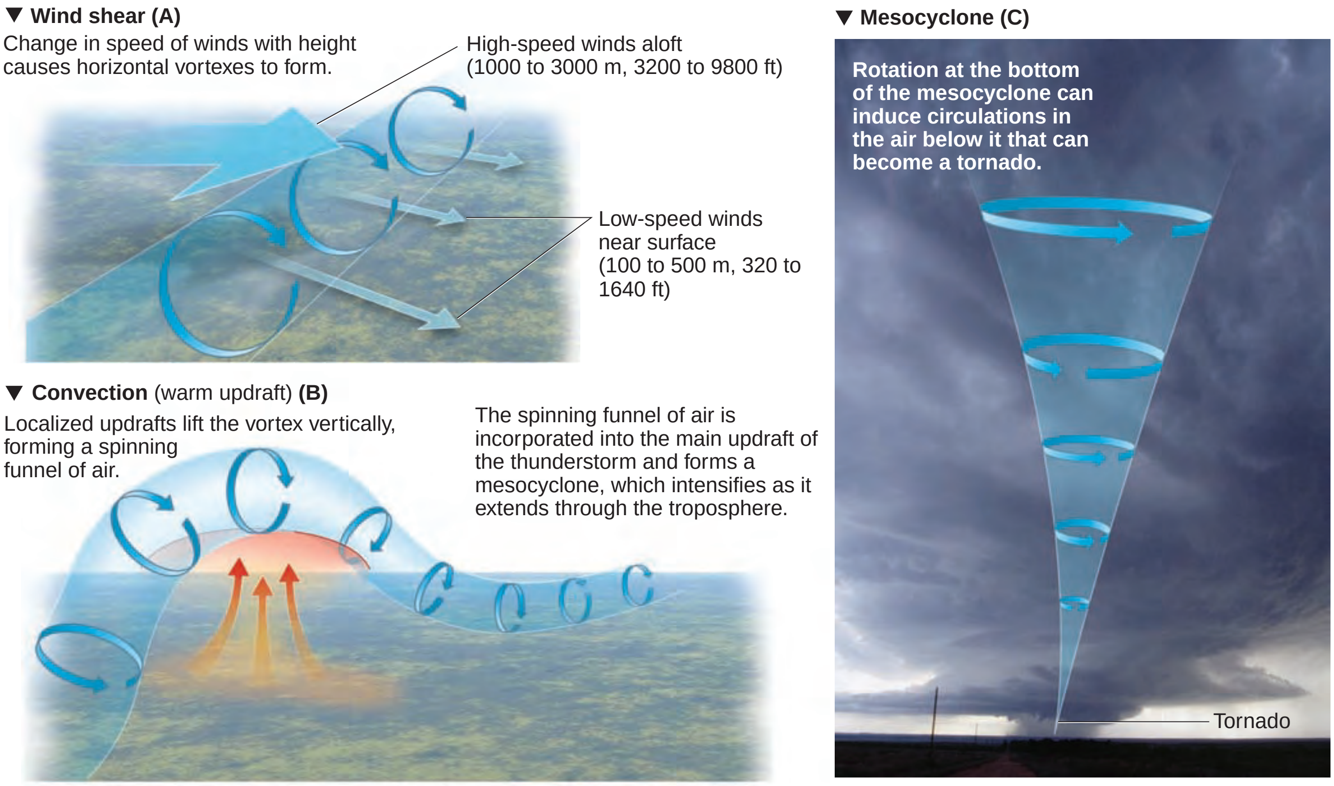
TORNADO DEVELOPMENT

Tornadoes are usually associated with the presence of severe thunderstorms, which provide one of the key ingredients in the initial development of the tornado—namely, a very strong vertical circulation. The other key ingredient is the presence of significant change in wind speed and direction with height, termed *wind shear* (Figure 4.33A). In regions where there is significant wind shear, spinning circulations aligned with the ground—*horizontal vortexes*—can form. Strong convection can then lift portions of the vortex (Figure 4.33B), which results in a vertical tower of slowly rotating air, called a *mesocyclone* (Figure 4.33C).

Initially, the mesocyclone is fairly broad. However, as the storm's vertical convection extends the top of the mesocyclone high in the atmosphere, the mesocyclone stretches and narrows. As it does so, it begins to spin faster, much as ice skaters spin faster as they pull their arms close to their bodies. The winds

4.32 Tornado

A tornado is a rapidly spinning funnel of air that touches the ground. It descends from the cloud base of a severe thunderstorm (National Geographic Image Collection).



4.33 Formation of mesocyclones and tornadoes

The combination of vertical wind shear with very strong convection can produce mesocyclones that extend through the troposphere. Rapidly rotating circulations extending from the bottom of the mesocyclones to the surface can then develop into tornadoes.

associated with the mesocyclone begin to cause the air below it to spin as well. About a fifth of the time, a narrow, rapidly circulating vortex stretches from the base of the mesocyclone down to the ground. When it touches the ground, it officially becomes a tornado.

GEODISCOVERIES **Occurrence of Tornadoes**
See a cold front develop a line of *tornado*-generating thunderstorms near Fort Worth, Texas, in this animation of GOES satellite imagery.

TORNADO DESTRUCTION

The large majority of tornadoes are relatively weak, lasting only a few minutes and covering only a few hundred meters. On the other hand, large tornadoes, which make up only about 5 percent of all tornadoes, can last for hours and spread destruction over hundreds of kilometers. Devastation from these tornadoes is often complete within the narrow limits of their paths. Only the strongest buildings constructed of concrete and steel can withstand the extremely violent winds.

The most commonly used measure of tornado intensity is the *Fujita intensity scale*, or the *F-scale*. This scale ranks tornadoes from 1 to 5, weakest to strongest. The scale is based on the severity of damage found in the tornado's wake. The more severe the damage, the more intense is the tornado (Figure 4.34).

In 2007, an *enhanced Fujita intensity scale* was adopted to better relate the tornado's wind speed to its damage. The new scale now incorporates 28 types of structures, with up to 12 different "degree of damage" ratings for each. This scale allows scientists to compare tornadoes that have passed through very different regions (for example, industrial and rural areas) and better estimate the wind speed within each.

Only about 5 percent of tornadoes reach 4 or 5 on the Fujita intensity scale. However, these tornadoes are responsible for about 70 percent of all tornado deaths. On average, about 75 people in the United States die each year from tornadoes, more than from any other natural phenomena except flooding and lightning strikes.

GEODISCOVERIES **How Tornados Cause Damage**
Visualize how tornado winds spiral inward and stream across houses, raising and wrecking roofs. Watch a minimovie of tornadoes in action.

4.34 Fujita intensity scale of tornado damage

The Fujita tornado intensity scale estimates the peak wind speed of a tornado based on the nature and amount of damage done to structures.

F0: 18–32 m/s (40–72 mph); damage to chimneys or TV antennas; broken branches; shallow-trees uprooted; signs and sign boards damaged

▲ Palm trees were uprooted as a weak F0 tornado passed over Kuwait City's beach front on April 12, 2008.

F1: 33–50 m/s (73–112 mph); surface of roofs peeled away; windows broken; trees on soft ground uprooted; trailer houses moved or overturned

▲ The roof of a restaurant was torn off, but the walls were left standing after an F1 tornado hit Daleville, Alabama, on November 25, 2001 (National Geographic Image Collection).

F2: 51–70 m/s (113–157 mph); roofs torn off frame houses; weak structures or outbuildings demolished; large trees snapped or uprooted; cars blown off highways; walls badly damaged but standing

▲ An F2 tornado hit Greymouth, New Zealand on March 10, 2005, peeling the roof away from the steel beams of this video store and causing millions of dollars of damage to the city.

F3: 71–92 m/s (158–206 mph); roofs torn off well-constructed houses; some rural buildings completely demolished; steel-framed, warehouse-type structures badly damaged; cars lifted off the ground; most trees uprooted or leveled

▲ This middle-school gymnasium constructed of cinder block and concrete was severely damaged when a tornado struck Jackson, Mississippi on May 4, 2003 (National Geographic Image Collection.)

▼ The walls were torn from the foundation of this home when an F4 tornado struck Madisonville, Kentucky, on December 8, 2005.

F4: 93–116 m/s (207–260 mph); well-constructed houses leveled, leaving piles of debris; structures with weak foundations lifted and blown away; cars blown large distances; large projectiles generated

▼ This aerial photo shows the severity and extent of damage associated with an F5 tornado that hit Greensburg, Kansas, on May 4, 2007. This tornado destroyed more than 95 percent of the town.

F5: 117–142 m/s (261–318 mph); strong frame houses lifted clear off foundation and disintegrated; steel-reinforced concrete structures badly damaged; trees completely debarked; automobile-sized projectiles thrown 100 yards or more

Air Quality

Most people living in or near urban areas have experienced air pollution first hand. Perhaps you've felt your eyes sting or your throat tickle as you drive an urban freeway. Or you've noticed black dust on window sills or window screens and realized that you are breathing in that dust as well.

AIR POLLUTANTS

Air pollution is largely the result of human activity. An **air pollutant** is an unwanted substance injected into the atmosphere from the Earth's surface by either natural or human activities. Air pollutants come as aerosols, gases, and particulates. In earlier chapters we've met aerosols—small bits of matter in the air, so small that they float freely with normal air movements—and gases. Particulates are larger, heavier particles that sooner or later fall back to Earth.

Air pollutants are unwanted substances present in the air. They arise from both human and natural activity.

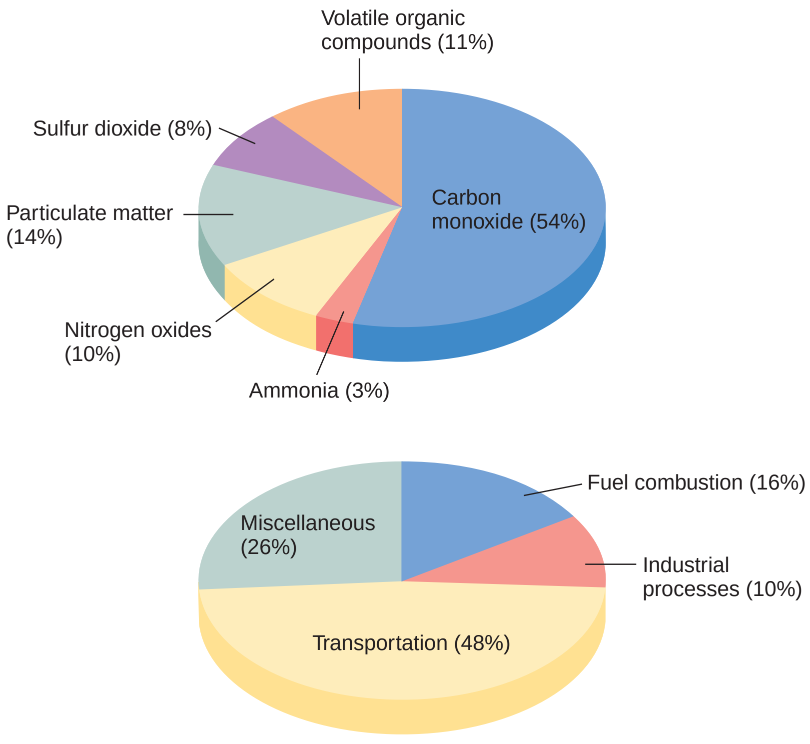
Most pollutants are generated by the everyday activities of large numbers of people, for example, driving cars, or through industrial activities, such as fossil fuel combustion or the smelting of mineral ores to produce metals. The most common air pollutant is carbon monoxide, followed by particulate matter, volatile organic compounds, nitrogen oxides, sulfur dioxide, and ammonia (Figure 4.35). Volatile organic compounds include evaporated gasoline, dry-cleaning fluids, and incompletely combusted fossil fuels. The buildup of these substances in the air can lead to many types of pollution, including acid deposition and smog.

SMOKE AND HAZE

When aerosols and gaseous pollutants are present in considerable density over an urban area, the resultant mixture is known as **smog** (Figure 4.36). Typically, smog allows hazy sunlight to reach the ground, but it may also be dense enough to hide aircraft flying overhead from view. Smog irritates the eyes and throat, and it can corrode structures over long periods of time.

Modern urban smog has three main toxic ingredients: nitrogen oxides, volatile organic compounds, and ozone. Nitrogen oxides and volatile organic compounds are largely automobile pollutants. Ozone forms through a photochemical reaction in the air in which nitrogen oxides react with volatile organic compounds in the presence of sunlight. Ozone is harmful to human lungs, and it aggravates bronchitis, emphysema, and asthma.

Haze is a condition of the atmosphere in which aerosols obscure distant objects. Haze builds up naturally in stationary air as a result of human and natural activity. When the air is humid and abundant water vapor is available, water films grow on suspended nuclei. This creates aerosol particles large enough to obscure and scatter light, reducing visibility.



◀ **Air pollutant emissions** Carbon monoxide is the largest air pollutant, accounting for more than half of all emissions. Nitrogen oxides, particulate matter, sulfur dioxide, and volatile organic compounds make up the rest. Ammonia constitutes only a small fraction.

◀ **Air pollutant sources** About half of the pollutants by weight are emitted by transportation, mainly in the form of carbon monoxide and volatile organic compounds. Miscellaneous sources make up about a quarter of the emissions, while fuel combustion and industrial processes divide the remainder.

4.35 Air pollutant emissions and sources by weight, 2007

4.36 Smog

This form of urban fog consists of aerosol haze mixed with toxic gases and hydrocarbon compounds. It is often irritating to the throats and lungs of city dwellers and can cause respiratory distress. Shown here is Beijing, China, on a day in March, 2008.

FALLOUT AND WASHOUT

Pollutants generated by a combustion process are at first carried aloft by convection. However, the larger particulates soon settle under gravity and return to the surface as *fallout*. Particles too small to settle out are later swept down to Earth by precipitation in a process called *washout*. Through a combination of fallout and washout, the atmosphere tends to be cleaned of pollutants.

Pollutants are also eliminated from the air over their source areas by wind. Strong, through-flowing winds will disperse pollutants into large volumes of cleaner air in the downwind direction. Strong winds can quickly sweep away most pollutants from an urban area, but during periods when winds are light or absent, the concentrations can rise to high values.

INVERSION AND SMOG

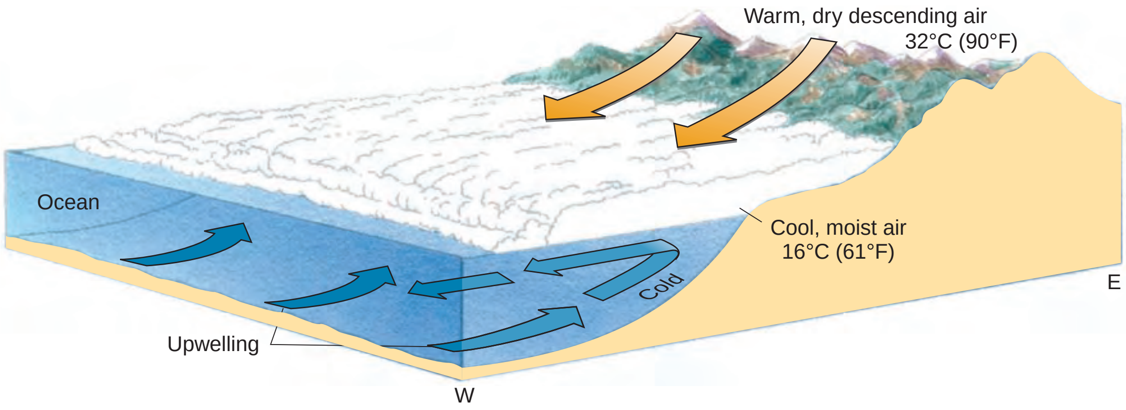
The concentration of pollutants over a source area rises to its highest levels when vertical mixing (convection) of the air is inhibited. This happens in an inversion—a condition in which the temperature of the air increases with altitude.

According to the adiabatic principle, a heated air parcel emerging from a smokestack or chimney will cool as it rises until it attains the same temperature as the surrounding air. In an inversion, however, the surrounding air gets warmer, not colder, with altitude. So the hot parcel will quickly arrive at the temperature of the surrounding air, and uplift will stop. Pollutants in the air parcel remain trapped below the inversion, keeping concentrations high near the ground.

Two types of inversions are important in causing high air pollutant concentrations—low-level and high-level inversions. When a *low-level temperature inversion* develops over an urban area with many air pollution sources, pollutants are trapped under the "inversion lid." Heavy smog or highly toxic fog can develop. London's poisonous "pea soup" fogs of the past are an example.

Another type of inversion is responsible for the smog problem experienced in the Los Angeles Basin and other California coastal regions, ranging north to San Francisco and south to San Diego. Here special climatic conditions produce prolonged inversions and

Persistent inversions can trap pollutants, resulting in low air quality and smog.



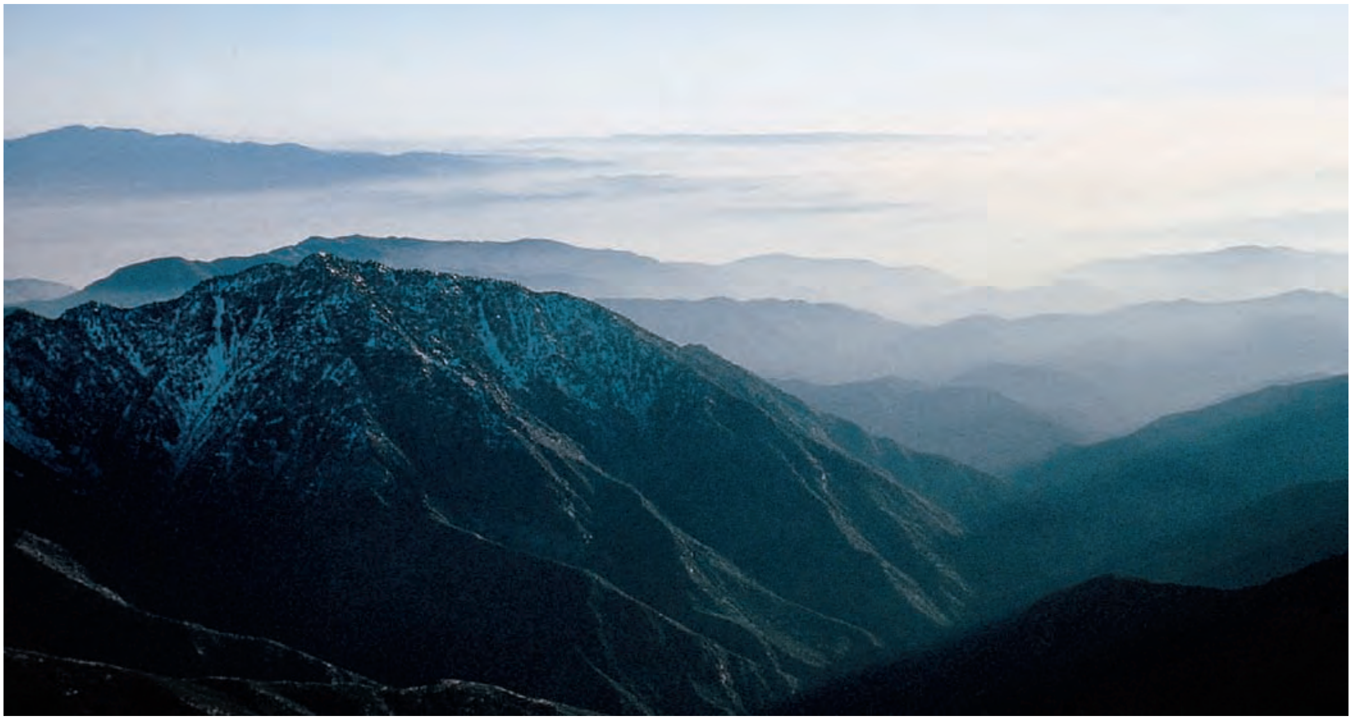
4.37 High-level temperature inversion on the California coast

A layer of warm, dry, descending air from a persistent fair-weather system rides over a cool, moist marine air layer at the surface to create a persistent temperature inversion.

smog accumulations (Figure 4.37). Off the California coast is a persistent fair-weather system that is especially strong in the summer. This system produces a layer of warm, dry air at upper elevations. However, a cold current of upwelling ocean bottom water runs along the coast, just offshore. Moist ocean air moves across this cool current and is chilled, creating a cool, marine air layer.

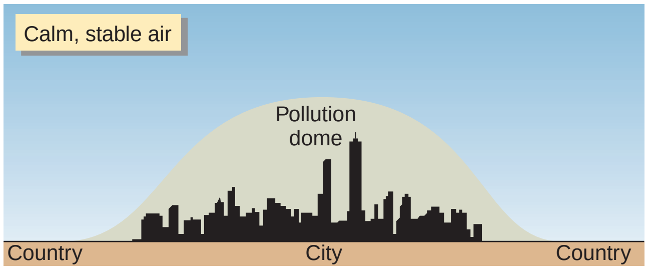
Now, the Los Angeles Basin is a low, sloping plain lying between the Pacific Ocean and a massive mountain barrier on the north and east sides. Weak winds from the south and southwest move the cool, marine air inland over the basin. Further landward movement is blocked by the mountain barrier. Since there is a warm layer above this cool marine air layer, the result is a *high-level temperature inversion*. Pollutants accumulate in the cool air layer and produce smog. The upper limit of the smog stands out sharply in contrast to the clear air above it, filling the basin like a lake and extending into valleys in the bordering mountains (Figure 4.38).

An actual temperature inversion, in which air temperature increases with altitude, is not essential for building a high concentration of pollutants above a city. Light or calm winds and stable air are all that are required. Stable air has a temperature profile that decreases with altitude but at a slow rate. Some convective mixing

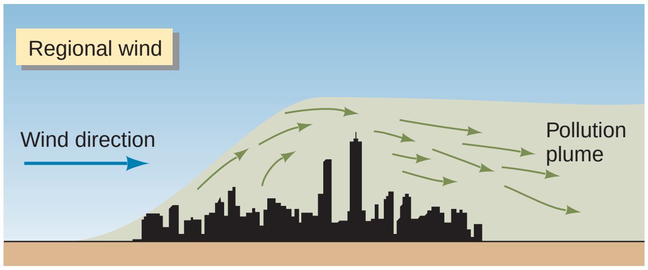


4.38 Smog and haze at Los Angeles

A dense layer of smog and marine haze fills the Los Angeles Basin. The view is from a point over the San Gabriel Mountains looking southwest.



▲ If calm, stable air overlies a major city, a pollution dome can form.



▲ When a wind is present, pollutants are carried away as a pollution plume.

4.39 Pollution dome and pollution plume

occurs in stable air, but the convective precipitation process is inhibited.

At certain times of the year, slow-moving masses of dry, stable air occupy the central and eastern portions of the North American continent. Under these conditions, a broad *pollution dome* can form over a city or region, and air quality will suffer (Figure 4.39). When there is a regional wind, the pollution from a large city will be carried downwind to form a *pollution plume*.

GEODISCOVERIES Web Quiz
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

This chapter has focused primarily on the process of precipitation, which we have examined largely on the scale of the individual cloud. To understand the global pattern of precipitation and how that pattern helps define global climate, we need to examine winds and the global circulation of the atmosphere. These topics are the subjects of the next chapter.

As we will see, wind results from pressure gradients that are created by uneven heating of the air coupled with the turning motion of the Earth's surface. The major role of precipitation in this process is to trap latent heat as water evaporates from warm ocean surfaces and release that latent heat when condensation and precipitation occur at distant locations. The effect is to move heat poleward in a process that creates the distinctive patterns of temperature and precipitation that we term global climates.

GEODISCOVERIES Web Links
Learn more about humidity and how to calculate it. Observe the different types of clouds and how they form. View some amazing images of lighting. Monitor global drought.

IN REVIEW ATMOSPHERIC MOISTURE AND PRECIPITATION

- **Acid deposition** of sulfate and nitrate particles, either dry or as acid raindrops, can acidify soils and lakes, causing fish and plant mortality.
- **Precipitation** is the fall of liquid or solid water from the atmosphere to reach the Earth's land or ocean surface. Evaporating, condensing, melting, freezing, **sublimation**, and **deposition** describe the changes of state of water.
- The **hydrosphere** is the realm of water in all its forms. Nearly all of the hydrosphere consists of saline ocean water. The remainder is fresh water on the continents and a very small amount of atmospheric water.
- Water moves freely between ocean, atmosphere, and land in the **hydrologic cycle**. The global water balance describes these flows.
- **Humidity** describes the amount of water vapor present in air. The ability of air to hold water vapor depends on temperature. Warm air can hold much more water vapor than cold air.
- **Specific humidity** measures the mass of water vapor in a mass of air, in grams of water vapor per kilogram of air. The **dew-point temperature** of a parcel of moist air is the temperature at which the air becomes saturated and condensation begins to occur when the parcel is chilled.

- **Relative humidity** measures water vapor in the air as the percentage of the maximum amount of water vapor that can be held at the given air temperature.
- The **adiabatic principle** states that when a gas is compressed, it warms, and when a gas expands, it cools. When an air parcel moves upward in the atmosphere, it encounters a lower pressure and so expands and cools. The **dry adiabatic lapse rate** describes the rate of cooling with altitude.
- If the air is cooled below the dew point, condensation or deposition occurs. The altitude at which condensation starts is the **lifting condensation level**. Condensation releases latent heat, which reduces the parcel's rate of cooling with altitude. When condensation or deposition is occurring, the cooling rate is described as the **moist adiabatic lapse rate**.
- **Clouds** are composed of droplets of water or crystals of ice that form on *condensation nuclei*. Clouds typically occur in layers, as *stratiform* clouds, or in globular masses, as *cumuliform* clouds.
- Fog occurs when a cloud forms at ground level. *Radiation fog* occurs on clear nights in valleys and low-lying areas. *Advection fog* results when a warm, moist air layer moves over a cold surface.
- Weather forecasters use images from the *GOES* satellite system—a pair of geostationary satellites with views of North America and the oceans to its east and west—to monitor clouds and precipitation and track storms.
- Precipitation forms when water droplets in warm clouds condense, collide, and coalesce into droplets that are large enough to fall as rain. In cool clouds, ice crystals grow by deposition, while water droplets shrink by evaporation.
- There are four types of precipitation processes—*orographic, convective, cyclonic*, and *convergent*. In **orographic precipitation**, air moves up and over a mountain barrier. As it moves up, it is cooled adiabatically and rain forms. As it descends the far side of the mountain, it is warmed, producing a *rain shadow* effect.
- In **convective precipitation**, unequal heating of the surface causes an air parcel to become warmer and less dense than the surrounding air. Because it is less dense, it rises. As it moves upward, it cools, and condensation with precipitation may occur. In *stable air*, the heated parcel rapidly reaches the temperature of the surrounding air. In **unstable air**, the surrounding air is always cooler than the parcel, making it rise to great heights with intense condensation.
- Precipitation from clouds occurs as *rain, hail, snow, sleet* and freezing rain, and *hail*. When *supercooled* rain falls on a surface below freezing, it produces an *ice storm*.
- Precipitation is measured with a *rain gauge*. Snow is measured either by its depth or by the amount of water it yields when melted.
- **Thunderstorms** produce thunder and lightning. They can also produce high winds, hail, and tornadoes. *Air-mass thunderstorms* are generated by daytime heating. *Severe thunderstorms*, enhanced by wind shear, last longer and have higher winds. A *microburst* is an intense downdraft that precedes some severe thunderstorms. Upper-air wind flow patterns sometimes produce large masses of severe thunderstorms called *mesoscale convective systems*.
- **Air pollutants** are unwanted gases, aerosols, and particulates injected into the air by human and natural activity. Polluting *gases, aerosols*, and *particulates* are generated largely by fuel combustion.
- **Smog**, a common form of air pollution, contains nitrogen oxides, volatile organic compounds, and ozone. *Inversions* can trap smog and other pollutant mixtures in a layer close to the ground, creating unhealthy air.

KEY TERMS

acid deposition, p. 112
precipitation, p. 112
sublimation, p. 114
deposition, p. 114
hydrosphere, p. 114
hydrologic cycle, p. 114
humidity, p. 117
specific humidity, p. 117
dew-point temperature, p. 118
relative humidity, p. 118
adiabatic principle, p. 119
dry adiabatic lapse rate, p. 120
lifting condensation level, p. 120
moist adiabatic lapse rate, p. 121
cloud, p. 121
fog, p. 122
orographic precipitation, p. 126
rain shadow, p. 127
convective precipitation, p. 127
unstable air, p. 128
thunderstorm, p. 132
tornado, p. 138
air pollutant, p. 141
smog, p. 141

REVIEW QUESTIONS

1. To what type of pollution does the term *acid deposition refer?* What are its causes? What are its effects?
2. Identify the three states of water and the six terms used to describe possible changes of state.
3. What is the *hydrosphere*? Where is water found on our planet? in what amounts? How does water move in the hydrologic cycle?
4. Define *specific humidity*. How is the moisture content of air influenced by air temperature?
5. Define *relative humidity*. How is relative humidity measured? Sketch a graph showing relative humidity and temperature through a 24-hour cycle.
6. Use the terms *saturation, dew point*, and *condensation* in describing what happens when an air parcel of moist air is chilled.
7. What is the *adiabatic principle*? Why is it important?
8. Distinguish between dry and moist adiabatic lapse rates. In a parcel of air moving upward in the atmosphere, when do they apply? Why is the moist adiabatic lapse rate less than the dry adiabatic rate? Why is the moist adiabatic rate variable in amount?
9. How are clouds classified? Name four cloud families, two broad types of cloud forms, and three specific cloud types.
10. What is *fog*? Explain how radiation fog and advection fog form.
11. How is precipitation formed? Describe the process for warm and cool clouds.
12. Identify a satellite system that is used to monitor clouds and track storms. What type of orbit does the system use and why?
13. Describe the orographic precipitation process. What is a *rain shadow*? Provide an example of the rain shadow effect.
14. What is unstable air? What are its characteristics?
15. Describe the convective precipitation process. What is the energy source that powers this source of precipitation? Explain.
16. Identify and describe three types of precipitation. How is the amount of precipitation measured?
17. What is a *thunderstorm*? Describe the typical life cycle of an air-mass thunderstorm.
18. What distinguishes a severe thunderstorm from an air-mass thunderstorm? How does a severe thunderstorm produce a microburst?
19. What is a *tornado*? What two ingredients are needed for its formation? How is the intensity of a tornado measured?
20. Define *air pollutant* and provide three examples.
21. What is *smog*? What important pollutant forms within smog, and how does this happen?
22. Distinguish between low-level and high-level inversions. How are they formed? What is their effect on air pollution? Give an example of a pollution situation of each type.

VISUALIZING EXERCISES

1. Lay out a simple diagram showing the main features of the hydrologic cycle. Include flows of water connecting land, ocean, and atmosphere. Label the flow paths.
2. Graph the temperature of a parcel of air as it moves up and over a mountain barrier, producing precipitation.
3. Sketch the anatomy of a thunderstorm cell. Show updraft, downdraft, lifting condensation level, anvil cloud, and other features.

ESSAY QUESTIONS

1. Water in the atmosphere is a very important topic for understanding weather and climate. Organize an essay or oral presentation on this topic, focusing on the following questions: What part of the global supply of water is atmospheric? Why is it important? What is its global role? How does the capacity of air to hold water vapor vary? How is the moisture content of air measured? Clouds and fog visibly demonstrate the presence of atmospheric water. What are they? How do they form?
2. Compare and contrast orographic and convective precipitation. Begin with a discussion of the adiabatic process and the generation of precipitation within clouds. Then compare the two processes, paying special attention to the conditions that create uplift. Can convective precipitation occur in an orographic situation? Under what conditions?
3. The thunderstorm is an atmospheric phenomenon that can be violent and dangerous. Tell the story of thunderstorms, including their life cycle and the types of thunderstorms that occur. Describe microbursts and tornadoes as examples of the destructive winds that sometimes occur with thunderstorms.

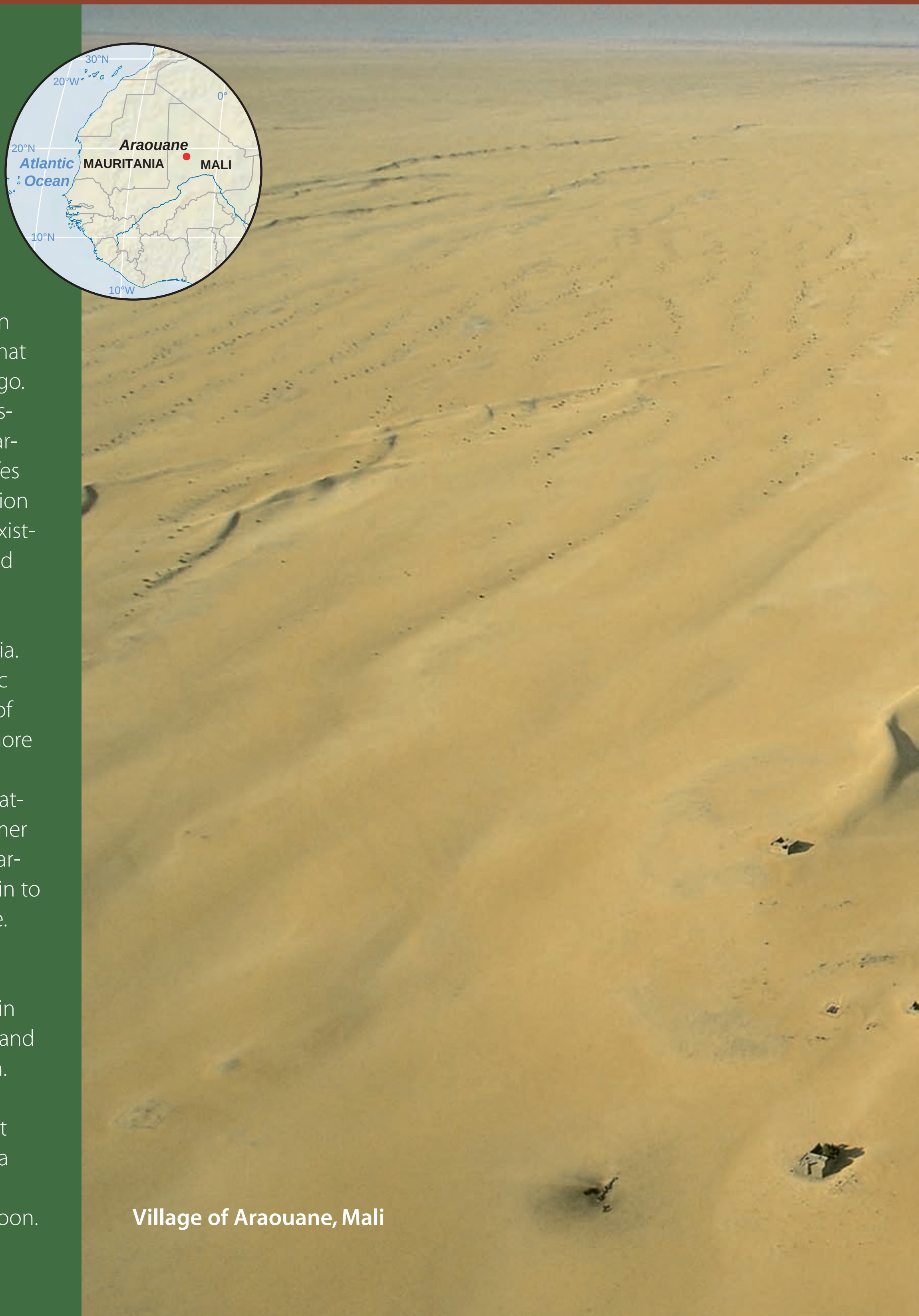
Chapter 5
Winds and Global Circulation

This ancient village in the southern Sahara, once a thriving stop on the great caravan route to Mauritania, is now slowly being buried by wind-driven sand. But it wasn't always this way.

About 14,000 years ago, just after the end of the last glacial period, the Sahara region experienced a wetter climate that lasted until about 6000 years ago. The Sahara was a savanna grassland, and animals now found farther to the south, such as giraffes and elephants, roamed the region freely. New lakes formed, and existing lakes to the south expanded their borders.

The cause was a monsoon climate, similar to Southeast Asia. The climate resulted from cyclic changes in the global pattern of solar insolation that brought more solar heating to the northern hemisphere in summer. The heating expanded the belt of summer rainfall in Africa and moved it farther north, bringing enough rain to support the savanna landscape.

In this case, the change in climate was brought about by long, slow astronomical cycles in the exact tilt of the Earth's axis and the annual timing of perihelion. These factors are unrelated to human activity. However, recent forecasts are for a wetter Sahara as global warming once again expands the African wet monsoon.



Village of Araouane, Mali

Winds and Global Circulation

The air around us is always in motion, from a gentle breeze on a summer's day to a cold winter wind. Why does the air move? What are the forces that cause winds to blow? Why do winds blow more often in some directions than others? What is the pattern of wind flow in the upper atmosphere, and how does it affect our weather? How does the global wind pattern produce ocean currents? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

El Niño

At irregular intervals of about three to eight years, a remarkable disturbance of ocean and atmosphere occurs in the equatorial Pacific region—**El Niño**. Its name comes from Peruvian fishermen, who refer to the Corriente del Niño or the "Current of the Christ Child," to describe an invasion of warm surface water once every few years around Christmas time that greatly depletes their catch of fish. It lasts more than a year, bringing droughts, heavy rainfalls, severe spells of heat and cold, and a high incidence of cyclonic storms to various parts of the Pacific and its eastern coasts.

Normally, the cool Humboldt (Peru) Current flows northward off the South American coast, and then at about the Equator it turns westward across the Pacific as the south equatorial current. The Humboldt Current is fed by upwelling of cold, deep water, bringing with it nutrients that serve as food for marine life. With the onset of El Niño, upwelling ceases, the cool water is replaced by warm, sterile water from the west, and the abundant marine life disappears. In contrast to El Niño is *La Niña*, in which normal Peruvian coastal upwelling is enhanced, trade winds strengthen, and cool water is carried far westward in an equatorial plume. Figure 5.1 shows two satellite images of sea-surface temperature observed during El Niño and La Niña years.

The major change in sea-surface temperatures that accompanies an El Niño can also shift weather patterns across large regions of the globe. The winter of 1997–1998 experienced one of the strongest El Niños in a century. Torrential rains drenched Peruvian and Ecuadorean coast ranges, producing mudflows, debris avalanches, and extensive river flooding.

Large portions of Australia and the East Indies went rainless for months, and forest fires burned out of control in Sumatra, Borneo, and Malaysia. In East Africa, Kenya experienced rainfall 1000 mm (80 in.) above normal.

In North America, a series of powerful winter storms lashed the Pacific coast, doing extensive damage in California. Monstrous tornadoes ripped through Florida, killing over 40 people and destroying more than 800 homes. Meanwhile, mild winter conditions east of the Rockies saved vast amounts of fossil fuel while generating an ice storm that left 4 million people without power in Quebec and the northeastern United States. All told, the deranged weather of the El Niño of 1997–1998 did property damage estimated at $33 billion and killed an estimated 2100 people.

The El Niño of 1997–1998 was rapidly followed by the La Niña of 1998–1999. The result was heavier monsoon rains in India and more rain in Australia. In North America, winter conditions were colder than normal in the Northwest and upper Midwest. The eastern Atlantic region endured drought through spring and early summer. The hurricane season of 1998, spawning the monster storm Hurricane Mitch, was the deadliest in the past two centuries.

What effect will global warming have on El Niño? Because global warming raises sea-surface temperatures and increases equatorial rainfall, climatologists think that global warming will enhance the strength and frequency of El Niño events while reducing La Niñas. But the mechanism responsible for the El Niño–La Niña cycle is still not well understood. We'll return to the El Niño–La Niña cycle later in this chapter.

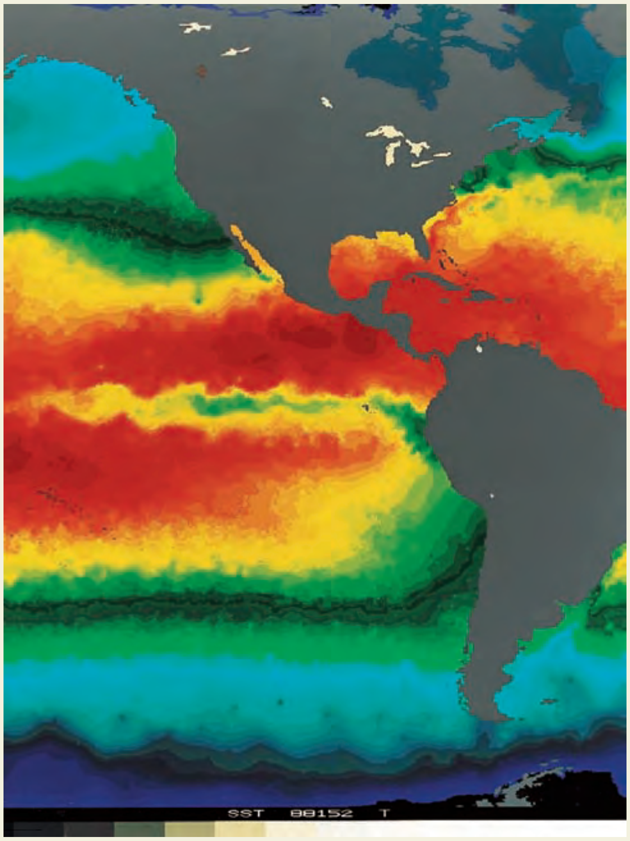
Atmospheric Pressure

We live at the bottom of a vast ocean of air—the Earth's *atmosphere* (Figure 5.2). Like the water in the ocean, the air in the atmosphere is constantly pressing on the Earth's surface beneath it and on everything that it surrounds. The atmosphere exerts pressure because *gravity* pulls the gas molecules of the air toward the Earth. Gravity is an attraction among all masses—in this case, between gas molecules and the Earth's vast bulk.

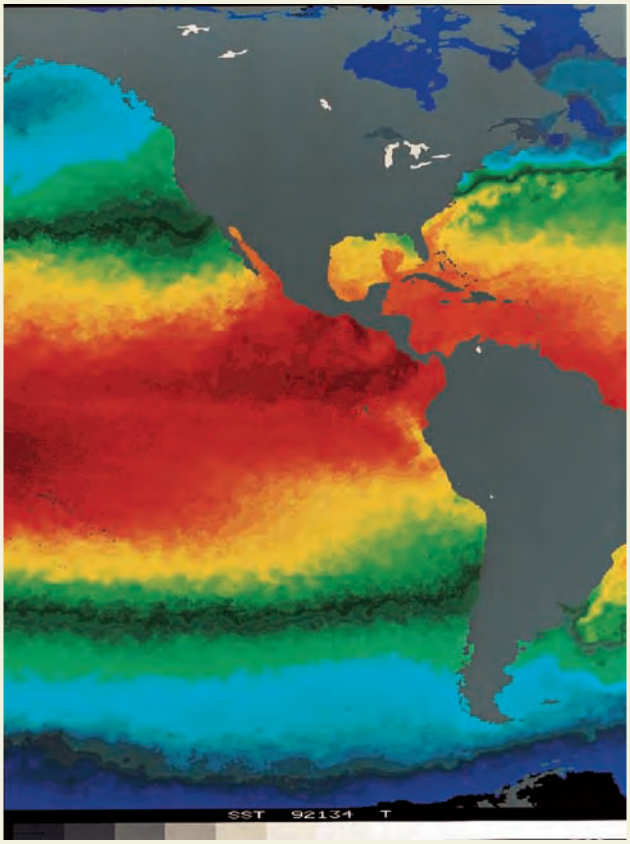
Atmospheric pressure is produced by the weight of a column of air above a unit area of the Earth's surface. At sea level, about 1 kilogram of air presses down on each square centimeter of surface (1 kg/cm^2)—about 15 pounds on each square inch of surface (15 lb/in.^{2}).

5.1 La Niña and El Niño sea-surface temperatures

This striking image shows sea-surface temperatures in the eastern tropical Pacific during La Niña and El Niño years as measured by the NOAA-7 satellite. Green tones indicate cooler temperatures, while red tones indicate warmer temperatures.



▲ **La Niña** An unusually strong flow of cold water moves up the South American coast toward Peru. Strong upwelling brings more cold water to the surface, which is carried westward in a plume within the south equatorial current. Normal conditions resemble the La Niña, except that current patterns and upwelling are significantly weaker.



▲ **El Niño** Cold water along the South American coast stays to the south. Upwelling off Peru is weak. A region of very warm water develops in the eastern Pacific as the trade winds fail and become weak westerlies.

The basic metric unit of pressure is the *pascal* (Pa). At sea level, the average pressure of air is 101,320 Pa. Many atmospheric pressure measurements are reported in bars and *millibars* (mb) (1 bar = 1000 mb = 10,000 Pa). In this book we will use the millibar as the metric unit of atmospheric pressure. Standard sea-level atmospheric pressure is 1013.2 mb.

MEASURING AIR PRESSURE

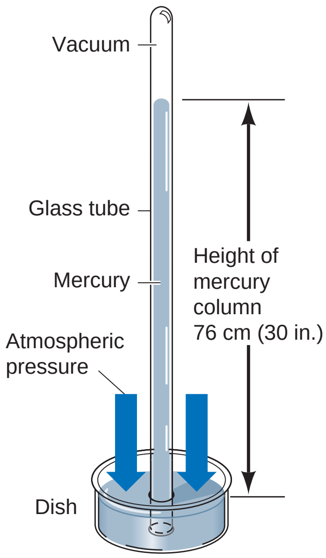
You probably know that a **barometer** measures atmospheric pressure. But do you know how it works? It's based on the same principle as drinking soda through a straw. When using a straw, you create a partial vacuum in your mouth by lowering your jaw and moving your tongue. The pressure of the atmosphere then forces soda up through the straw. The oldest, simplest, and most accurate instrument for measuring atmospheric pressure, the *mercury barometer,* works the same way (Figure 5.3).

Because the mercury barometer is so accurate and is used so widely, atmospheric pressure is commonly expressed using the height of the column in centimeters or inches. The chemical symbol for mercury is Hg, and standard sea-level pressure is expressed as 76 cm Hg (29.92 in. Hg).

In the mercury barometer, air pressure balances the pull of gravity of a column of mercury about 76 cm (30 in.) high.

5.2 Ocean of air

The Earth's terrestrial inhabitants live at the bottom of an ocean of air. This buoyant weather balloon will upward carry a package of instruments, known as a radiosonde, that radio back temperature and pressure at levels aloft. Sable Island, Nova Scotia (National Geographic Image Collection).



5.3 Measuring atmospheric pressure

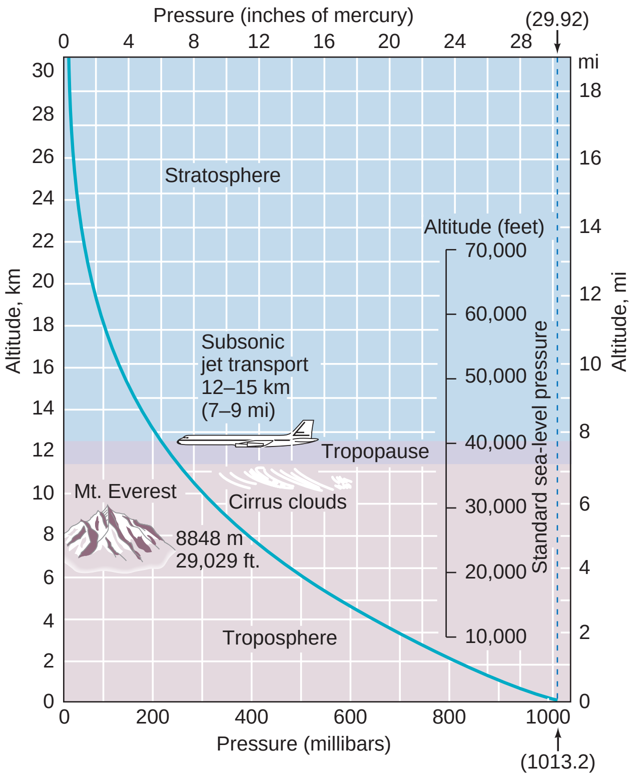
Mercury barometer Atmospheric pressure pushes the mercury upward into the tube, where a vacuum is present. As atmospheric pressure changes, the level of mercury in the tube rises and falls.

In this book, we will use in. Hg as the English unit for atmospheric pressure.

Atmospheric pressure at a single location varies only slightly from day to day. On a cold, clear winter day, the sea-level barometric pressure may be as high as 1030 mb (30.4 in. Hg), while in the center of a storm system it may drop by about 5 percent to 980 mb (28.9 in. Hg). Changes in atmospheric pressure are associated with traveling weather systems.

AIR PRESSURE AND ALTITUDE

If you have felt your ears "pop" during an elevator ride in a tall building, or when you're on an airliner that is climbing or descending, you've experienced a change in air pressure related to altitude (Figure 5.4). Changes in pressure at higher elevations can have more serious effects on the human body. In the mountains or at high altitudes, with decreased air pressure, less oxygen moves into lung tissues, producing fatigue and shortness of breath (Figure 5.5). These symptoms, sometimes accompanied by headache, nosebleed, or nausea, are



5.4 Atmospheric pressure and altitude

Atmospheric pressure decreases rapidly with altitude near the Earth's surface but much more slowly at higher altitudes.

known as mountain sickness. They are likely to occur at altitudes of 3000 m (about 10,000 ft) or higher.

Local Wind Patterns

Wind is defined as air moving horizontally over the Earth's surface. Air motions can also be vertical, but these are known by other terms, such as updrafts or downdrafts. Wind direction is identified by the direction from which the wind comes—a west wind blows from west to east, for example. Like all motion, the movement of wind is defined by its direction and velocity. The most common instrument for tracking wind direction is a simple vane with a tail fin that keeps it always pointing into the wind (Figure 5.6).

Anemometers measure wind speed. The most common type consists of three funnel-shaped cups on the ends of the spokes of a horizontal wheel that rotates as the wind strikes the cups. Some anemometers use a small electric generator that produces more current when the wheel rotates more rapidly. This is connected to a meter calibrated in meters per second or miles per hour.

PRESSURE GRADIENTS

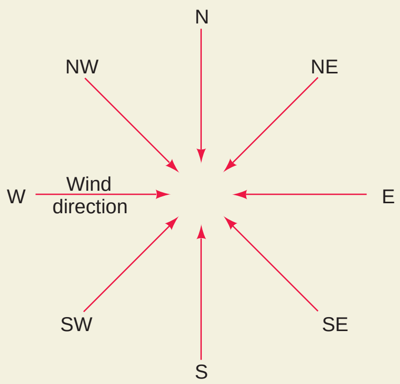
Wind is caused by differences in atmospheric pressure from one place to another. Air tends to move from regions of high pressure to regions of low pressure, until

5.5 Climbers on Everest

Most people who stay in a high-altitude environment for several days adjust to the reduced air pressure. Climbers who are about to ascend Mount Everest usually spend several weeks in a camp partway up the mountain before attempting to reach the summit (National Geographic Image Collection).

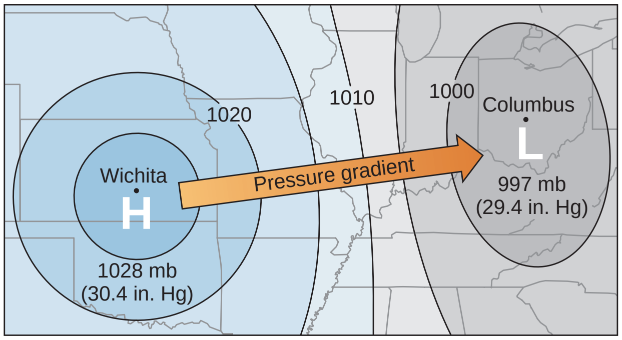
5.6 Measurement of wind

Measuring the wind requires noting both its speed and its direction.



▲ **Wind direction** Winds are designated according to the compass point from which the wind comes. A west wind comes from the west, but the air is moving eastward.

▲ **Combination cup anemometer and wind vane** The anemometer and wind vane observe wind speed and direction, which are displayed on the meter below. The wind vane and anemometer are mounted outside, with a cable from the instruments leading to the meter, which is located indoors. Also shown are a barometer and a maximum–minimum thermometer. (Courtesy of Taylor Instrument Company and Ward's Natural Science Establishment, Rochester, NY).



5.7 Isobars and a pressure gradient

This figure shows a pressure gradient. Because atmospheric pressure is higher at Wichita than at Columbus, the pressure gradient will push air toward Columbus, producing wind. A greater pressure difference between the two locations would produce a greater force and a stronger wind.

the pressure at every level is uniform. On a weather map, lines that connect locations with equal pressure are called **isobars**. A change of pressure, or pressure gradient, occurs at a right angle to the isobars (Figure 5.7). **Pressure gradients** develop because of unequal heating in the atmosphere. Figure 5.8 shows how unequal heating creates a **thermal circulation.**

Heating of the atmosphere creates a pressure gradient that moves air toward the warm region at low levels and away from the warm region at high levels in a thermal circulation.

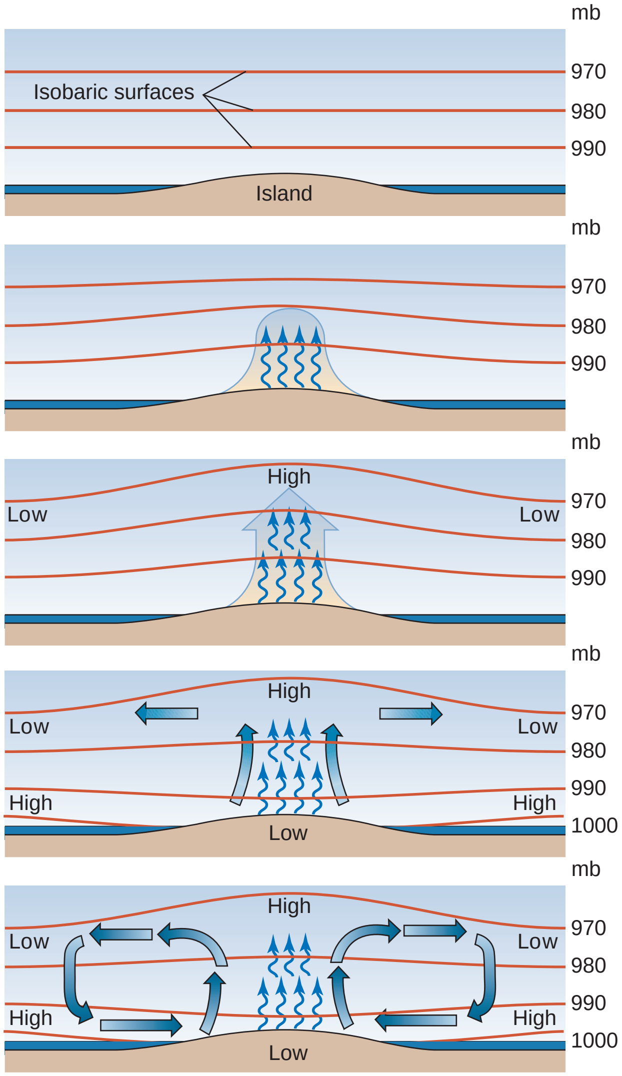
LOCAL WINDS

Local winds include land and sea breezes, mountain and valley winds, and Santa Ana, chinook, and mistral winds.

Local winds are driven by local effects. *Sea* and *land breezes* are simple examples of how uneven heating and cooling of the air can set up thermal circulations and create local winds (Figure 5.9). A similar situation creates *mountain* and *valley winds* (Figure 5.10). Often these winds are moderate and just part of the local environment. But some local winds are more dangerous.

If you're from Southern California, you're probably familiar with the *Santa Ana*, a fierce, searing wind that often drives raging wildfire into foothill communities (Figure 5.11). It blows from the interior desert region of Southern California across coastal mountain ranges to reach the Pacific coast. It warms as it descends, and it is often funneled through local mountain gaps and across canyon floors with great force.

Other local winds include the *chinook*, a warm and dry local wind that results when air passes over a mountain range and descends on the lee side. It is known for rapidly evaporating and melting snow. The *mistral* of the Rhône Valley in southern France is a cold, dry local wind



◀ **Uniform atmosphere (heated equally)** Imagine a uniform atmosphere above a ground surface. The isobaric levels (or "surfaces") are parallel with the ground surface (Isobar = equal pressure).

◀ **Uneven heating** Imagine now that the underlying ground surface, an island, is warmed by the Sun, with cool ocean water surrounding it. The warm surface air rises and mixes with the air above, warming the column of air above the island. Since the warmer air occupies a large volume, the isobaric levels are pushed upward.

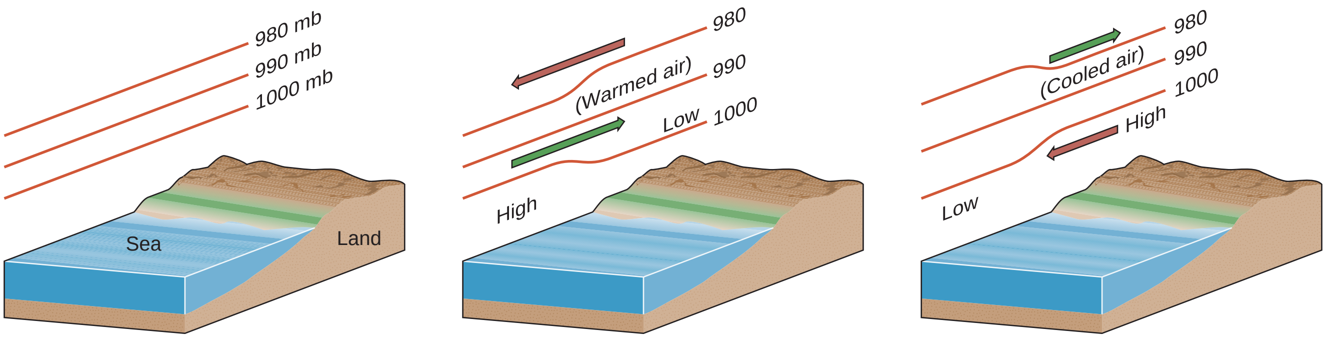
◀ **Pressure gradient** The result is that a pressure gradient is created, and air at higher pressure (above the island) flows toward lower pressure (above the ocean).

◀ **Surface pressure** Because air is moving away from the island and over the ocean surfaces, the surface pressure changes. There is less air above the island, so the ground pressure there drops. Since more air is now over the ocean surfaces, the pressure there rises.

◀ **Thermal circulations** The new pressure gradient at the surface moves air from the ocean surfaces toward the island, while air moving in the opposite direction at upper levels completes the two loops.

5.8 Thermal circulations

Unequal heating of the Earth's surface produces a thermal circulation.



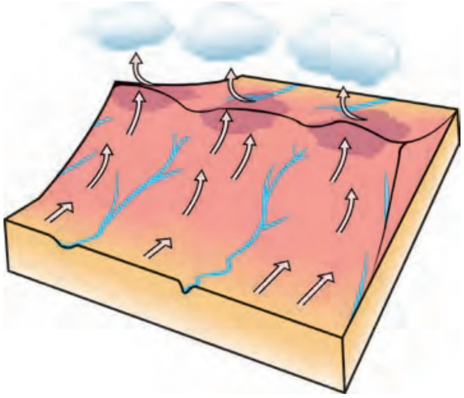
▲ **Early morning–calm** Early in the day, winds are often calm. Pressure decreases uniformly with altitude.

▲ **Afternoon–sea breeze** Later in the day, the Sun has warmed the land and the air above it, creating lower pressure at the surface and higher pressure aloft. The warmed air moves oceanward aloft, while surface winds bring cool marine air landward at the surface to replace it. This is the sea breeze.

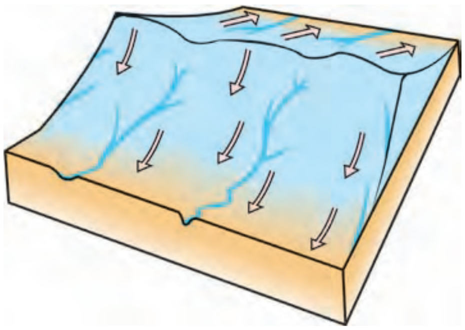
▲ **Night–land breeze** At night, radiation cooling over land creates a reversed situation, with higher pressure at the surface and lower pressure aloft, developing a land breeze.

5.9 Sea and land breezes

The contrast between the land surface, which heats and cools rapidly, and the ocean surface, which has a more uniform temperature, induces pressure gradients to create sea and land breezes.



▲ **Day—valley breeze** During the day, mountain hillslopes are heated intensely by the Sun, making the air expand and rise. This draws in air from the valley below, creating a valley breeze.



▲ **Night—mountain breeze** At night, the hillslopes are chilled by radiation, setting up a reversed convection loop. The cooler, denser hillslope air moves valley-ward, down the hillslopes, to the plain below. This is the mountain breeze.

5.10 Valley and mountain breezes

5.11 Brush fire

Residents of the Sylmar area of the San Fernando Valley, in Los Angeles, flee from their hillside homes as a brushfire approaches in October, 2008. Driven by intense Santa Ana winds, the fires torched mobile homes and industrial buildings in addition to closing a major freeway during rush hour.

that descends from high plateaus through mountain passes and valleys.

WIND POWER

Wind power is an indirect form of solar power that has been used for centuries. The total supply of wind energy is enormous. The World Meteorological Organization has estimated that about 20 million megawatts could be generated at favorable sites throughout the world, an amount about 100 times greater than the total electrical generating capacity of the United States. Figure 5.12 shows some different types of windmills and wind turbines.

5.12 Windmills and wind turbines

Wind turbines vary in size and design. Some are suitable for individual farms, ranches, and homes, whereas others generate power on a commercial scale.

▼ **Vertical wind turbines** These vertical wind turbines are Darrieus rotors—circular blades turning on a vertical axis. They generate power without needing to face the wind. These rotors are at a "wind farm" east of San Francisco in the Altamont Pass area of Alameda and Contra Costa counties. A group of wind farms here with a total of about 3000 turbines provides 500 million kilowatt-hours of electricity per year.

▲ **Modern windmills** A wind farm in San Gorgonio Pass, near Palm Springs, California. Wind speeds here average 7.5 m/s (17 mi/hr). Wind farms use wind turbines with a generating capacity in the range of 50 to 100 kilowatts.

Cyclones and Anticyclones

THE CORIOLIS EFFECT

We have seen that the pressure gradient force moves air from high pressure to low pressure. For sea and land breezes, which are local in nature, this pushes wind in about the same direction as the pressure gradient. But on global scales, the direction of air motion is more complicated. The difference is caused by the Earth's rotation, through the **Coriolis effect** (Figure 5.13).

> **The Coriolis effect causes the apparent motion of winds to be deflected away from the direction of the pressure gradient. Deflection is to the right in the northern hemisphere and to the left in the southern hemisphere as viewed from the starting point.**

The Coriolis effect was first identified by the French scientist Gaspard-Gustave de Coriolis in 1835. Because of the Coriolis effect, an object in the northern hemisphere moves as if a force were pulling it to the right. In the southern hemisphere, objects move as if pulled to the left. This apparent deflection does not depend on direction of motion—it occurs whether the object is moving toward the north, south, east, or west.

Geographers are usually concerned with analyzing the motions of air masses or ocean currents from the viewpoint of an Earth observer on the geographic grid, not from the viewpoint of space. So, as a shortcut, we treat the Coriolis effect as a sideward-turning force that always acts at right angles to the direction of motion. The strength of this Coriolis "force" increases with the speed of motion but decreases with latitude. This trick allows us to describe motion properly within the geographic grid (Figure 5.14).

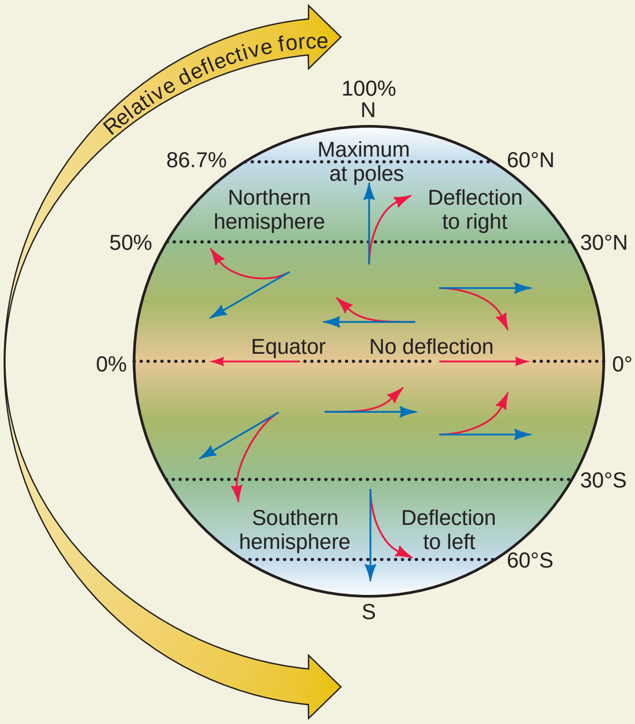
GEODISCOVERIES **Coriolis Effect**
Animations 1 and 2. Still confused about the Coriolis effect? A view of the rotating Earth from above either pole shows how an object moving in a straight line appears to follow a curving path. A game of catch between two players on a turntable also demonstrates the concept.

CYCLONES AND ANTICYCLONES

We're used to seeing low- and high-pressure centers on the daily weather maps. You can think of them as marking vast whirls of air in spiraling motion. In low-pressure centers, known as **cyclones**, air spirals inward and upward (Figure 5.15). This inward spiraling motion is called *convergence*. In high-pressure centers,

5.13 The Coriolis effect

▼ The Coriolis effect appears to deflect winds and ocean currents to the right in the northern hemisphere and to the left in the southern hemisphere. Blue arrows show the direction of initial motion, and red arrows show the direction of motion apparent to the Earth observer. The Coriolis effect is strongest near the poles and decreases to zero at the Equator.



▼ Imagine that a rocket is launched from the North Pole toward New York, aimed along the 74° W longitude meridian. As it travels toward New York, the Earth rotates from west to east beneath its straight flight path. If you were standing at the launch point on the rotating Earth below, you would see the rocket's trajectory curve to the right, away from New York and toward Chicago—despite the fact that the rocket has been flying in a straight line from the viewpoint of space. To reach New York, the rocket's flight path would have to be adjusted to allow for the Earth's rotation.

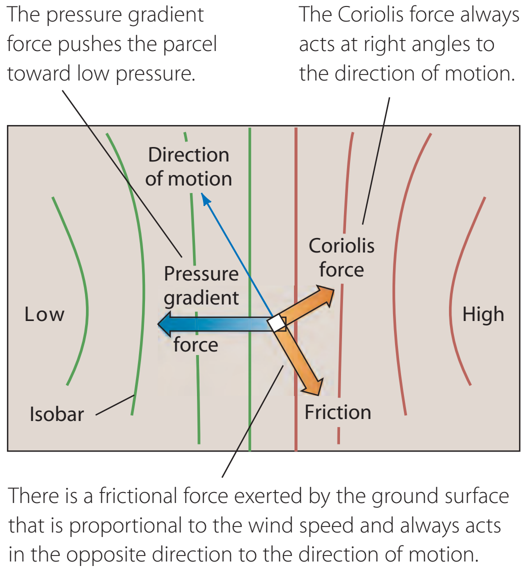
known as **anticyclones**, air spirals downward and outward. This outward spiraling motion is called *divergence*.

> **In a cyclone, winds converge, spiraling inward and upward. In an anticyclone, winds diverge, spiraling downward and outward.**

Low-pressure centers (cyclones) are often associated with cloudy or rainy weather, whereas high-pressure centers (anticyclones) are often associated with fair weather. Why is this? When air is forced upward, it is cooled according to the *adiabatic principle*, allowing condensation and precipitation to begin. So, cloudy and rainy weather often accompanies the inward and upward air motion of cyclones. In contrast, in anticyclones the air sinks and spirals outward. When air descends, it is warmed by the adiabatic process, so condensation can't occur. That is why anticyclones are often associated with fair weather. Cyclones and anticyclones can be a thousand kilometers (about 600 mi) across, or more. A fair-weather system—an anticyclone—may stretch from the Rockies to the Appalachians. Cyclones and anticyclones can remain more or less stationary, or they can move, sometimes rapidly, to create weather disturbances.

Global Wind and Pressure Patterns

For simplicity, let's begin by looking at surface winds and pressure patterns on an ideal Earth that does not have oceans and continents, or seasons (Figure 5.16). **Hadley cells** are key to an understanding of the wind patterns on our ideal Earth. These form because the Equator is heated more strongly by the Sun than other places, creating thermal circulations. Air rises over the Equator and is drawn poleward by the pressure gradient. But as the air moves poleward, the Coriolis force



5.14 Balance of forces on a parcel of surface air

A parcel of air in motion near the surface is subjected to three forces. The sum of these three forces produces motion toward low pressure but at an angle to the pressure gradient. This example is for the northern hemisphere.

turns it westward, so it eventually descends at about a 30° latitude, completing the thermal circulation loop. This is a Hadley cell.

The rising air at the equator produces a zone of surface low pressure known as the *equatorial trough*. Air in both hemispheres moves toward this equatorial trough. There it converges and rises as part of the Hadley circulation. The narrow zone where the air converges is called the **intertropical convergence zone (ITCZ)**. Because the air is largely moving upward, surface winds are light and variable. This region is known as the *doldrums*.

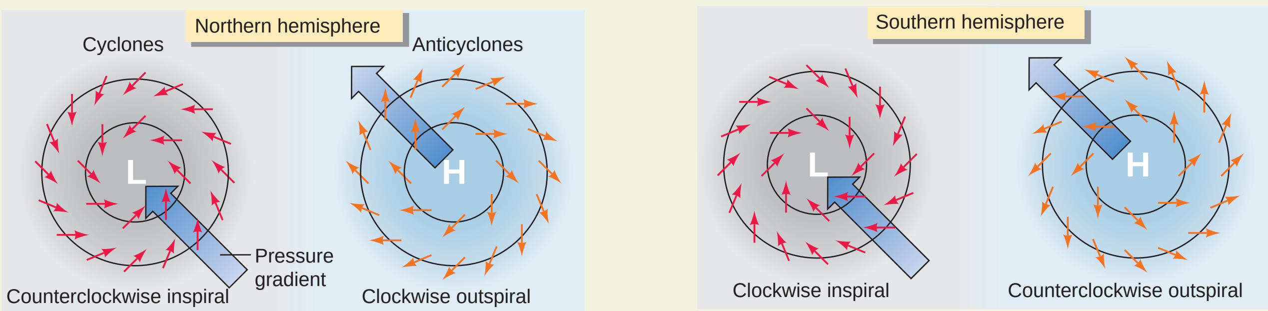
Air descends on the poleward side of the Hadley cell circulation, so there surface pressures are high. This produces two **subtropical high-pressure belts**, each centered at about 30° latitude. Two, three, or four very large and stable anticyclones form within these belts. At the centers of these anticyclones, air descends and winds are weak. The air is calm as much as one-quarter of the time.

In the Hadley cell thermal circulation, air rises at the intertropical convergence zone and descends in the subtropical high-pressure cells.

Winds around the subtropical high-pressure centers spiral outward and move toward equatorial as well as middle latitudes. The winds moving equatorward are the dependable trade winds that drove the sailing ships of merchant traders. North of the Equator, they blow from the northeast and are called the *northeast trade winds*. South of the equator, they blow from the southeast and are the *southeast trades*. Poleward of the subtropical highs, air spirals outward, producing southwesterly winds in the northern hemisphere and northwesterly winds in the southern hemisphere.

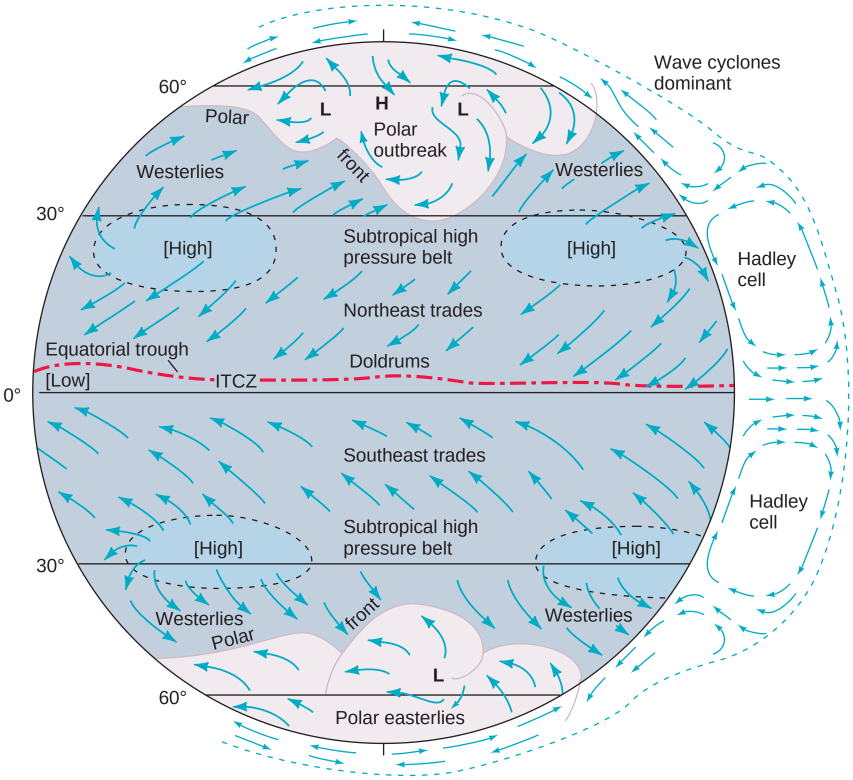
Between about 30° and 60° latitude, the pressure and wind patterns become more complex. This is a zone of conflict between air bodies with different characteristics—masses of cool, dry air—*polar outbreaks*—move into the region, heading eastward and equatorward along a border known as the **polar front**.

5.15 Air motion in cyclones and anticyclones



▲ In a cyclone, low pressure is at the center, so the pressure gradient is straight inward. In an anticyclone, high pressure is at the center, so the gradient is straight outward. But because of the rightward Coriolis force and friction with the surface, the surface air moves at an angle across the gradient, creating a counterclockwise inspiraling motion and a clockwise outspiraling motion.

▲ In the southern hemisphere, the cyclonic spiral will be clockwise because the Coriolis force acts to the left. For anticyclones, the situation is reversed.



5.16 Global surface winds on an ideal Earth

We can see what global surface winds and pressures would be like on an ideal Earth, without the disrupting effect of oceans and continents and the variation of the seasons. Surface winds are shown on the disk of the Earth, while the cross section at the right shows winds aloft.

This results in highly variable pressures and winds. On average, however, winds are more often from the west, so the region is said to have *prevailing westerlies.*

At the poles, the air is intensely cold and high pressure occurs. At the South Pole, outspiraling of winds around this polar anticyclone creates surface winds from a generally easterly direction, known specifically as *polar easterlies.* In the north polar region, polar easterlies are weaker and other wind directions are common.

GEODISCOVERIES **General Atmospheric Circulation**

Start your mastery of global surface and upper-level winds with an overview animation showing the principal features of global atmospheric circulation.

SUBTROPICAL HIGH-PRESSURE BELTS

So far we've looked at wind and pressure patterns for a seasonless, featureless Earth. Let's turn now to actual global surface wind and pressure patterns, shown in Figure 5.17. The subtropical high-pressure belts, created by the Hadley cell circulation, are important features. In the northern hemisphere, they include two large high-pressure cells that flank North America—the *Hawaiian* and *Azores highs.* In the southern hemisphere, similar high-pressure cells flank South America and southern Africa.

The intertropical convergence zone and subtropical high-pressure belts are prominent features of the global wind and pressure pattern. They shift northward and southward with the seasons.

We've seen that insolation is most intense when the Sun is directly overhead, and the latitude at which the Sun is directly overhead changes with the seasons. This cycle causes the Hadley cells to intensify and move poleward during their high-sun season, which also moves the subtropical high-pressure belts.

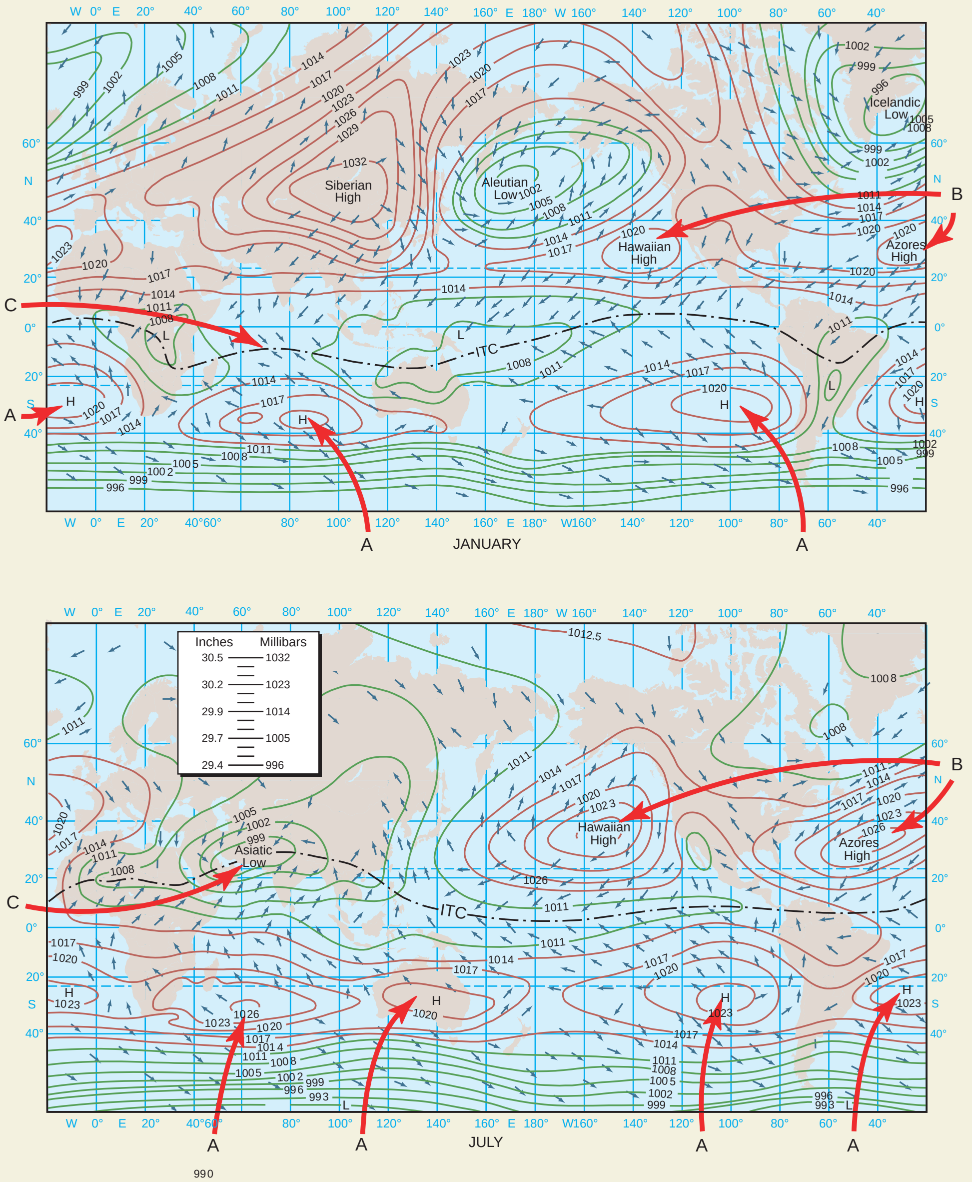
When the Hawaiian and Azores highs intensify and move northward in the summer, the east and west coasts of North America feel their effects. On the west coast, dry, descending air from the Hawaiian high dominates, so fair weather and rainless conditions prevail. On the east coast, air from the Azores high flows across the continent from the southeast. These winds travel long distances across warm, tropical ocean surfaces before reaching land, picking up moisture and heat. So they generally produce hot, humid weather for the central and eastern United States. In winter, these two anticyclones weaken and move to the south—leaving North America's weather at the mercy of colder winds and air masses from the north and west.

ITCZ AND THE MONSOON CIRCULATION

The ITCZ also shifts along with the Hadley cell circulation. The shift in the ITCZ is moderate in the western hemisphere, with the ITCZ moving a few degrees north

5.17 Global winds and pressures, January and July—Mercator projections

These global maps show average sea-level pressures and winds for daily observations in January and July. Values greater than average (1013 mb, 29.2 in. Hg) are shown in red, while values lower than average are shown in green. Pressure units are millibars reduced to sea level. Arrows indicate prevailing wind direction.



A Southern hemisphere subtropical high-pressure belt
The most prominent features of the maps are the subtropical high-pressure belts, created by the Hadley cell circulation. The southern hemisphere high-pressure belt has three large high-pressure cells, each developed over oceans, that persist year round. A fourth, weaker high-pressure cell forms over Australia in July, as the continent cools during the southern hemisphere winter.

B Northern hemisphere subtropical high-pressure belt
The situation is different in the northern hemisphere. The subtropical high-pressure belt shows two large anticyclones centered over oceans—the Hawaiian High in the Pacific and the Azores High in the Atlantic. From January to July, these intensify and move northward.

C Seasonal shift in the ITCZ
There is a huge shift in Africa and Asia that you can see by comparing the two maps. In January, the ITCZ runs south across eastern Africa and crosses the Indian Ocean to northern Australia at a latitude of about 15° S. In July, it swings north across Africa along the south rim of the Himalayas, in India, at a latitude of about 25° N—a shift of about 40 degrees of latitude!

from January to July over the oceans (Figure 5.17). In South America, the ITCZ lies across the Amazon in January and swings northward by about 20°.

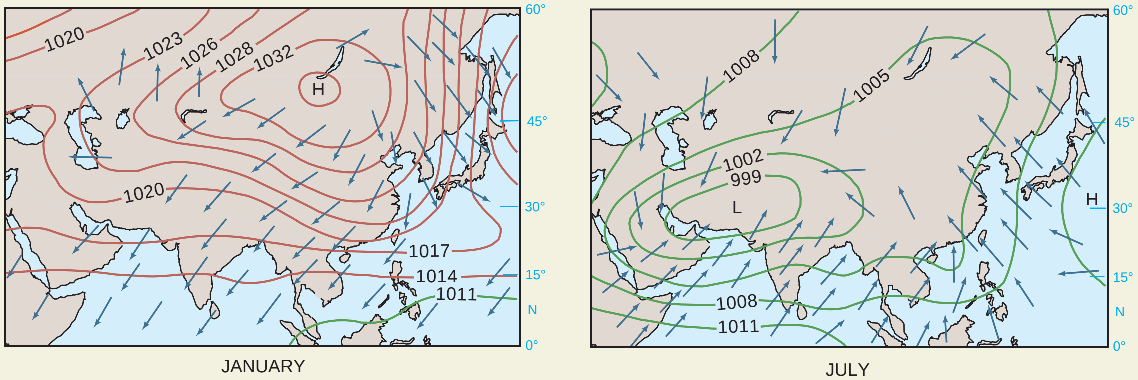
However, there is a huge shift of the ITCZ in Asia—about 40° of latitude—that is readily visible on the two Mercator maps of Figure 5.17C. Why does such a large shift occur? In winter (January map), the snow cover and low insolation in eastern Siberia create an intense and very cold surface high-pressure center—the *Siberian high*. In summer (July map), this high-pressure center has disappeared and is replaced by a surface low centered over the Middle Eastern region. This Asiatic low is produced by the intense summer heating of the desert landscape.

The movement of the ITCZ and the change in these surface pressure patterns with the seasons create a

5.18 Asian monsoon

The Asian monsoon is an alternation of cool, dry northeasterly airflow with warm, moist southwesterly airflow experienced in south Asia.

▶ **Monsoon rains** Heavy monsoon rains turn streets into canals in Delhi, India.



▲ **Monsoon wind and pressure patterns** The Asiatic monsoon winds alternate in direction from January to July, responding to reversals of barometric pressure over the large continent.

reversing wind pattern in Asia known as the **monsoon** (Figure 5.18). In the winter, there is a strong outflow of dry, continental air from the north across China, Southeast Asia, India, and the Middle East. During this *winter monsoon*, dry conditions prevail. In the *summer monsoon*, warm, humid air from the Indian Ocean and the southwestern Pacific moves northward and northwestward into Asia. The cool, dry winter weather is replaced with steamy summer showers.

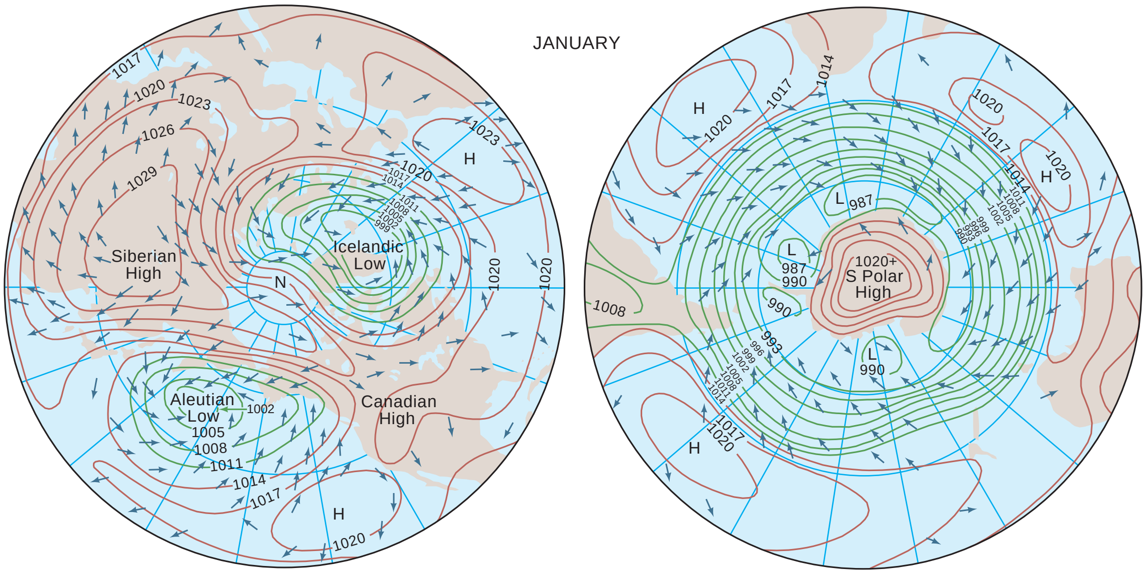
The Asian monsoon wind pattern consists of a cool, dry air flow from the northeast during the low-Sun season, and a warm, moist airflow from the southwest during the high-Sun season.

North America also experiences a monsoon effect, but it is considerably weaker. During summer, warm, moist air from the Gulf of Mexico tends to move northward across the central and eastern United States. In winter, the airflow across North America generally reverses, and dry, continental air from Canada moves south and eastward.

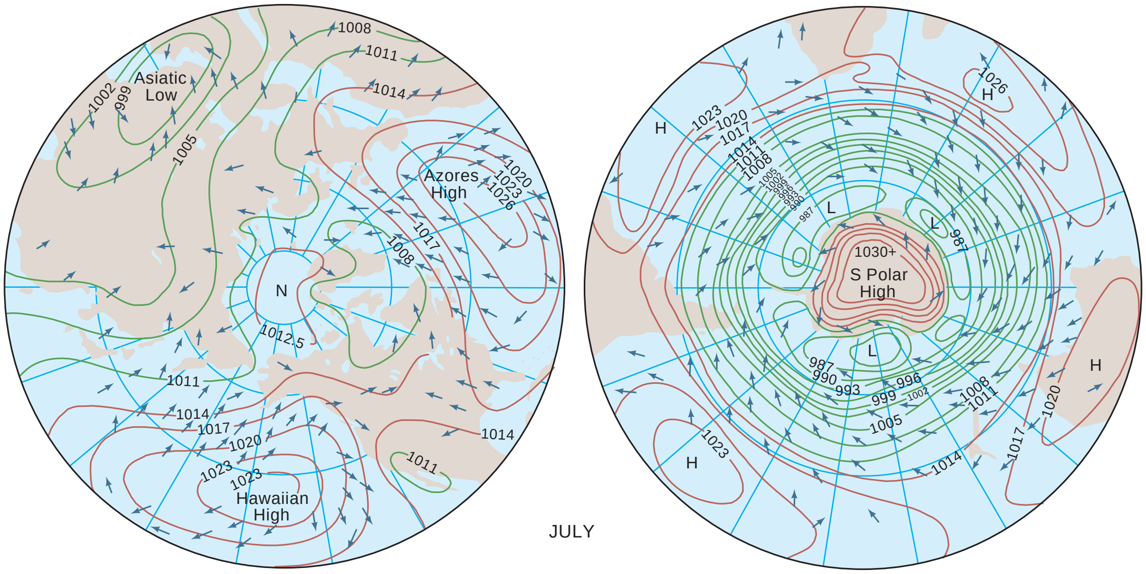
WIND AND PRESSURE FEATURES OF HIGHER LATITUDES

The northern hemisphere has two large continental masses separated by oceans and an ocean at the pole. The southern hemisphere has a large ocean with a cold, ice-covered continent at the center. These differing land–water patterns strongly influence the development of high- and low-pressure centers with the seasons (Figure 5.19).

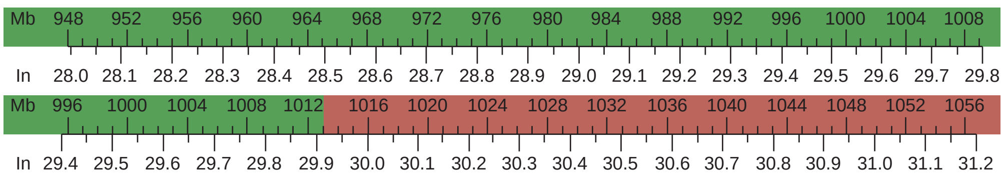
Now, continents are colder in winter and warmer in summer than oceans at the same latitude. We know that



▲ **January** In the northern hemisphere winter, air spirals outward from the strong Siberian high and its weaker cousin, the Canadian high. The Icelandic low and Aleutian low spawn winter storm systems that move southward and eastward on to the continents. In the southern hemisphere summer, air converges toward a narrow low-pressure belt around the south polar high.



▲ **July** In the northern hemisphere summer, the continents show generally low-surface pressure, while high pressure builds over the oceans. The strong Asiatic low brings warm, moist Indian Ocean air over India and Southeast Asia. A weaker low forms over the deserts of the southwestern United States and northwestern Mexico. Outspiraling winds from the Hawaiian and Azores highs keep the west coasts of North America and Europe warm and dry, and the east coasts of North America and Asia warm and moist. In the southern hemisphere winter, the pattern is little different from winter, although pressure gradients are stronger.



5.19 Atmospheric pressure—polar projections

These global maps show average sea-level pressure and wind for daily observations in January and July. Values greater than average barometric pressure are shown in red, while lower values are in green.

cold air is associated with surface high pressure and warm air with surface low pressure. So, continents have high pressure in winter and lower pressure in summer.

In January in the northern hemisphere, we see a pattern of strong high pressure (Siberian and Canadian highs) over continents and strong low pressure (Icelandic low and Aleutian low) over northern oceans that is driven by winter temperature contrasts. In July, this pattern nearly disappears as continents and northern oceans warm to similar temperatures.

In the southern hemisphere, there is a permanent anticyclone—the South Polar high—centered over Antarctica that varies little from January to July. It occurs because the continent is covered by thousands of meters of ice and is always cold. Surrounding the high is a band of deep low pressure, with strong, inward-spiraling westerly winds on its northern side. As early mariners sailed southward, they encountered this band, where wind strength intensifies toward the pole. Because of the strong prevailing westerlies, they named these southern latitudes the "roaring forties," "flying fifties," and "screaming sixties."

Winds Aloft

We've looked at airflows at or near the Earth's surface, including both local and global wind patterns. But how does air move at the higher levels of the troposphere? Like air near the surface, winds at upper levels of the atmosphere move in response to pressure gradients and are influenced by the Coriolis effect.

How do pressure gradients arise at upper levels? There is a simple physical principle that states that pressure decreases less rapidly with height in warmer air than in colder air. Also recall that the solar energy input is greatest near the Equator and least near the poles, resulting in a temperature gradient from the Equator to the poles. This gives rise to a pressure gradient (Figure 5.20).

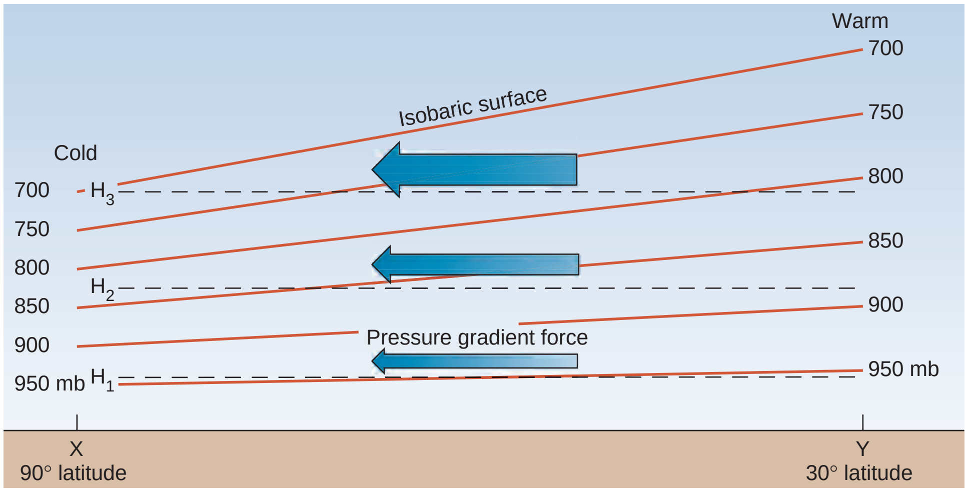
THE GEOSTROPHIC WIND

How does a pressure gradient force pushing poleward produce wind, and what will the wind direction be? Any wind motion is subject to the Coriolis force, which turns it to the right in the northern hemisphere and to the left in the southern hemisphere. So, poleward air motion is toward the east, creating west winds in both hemispheres.

Unlike air moving close to the surface, an upper-air parcel moves without a friction force because it is so far from the source of friction—the surface. So, there are only two forces on the air parcel—the pressure gradient force and the Coriolis force.

Imagine a parcel of air, as shown in Figure 5.21. The air parcel begins to move poleward in response to the pressure gradient force. As it accelerates, the Coriolis force pulls it increasingly toward the right. As its velocity increases, the parcel turns increasingly rightward until the Coriolis

At high altitudes, a moving parcel of air is subjected to two forces—a pressure gradient force and the Coriolis force. When the forces balance, air moves at right angles to the pressure gradient, parallel to the isobars, as the geostrophic wind.



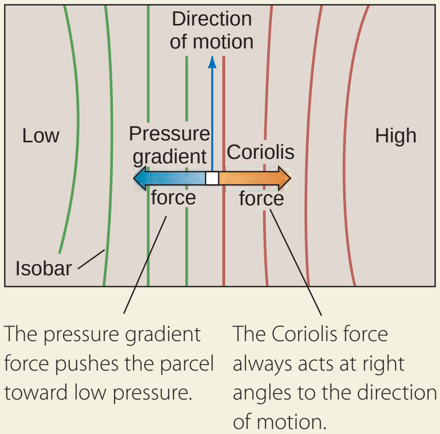
5.20 Upper-air pressure gradient

The isobaric surfaces in this upper-air pressure gradient map slope downward from the low latitudes to the pole, creating a pressure gradient force. Because the atmosphere is warmer near the Equator than at the poles, a pressure gradient force pushes air poleward. The pressure gradient force increases with altitude, bringing strong winds at high altitudes.

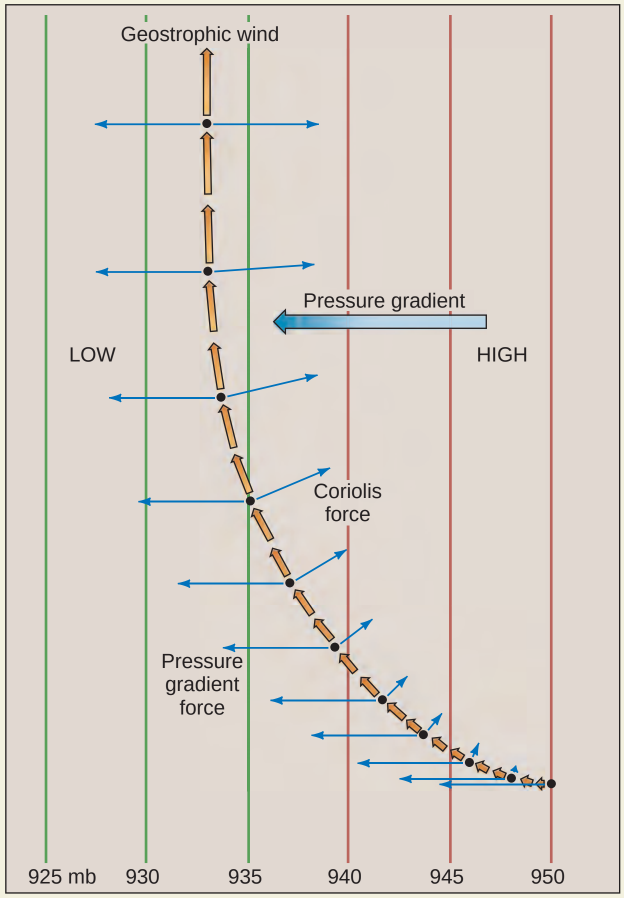
5.21 Geostrophic wind

The geostrophic wind blows parallel to the isobars at high altitudes. (Northern hemisphere example.)

▼ **Forces on an air parcel** At upper levels in the atmosphere, a parcel of air is subjected to a pressure gradient force and a Coriolis force.



▶ **Motion of an air parcel** The parcel of air moves in response to a pressure gradient. As it moves, it is turned progressively sideward until the pressure gradient and Coriolis forces balance, producing the geostrophic wind.



force just balances the gradient force. At that point, the sum of forces on the parcel is zero, so its speed and direction remain constant. We call this type of airflow the **geostrophic wind**. It occurs at upper levels in the atmosphere, and we can see from the diagram that it flows parallel to the isobars.

Figure 5.22 shows an upper-air map for North America on a late June day. A large, upper-air low is centered over the Great Lakes. Since low pressure aloft indicates cold air (Figure 5.20), this is a mass of cool Canadian air that has moved southward to dominate the eastern part of the continent. A large, but weaker, upper-air high is centered over the southwestern desert. This will be a mass of warm air, heated by intense surface insolation on the desert below.

The geostrophic wind flow, shown by the wind arrows, follows the contours closely. It is strongest where the contours are closest together, because there the pressure gradient force is strongest. The wind around the upper-air low also tends to spiral inward and converge on the low. The converging air descends toward the surface, where surface high pressure is present, and then spirals outward. Similarly, the wind around the upper-air high spirals outward and diverges away from the center. At the surface, low pressure causes air to spiral inward and upward.

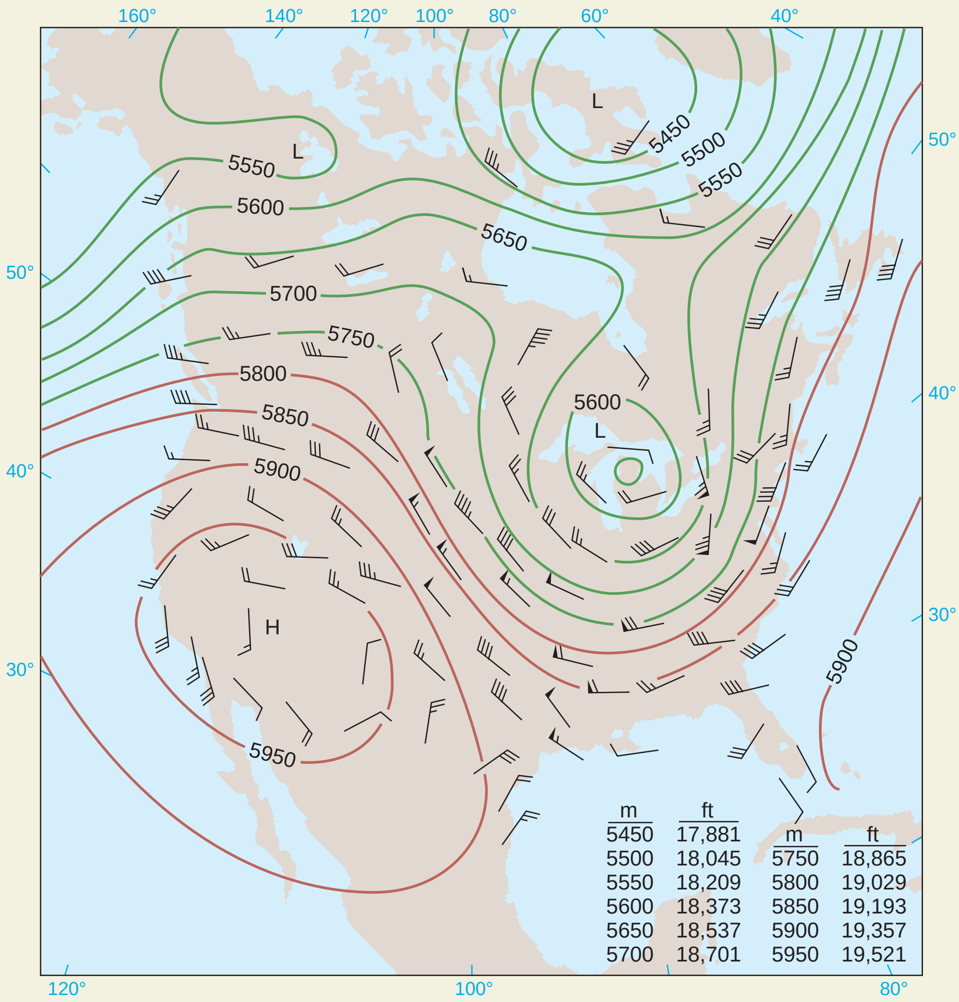
GLOBAL CIRCULATION AT UPPER LEVELS

Figure 5.23 sketches the general airflow pattern at higher levels in the troposphere. It has four major features—a polar low, upper-air easterlies, tropical high-pressure belts, and weak equatorial westerlies. We've seen that the general temperature gradient from the tropics to the poles creates a pressure gradient force that

The general pattern of winds aloft is a band of equatorial easterly winds, flanked by tropical high-pressure belts, and a zone of westerly winds to poleward.

5.22 Upper-air wind and pressure map

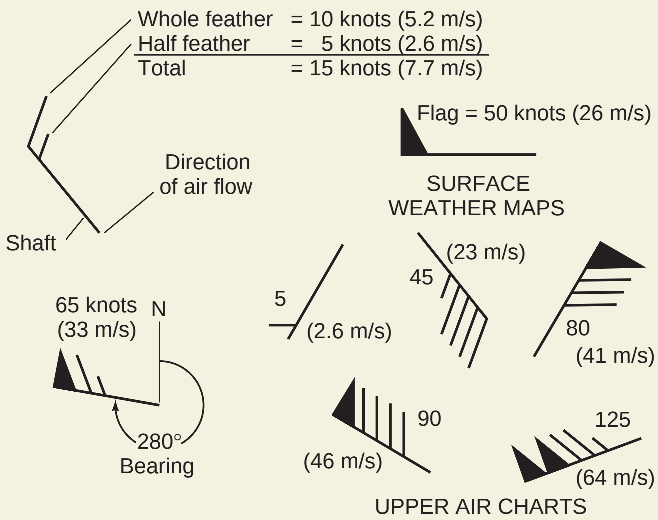
The upper-air winds blow along the elevation contours of the 500-mb pressure level.

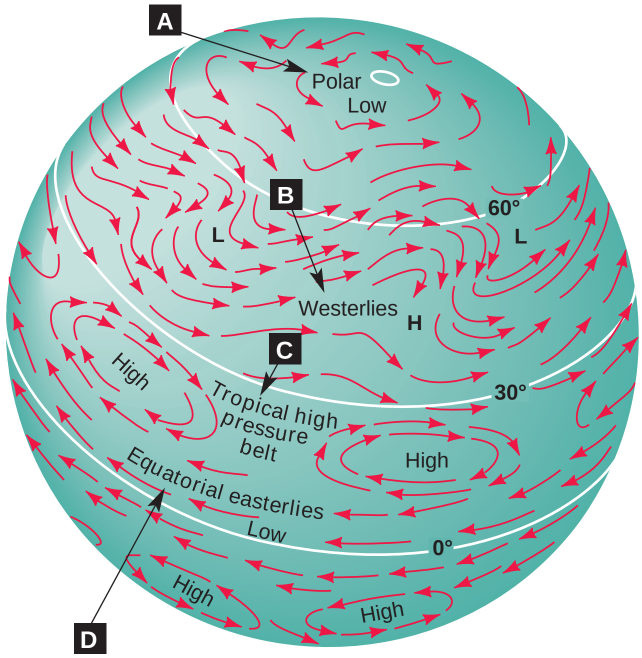


m	ft	m	ft
5450	17,881		
5500	18,045	5750	18,865
5550	18,209	5800	19,029
5600	18,373	5850	19,193
5650	18,537	5900	19,357
5700	18,701	5950	19,521

◀ **An upper-air map for a day in late June** Lines are height contours for the 500-mb surface. This surface dips downward where the air column is colder (low pressure aloft) and domes upward where the air column is warmer (high pressure aloft). So the height contours follow the pressure gradient, and the geostrophic wind follows the height contours.

▶ **Explanation of wind arrows** 1 knot (nautical mile per hour) = 0.514 meters per second.





5.23 Global upper-level winds

A Polar low At high latitudes the westerlies form a huge circumpolar spiral, circling a great polar low-pressure center.

B Upper-air westerlies In this generalized plan of global winds high in the troposphere, strong west winds dominate the mid- and high-latitude circulation. They often sweep to the north or south around centers of high and low pressure aloft.

C Tropical high-pressure belt Toward lower latitudes, atmospheric pressure rises steadily, forming a tropical high-pressure belt at 15° to 20° N and S lat. This high-altitude part of the surface subtropical high-pressure belt is shifted equatorward.

D Equatorial easterlies In the equatorial region, there is a zone of low pressure between the high-pressure ridges in which the winds are light but generally easterly. These winds are called the *equatorial easterlies*.

generates westerly winds in the upper atmosphere. These *upper-air westerlies* blow in a complete circuit about the Earth, from about 25° lat. almost to the poles, often undulating from their westerly track.

So, the overall picture of upper-air wind patterns is really quite simple—a band of weak easterly winds in the equatorial zone, belts of high pressure near the Tropics of Cancer and Capricorn, and westerly winds, with some variation in direction, spiraling around polar lows.

JET STREAMS AND THE POLAR FRONT

Jet streams are wind streams that reach great speeds in narrow zones at a high altitude. They occur where atmospheric pressure gradients are strong. Along a jet stream, the air moves in pulses along broadly curving tracks. The greatest wind speeds occur in the center of the jet stream, with velocities decreasing away from it.

There are three kinds of jet streams. Two are westerly streams, and the third is a weaker jet with easterly winds that develops in Asia as part of the summer monsoon circulation. These are shown in Figure 5.24A. The most poleward type of jet stream is located along the polar front. It is called the *polar-front jet stream* (or simply the "polar jet") (Figure 5.24B).

Jet streams are streams of fast-moving air aloft that occur where atmospheric temperature gradients are strong. Each hemisphere normally exhibits westerly polar and subtropical jet streams. An easterly jet occurs in summer over Asia and Africa.

The polar jet is generally located between 35° and 65° latitude in both hemispheres. It follows the boundary between cold polar air and warm subtropical air (Figure 5.24C). It is typically found at altitudes of 10 to 12 km (about 30,000 to 40,000 ft), and wind speeds in the jet range from 75 to as much as 125 m/s (about 170 to 280 mi/hr).

The subtropical jet stream occurs at the tropopause, just above subtropical high-pressure cells in the northern and southern hemispheres (Figure 5.25). There, westerly wind speeds can reach 100 to 110 m/s (about 215 to 240 mph), associated with the increase in velocity that occurs as an air parcel moves poleward from the Equator.

The tropical easterly jet stream occurs at even lower latitudes. It runs from east to west—opposite in direction to that of the polar-front and subtropical jet streams. The tropical easterly jet occurs only in summer and is limited to a northern hemisphere location over Southeast Asia, India, and Africa.

GEODISCOVERIES **Remote Sensing and Climate Interactivity**

View satellite images to test your knowledge of global circulation and global cloud patterns. Check out pictures of planet Earth.

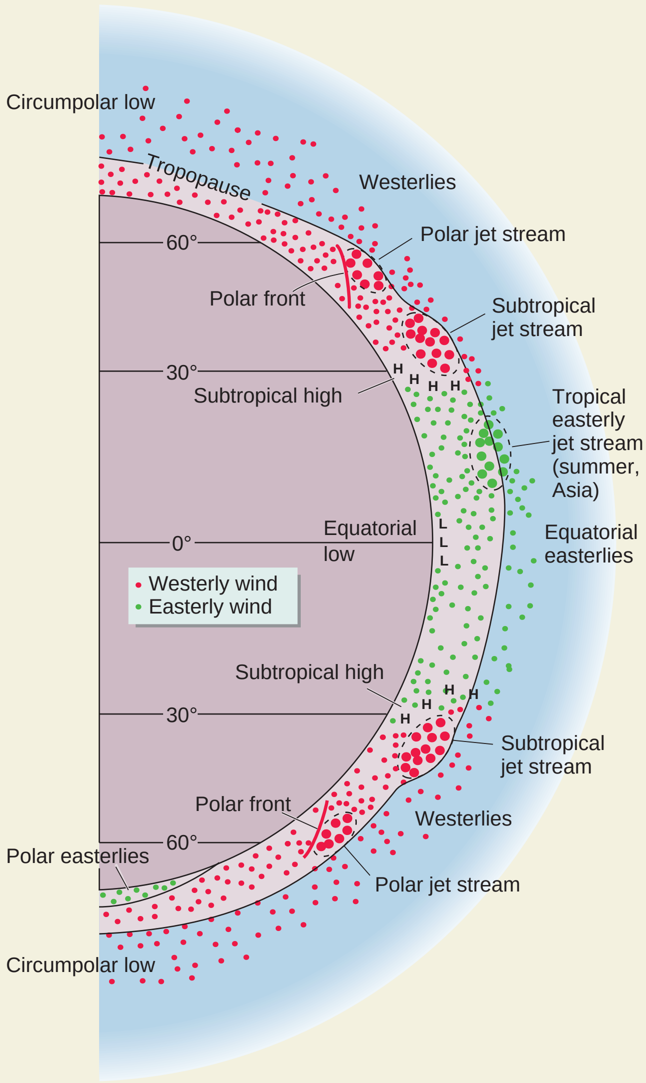
DISTURBANCES IN THE JET STREAM

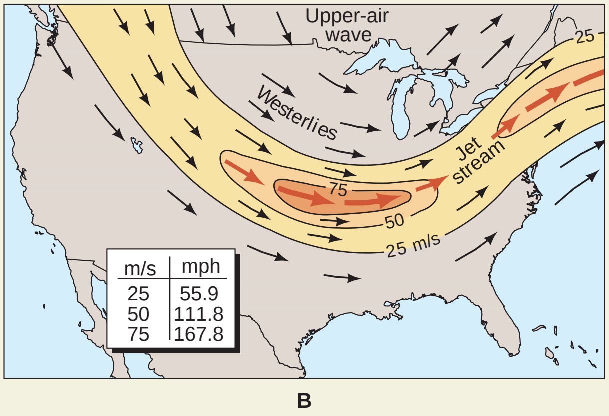
While the jet stream is typically a region of confined, high-velocity westerly winds found in the midlatitudes, the jet stream can actually contain broad wavelike undulations called **jet stream disturbances**. These are sometimes also called *Rossby* waves, after Carl-Gustaf Rossby, a Swedish-American meteorologist who first observed and studied them.

Many processes can produce disturbances in the eastward flow of the jet stream. One of the most important is related to *baroclinic instability*, which makes the atmosphere unstable to small disturbances in the jet stream and allows these disturbances to grow over time. (The word "baroclinic" comes from the prefix baro-, meaning pressure, and the suffix cline, meaning gradient.)

5.24 Jet Streams

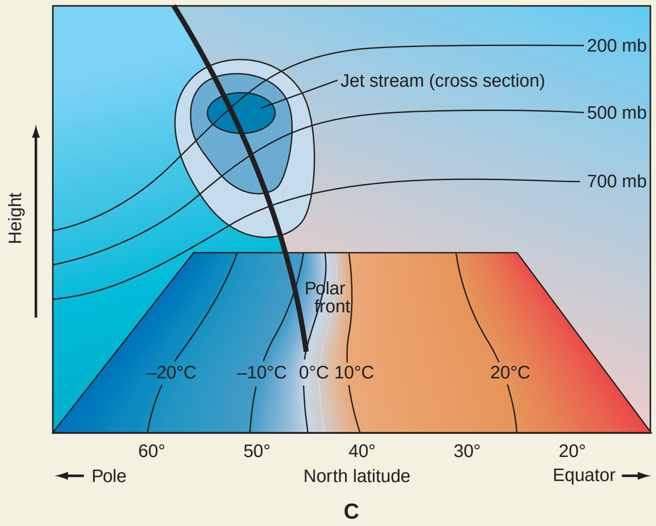
▼ **Upper-level circulation cross section** A schematic diagram of wind directions and jet streams along a meridian from pole to pole. The four polar and subtropical jets are westerly in direction, in contrast to the single tropical easterly jet.





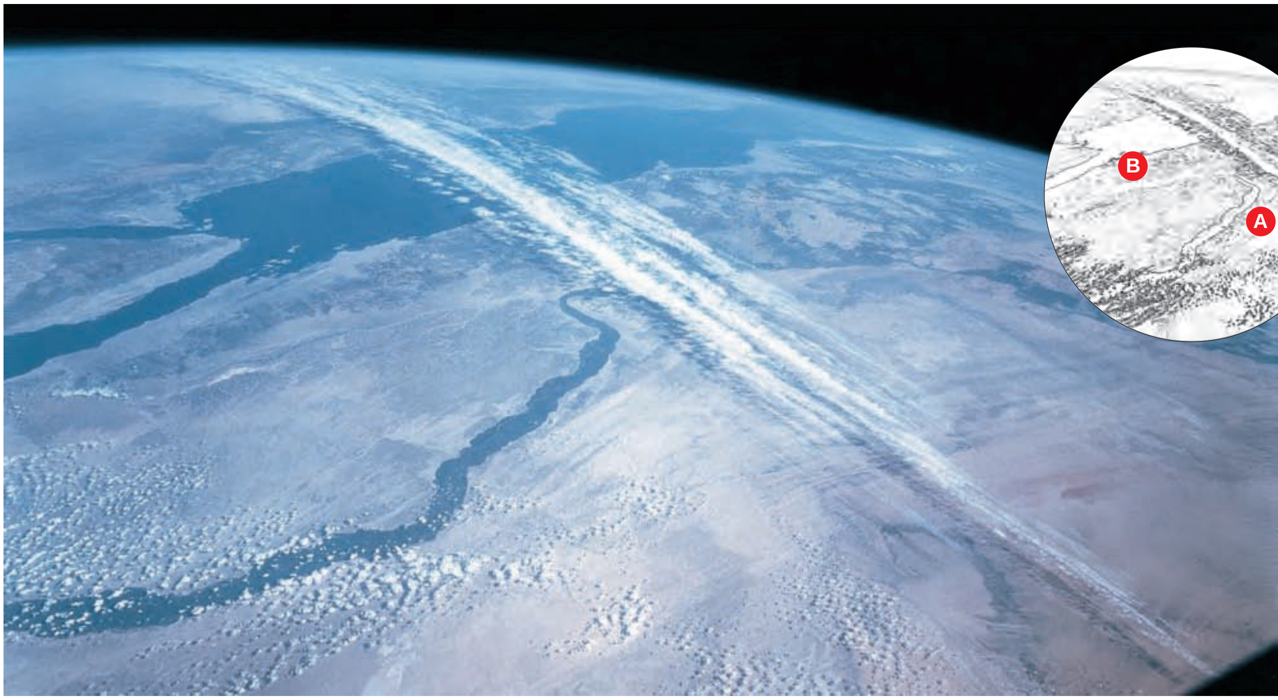
▲ **Polar jet stream** The polar jet stream is shown on this map by lines of equal wind speed.

▼ **Polar jet stream and the polar front** The polar jet stream is normally located over the polar front. Here, the strong temperature gradient between warm air to the south and cold air to the north produces a strong pressure gradient that can support the high-velocity jet stream.



The development of these disturbances is shown in Figure 5.26. For a period of several days or weeks, the jet stream flow may be fairly smooth. Then, an undulation develops. As the undulation grows, warm air pushes poleward, while a tongue of cold air is brought to the south. Eventually, the cold tongue is pinched off, leaving a pool of cold air at a latitude far south of its original location. This cold pool may persist for some days or weeks, slowly warming with time. Because of its cold center, it will contain low pressures aloft. In addition, the cold air in the core will descend and diverge at the surface, creating surface high pressure. Similarly, a warm air pool will be pinched off far to the north of its original location. Within the core of the warm pool will be rising air, with convergence and low pressure at the surface, as well as high pressure aloft.

What causes a jet stream disturbance to grow over time? This growth is actually a complicated process and involves the interaction of the upper-air circulations—formed by the high- and low-pressure centers—with



5.25 Jet stream clouds

A strong subtropical jet stream is marked in this space photo by a narrow band of cirrus clouds that occurs on the equatorward side of the jet. The jet stream is moving from west to east at an altitude of about 12 km (40,000 ft). The cloud band lies at about 25° N lat. In this view, astronauts aimed their camera toward the southeast, taking in the Nile River Valley and the Red Sea. At the left is the tip of the Sinai Peninsula.

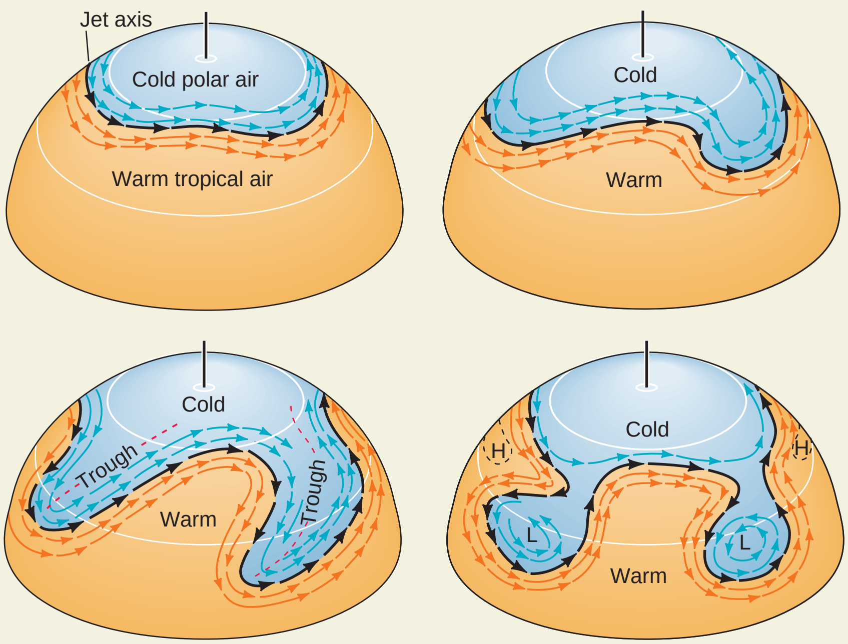
EYE ON THE LANDSCAPE **What else would the geographer see?** Large expanses of the Middle East are essentially devoid of vegetation, and so a space photo such as this shows variation in soil and surface color. Many of the white areas (A) are wind-blown sand sheets. Ranges of hills and low mountains (B) appear darker.

5.26

Disturbances form in the upper-air westerlies of the northern hemisphere, marking the boundary between cold polar air and warm tropical air.

▶ The flow of air along the polar front is fairly smooth for several days or weeks, but then it begins to undulate.

◀ As the undulation becomes stronger, disturbances in the jet stream begin to form. Warm air pushes poleward, while cold air is brought to the south.



▶ The waves become stronger and more developed. Tongues of cold air are brought to the south, where they occupy low-pressure troughs.

◀ Eventually, the tongues are pinched off, leaving pools of cold air at latitudes far south of their original location. These pools of cold air form cyclones that can persist for some days or weeks.

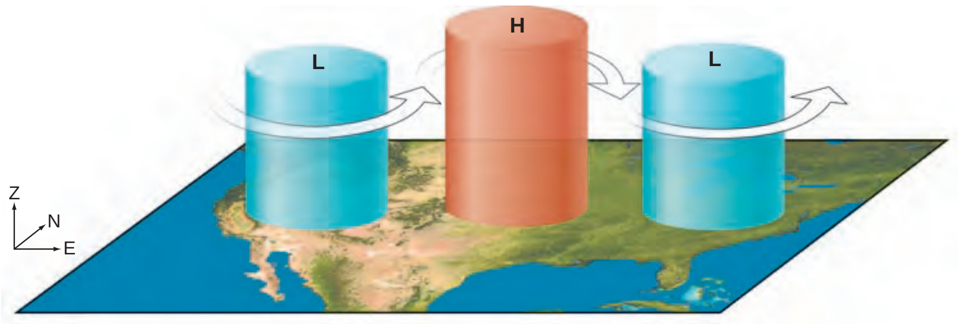
the global temperature gradient between the warmer, low-latitude air and colder, high-latitude air. This growth process is described in Figure 5.27.

Consider first what happens to a slight disturbance in the jet stream. These disturbances arise from pressure differences between one location and another, resulting in geostrophic wind variations. In addition, the pressure differences are accompanied by temperature differences, with high pressures aloft found over regions of warm air and low pressures aloft over regions of cool air.

As air circulates around these disturbances, the counterclockwise circulations associated with the low-pressure system bring warm, low-latitude air into a region that is already warm. In contrast, the clockwise circulation around the high-pressure region brings cold, high-latitude air into a region that is already cold. As a result, the warm regions tend to get warmer and the cold regions tend to get colder. In turn, the high pressures associated with the warm-air region tend to get higher and the low pressures associated with the cold-air region tend to get lower. This process intensifies the pressure gradient between the two regions, resulting in stronger winds and an even larger disturbance.

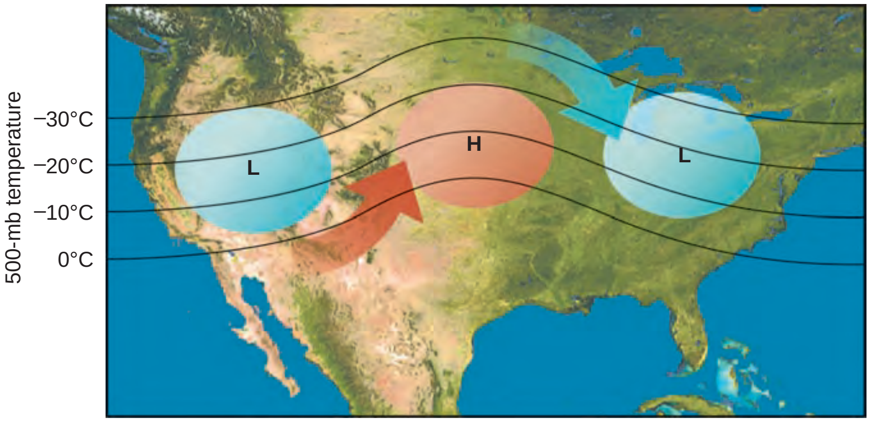
Ocean Circulation

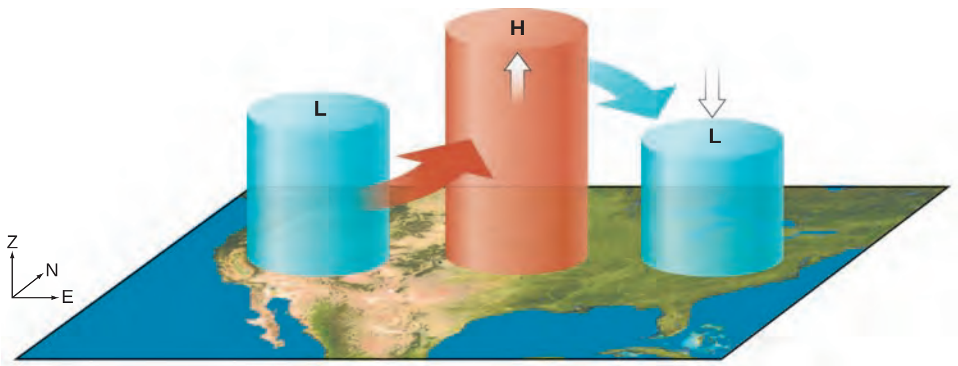
Just as there is a circulation pattern to the atmosphere, there is also a circulation pattern to the oceans that it is driven by differences in density and pressure acting



◀ **Step 1** Pressure disturbances in the upper atmosphere are associated with gradients in temperature. Here, the warmer air column (red) produces high pressures aloft, while the cooler air columns (blue) produce lower pressures. The pressure patterns produce disturbances in the jet stream, which circulates geostrophically around the pressure centers.

▶ **Step 2** Looking down from above, we see that the change in temperature from one location to another results in a disturbance in the global-scale north–south temperature gradient between low and high latitudes, as shown by the isotherms. The counterclockwise flow around the low-pressure center aloft brings warm, tropical air from the south into the vicinity of the warm-air column, which tends to heat this region even further. Conversely, the high-pressure center aloft brings cold air from the north into the vicinity of the cold-air column, cooling it even further.





◀ **Step 3** As the warm-air column continues to warm, it expands, producing even higher pressures aloft. In addition, the cold-air column continues to cool, thereby decreasing pressures further. The pressure gradient between the cold-air region and the warm-air region intensifies, and so the wind speeds also intensify.

5.27 Growth of disturbances in the jet stream

along with the Coriolis force. Pressure differences are created in the water when the ocean is heated unequally, because warm water is less dense than cold water. These pressure differences induce the water to flow. Saltier water is also more dense than less salty water, so differences in salinity can also cause pressure differences. The force of wind on the surface water also creates oceanic circulation.

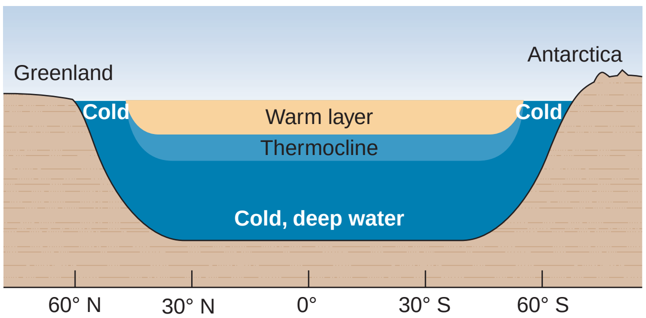
TEMPERATURE LAYERS OF THE OCEAN

The ocean's layered temperature structure is shown in Figure 5.28. At low latitudes throughout the year and in middle latitudes in the summer, a warm surface layer develops, heated by the Sun. Wave action mixes heated surface water with the water below it to form the *warm layer*, which may be as thick as 500 m (about 1600 ft) with a temperature of 20° to 25°C (68° to 77°F) in oceans of the equatorial belt. Below the warm layer, temperatures drop rapidly in a zone known as the *thermocline*. Below the thermocline is a layer of very cold water extending to the deep ocean floor. Temperatures near the base of the deep layer range from 0°C to 5°C (32° to 41°F). This layering is quite stable because the warm layer is less dense than the cold water and rests on top. In arctic and antarctic regions, the warm layer and thermocline are absent.

SURFACE CURRENTS

An **ocean current** is any persistent, dominantly horizontal flow of ocean water. Current systems exchange heat between low and high latitudes and are essential in sustaining the global energy balance. Surface currents are driven by prevailing winds, while deep currents are powered by changes in temperature and density in surface waters that cause them to sink.

In surface currents, energy is transferred from the prevailing surface wind to water by the friction of the air blowing over the water surface. Because of the Coriolis effect, the actual direction of water drift is deflected about 45° from the direction of the driving wind.



5.28 Ocean temperature structure

A schematic north–south cross section of the world ocean shows that the warm surface water layer disappears in arctic and antarctic latitudes, where very cold water lies at the surface. The thickness of the warm layer and thermocline is greatly exaggerated.

Global surface ocean currents are dominated by huge, wind-driven circular gyres centered near the subtropical high-pressure cells. Upwelling of cold bottom water often occurs on the west coasts of continents in the subtropical zones.

The general features of the circulation of the ocean bounded by two continental masses (Figure 5.29) include two large circular movements, called **gyres**, that are centered at latitudes of 20°–30°. These gyres track the movements of air around the subtropical high-pressure cells. An equatorial current with westward flow marks the belt of the trade winds. Although the trades blow to the southwest and northwest at an angle across the parallels of latitude, the surface water movement follows the parallels. The equatorial currents are separated by an equatorial countercurrent. A slow, eastward movement of surface water over the zone of the westerlies is named the west-wind drift. It covers a broad belt between latitudes 35° and 45° in the northern hemisphere and between latitudes 30° and 60° in the southern hemisphere. These features, as well as others, appear on our map of January ocean currents (Figure 5.30).

Because ocean currents move warm waters poleward and cold waters toward the Equator, they are important regulators of air temperatures. Warm surface currents keep winter temperatures in the British Isles from falling much below freezing in winter. Cold surface currents keep weather on the California coast cool, even in the height of summer.

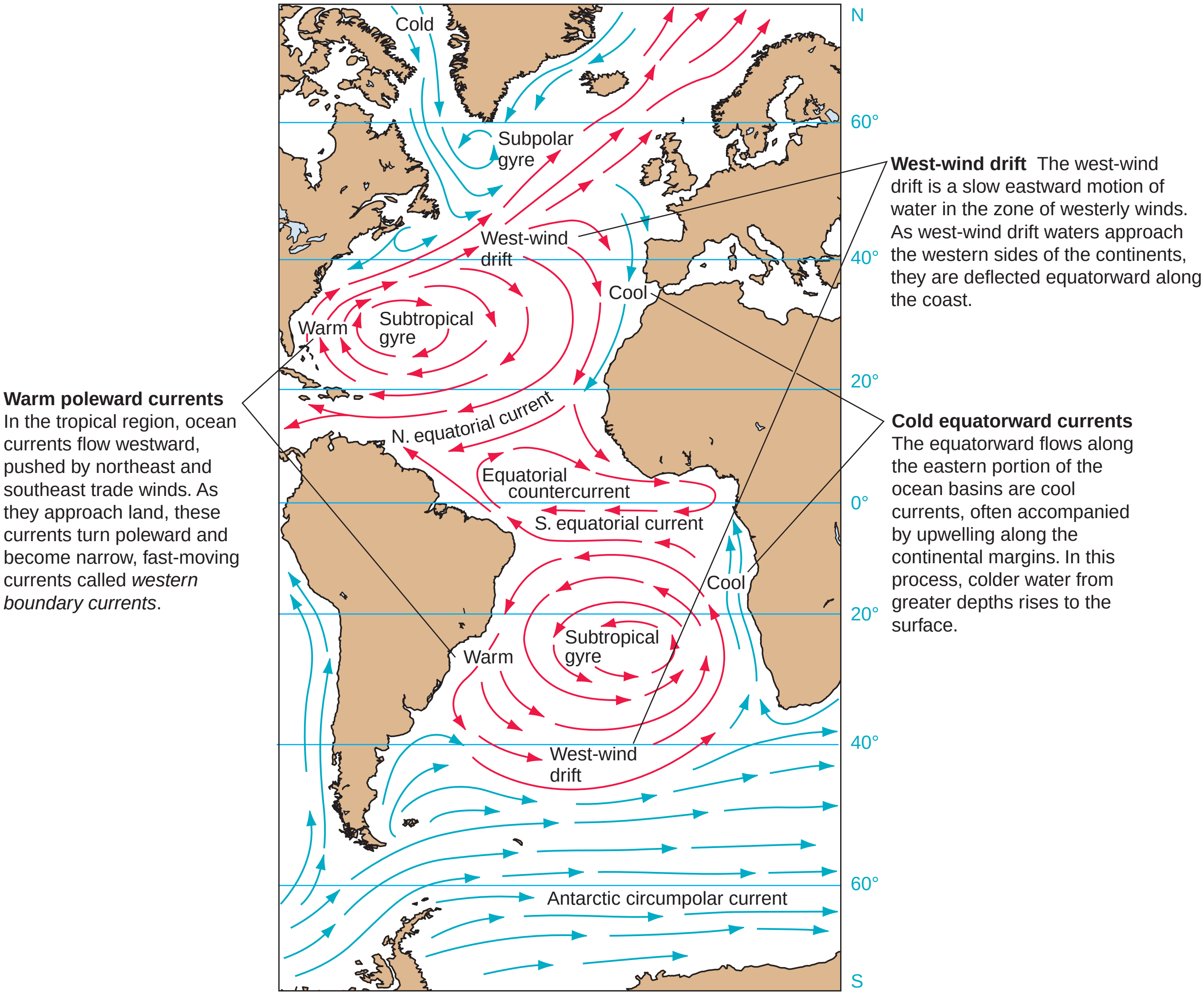
Figure 5.31 shows a satellite image of ocean temperature along the east coast of North America for a week in April. The Gulf Stream stands out as a tongue of warm water, moving northward along the southeastern coast. Cooler water from the Labrador Current moves southward along the northern Atlantic coast. Instead of mixing, the two flows remain quite distinct. The boundary between them shows a wavelike flow, much like jet stream disturbances in the atmosphere.

GEODISCOVERIES **Remote Sensing and Climate Interactivity**

Check out global satellite images of sea surface temperatures and quiz yourself on ocean surface current patterns.

EL NIÑO AND ENSO

Another phenomenon of ocean surface currents is *El Niño*, described in our opening feature, *Eye on Global Change—El Niño*. In an El Niño year, a major change in barometric pressure occurs across the entire stretch of the equatorial zone as far west as southeastern Asia.



5.29 Ocean current gyres

Two great gyres, one in each hemisphere, dominate the circulation of ocean waters from the surface through 500 to 1000 m (1600 to 3300 ft).

Normally, low pressure prevails over northern Australia, the East Indies, and New Guinea, where the largest and warmest body of ocean water is located (Figure 5.32). Abundant rainfall occurs in this area during December, which is the high-Sun period in the southern hemisphere. During an El Niño event, the low-pressure system is replaced by a weak high pressure zone and local drought ensues (Figure 5.32). Pressures drop in the equatorial zone of the eastern Pacific, strengthening the equatorial trough. Rainfall is abundant in this new low-pressure region (right part of figure). The shift in barometric pressure patterns is known as the *Southern Oscillation*, and the two phenomena taken together are often referred to as *ENSO*.

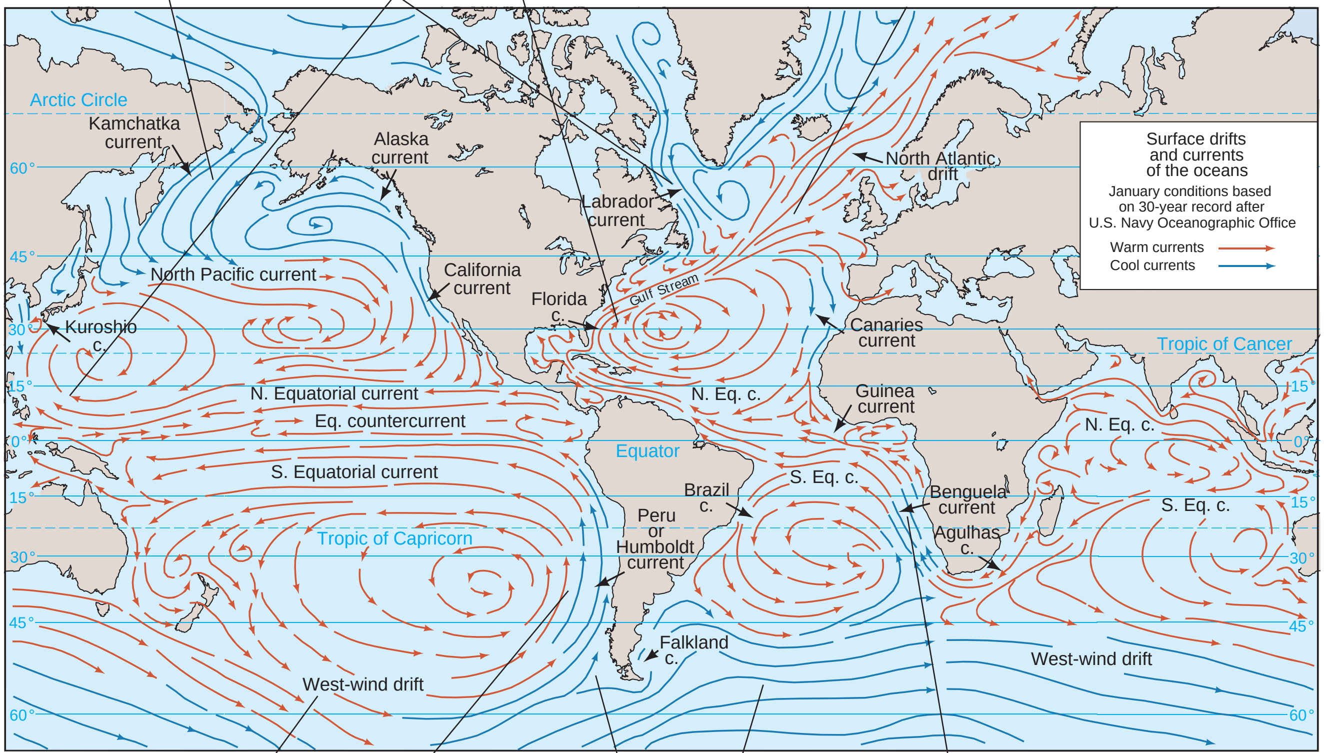
Surface winds and currents also change with this change in pressure. During normal conditions, the strong, prevailing trade winds blow westward, causing very warm ocean water to move to the western Pacific and to "pile up" near the western equatorial low. This westward motion causes the normal upwelling along the South American coast, as bottom water is carried up to replace the water dragged to the west. During an El Niño event, the easterly trade winds weaken with the change in atmospheric pressure. Without the westward pressure of the trade winds, warm waters surge eastward. Sea-surface temperatures and actual sea levels rise off the tropical western coasts of the Americas. Through teleconnections that are not completely understood, these changes in Pacific sea-surface temperature and wind fields can impact climate in faraway regions (Figure 5.33).

A related phenomenon, also capable of altering global weather patterns, is La Niña (the girl child), a condition roughly opposite to El Niño. During a La Niña period, sea-surface temperatures in the central and western

Cold western boundary currents In the northern hemisphere, where the polar sea is largely land-locked, cold currents flow equatorward along the east sides of continents. Two examples are the Kamchatka Current, which flows southward along the Asian coast across from Alaska, and the Labrador Current, which flows between Labrador and Greenland to reach the coasts of Newfoundland, Nova Scotia, and New England.

Warm poleward currents In the equatorial region, ocean currents flow westward, pushed by northeast and southeast trade winds. As they approach land, these currents are turned poleward. Examples are the Gulf Stream of eastern North America and the Kuroshio Current of Japan.

North Atlantic drift West-wind drift water also moves poleward to join arctic and antarctic circulations. In the northeastern Atlantic Ocean, the west-wind drift forms a relatively warm current. This is the North Atlantic drift, which spreads around the British Isles, into the North Sea, and along the Norwegian coast. The Russian port of Murmansk, on the Arctic circle, remains ice-free year round because of the warm drift current.



West-wind drift The west-wind drift is a slow eastward motion of water in the zone of westerly winds. As west-wind drift waters approach the western sides of the continents, they are deflected equatorward along the coast.

Circumpolar current The strong west winds around Antarctica produce an Antarctic circumpolar current of cold water. Some of this flow branches equatorward along the west coast of South America, adding to the Humboldt Current.

Upwelling The equatorward flows are cool currents, often accompanied by upwelling along the continental margins. In this process, colder water from greater depths rises to the surface. Examples are the Humboldt (or Peru) Current, off the coast of Chile and Peru, the Benguela Current, off the coast of southern Africa, and the California Current.

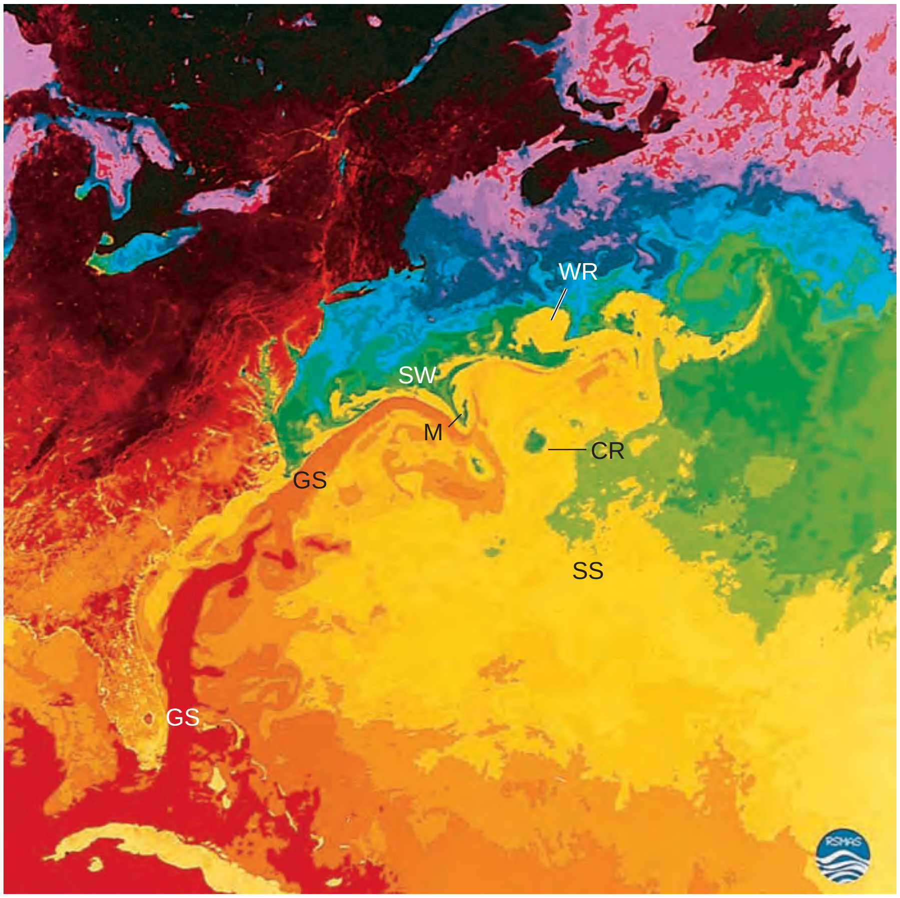
5.30 January ocean currents

Surface drifts and currents of the oceans in January.

Pacific Ocean fall to lower than average levels. This happens because the South Pacific subtropical high becomes very strongly developed during the high-Sun season. The result is abnormally strong easterly trade winds. The force of these winds drags a more-than-normal amount of warm surface water westward, which enhances upwelling along western continental coasts.

El Niño and La Niña occur at irregular intervals and with varying degrees of intensity. When severe, these events can have disastrous effects on weather around the world, as we noted in the *Eye on Global Change* section beginning this chapter. Rainfall and temperature cycles can change significantly in seemingly unrelated parts of the globe, producing floods, droughts, and temperature extremes. Notable recent El Niño events occurred in 1982–1983, 1989–1990, 1991–1992, 1994–1995, 1997–1998, and 2002–2003.

What causes the ENSO phenomenon? One view is that the cycle is a natural oscillation caused by the way in which the atmosphere and oceans are coupled through temperature and pressure changes. Each ocean–atmosphere state has positive feedback loops that tend to make that state stronger. Thus, the ocean and atmosphere tend to stay in one state or the other until something occurs to reverse the state. In any event, scientists now have good computer models that accept



5.31 Sea-surface temperatures in the western Atlantic

A satellite image showing sea-surface temperature for a week in April from data acquired by the NOAA-7 orbiting satellite. Cold water appears in green and blue tones, warm water in red and yellow tones. The image shows the Gulf Stream (GS) and its interactions with cold water of the Continental Slope (SW), brought down by the Labrador Current, and the warm water of the Sargasso Sea (SS). Other features include a meander (M), a warm-core ring (WR), and a cold-core ring (CR).

sea-surface temperature along with air temperature and pressure data and can predict El Niño events reasonably well some months before they occur.

El Niño and its alter ego La Niña show how dynamic our planet really is. As a grand-scale, global phenomenon, El Niño–La Niña shows how the circulation patterns of the ocean and atmosphere are linked and interact to provide teleconnections capable of producing extreme events affecting millions of people throughout the world,

GEODISCOVERIES **El Niño**

Watch an animation of monthly satellite images of sea-surface temperature to see the development of the El Niño of 1997–1998.

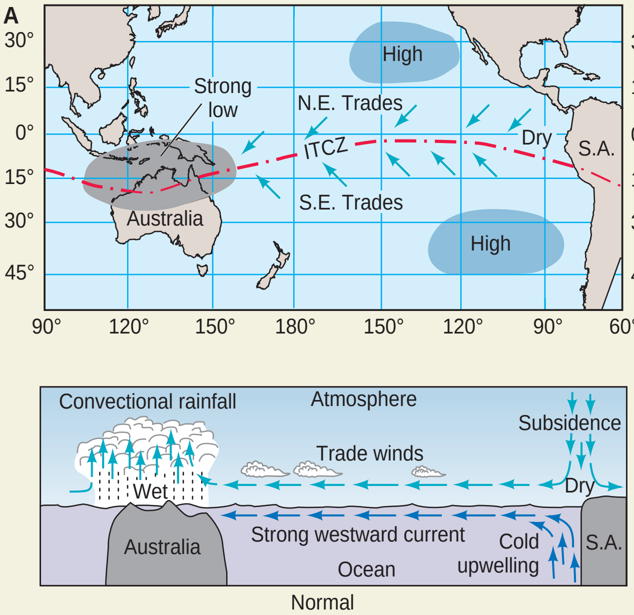
PACIFIC DECADAL OSCILLATION

Another oceanic phenomenon that influences climate is marked by changes in sea-surface temperature in the northern Pacific Ocean that can produce climate changes across parts of Eurasia, Alaska, and the western United States. These changes interact with ENSO-related changes, either strengthening or weakening them. The changes in the North Pacific pressure pattern can last from weeks to decades. The decadal changes, (Figure 5.34) are called the *Pacific decadal oscillation (PDO)*. They can persist on a scale of 20 to 30 years. The causes of the oscillation are not well understood.

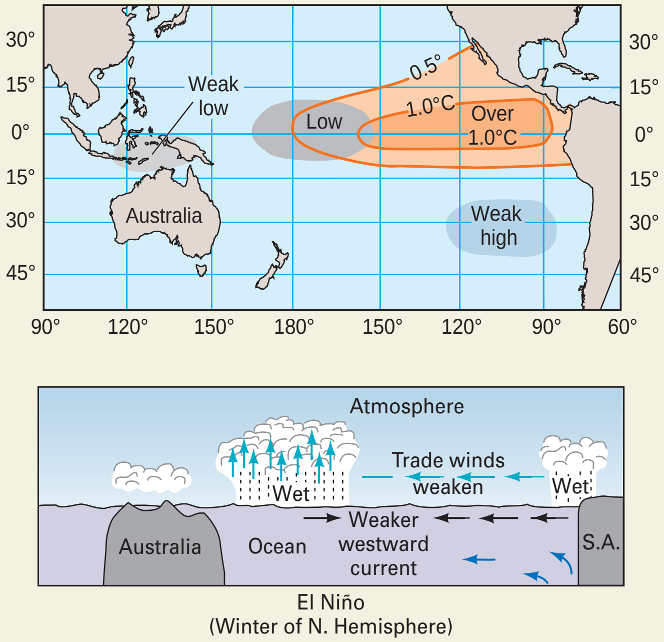
The Pacific decadal oscillation has shown two full cycles in the past century, with cool phases from 1890–1924 and 1947–1976 and warm phases from 1925–1946 and 1977 to the present. In the warm phase, eastward-moving Pacific storm systems track to the south, leaving the northwestern portion of the United States warm and dry, while the arid southwest receives more rainfall than normal. In the cool phase, the northwestern United States becomes cooler and wetter, while drought comes to California and the southwest. The phases also have strong effects on marine coastal fisheries, with the most productive regions shifted northward to Alaskan waters during the warm phase and southward in the cool phase.

5.32 El Niño

Maps of pressures in the tropical Pacific and eastern Indian Ocean in November during normal and El Niño years.

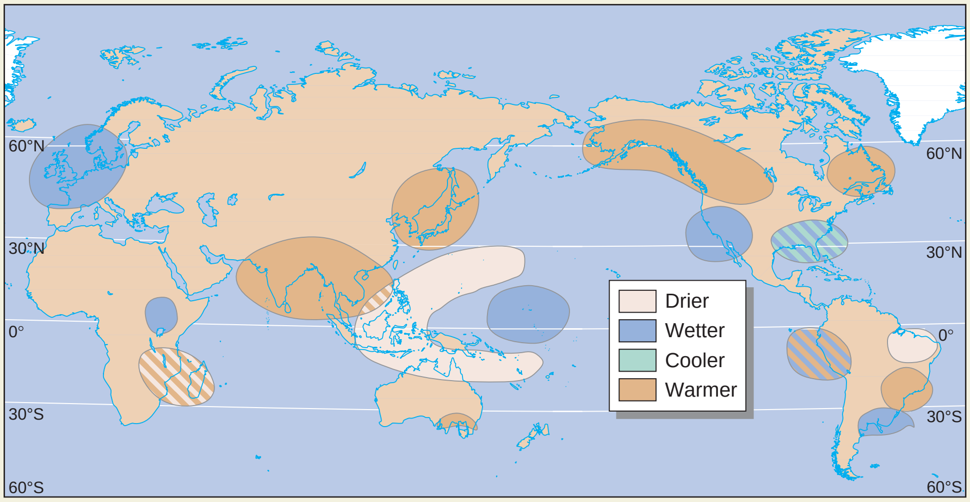


▲ In a normal year, low pressure dominates in Malaysia and northern Australia.

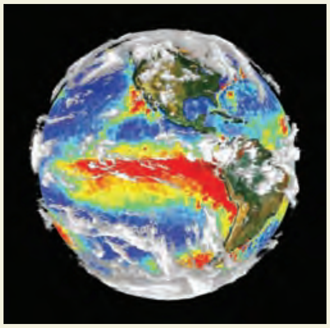


▲ In an El Niño year, low pressure moves eastward to the central part of the western Pacific, and sea-surface temperatures become warmer in the eastern Central Pacific.

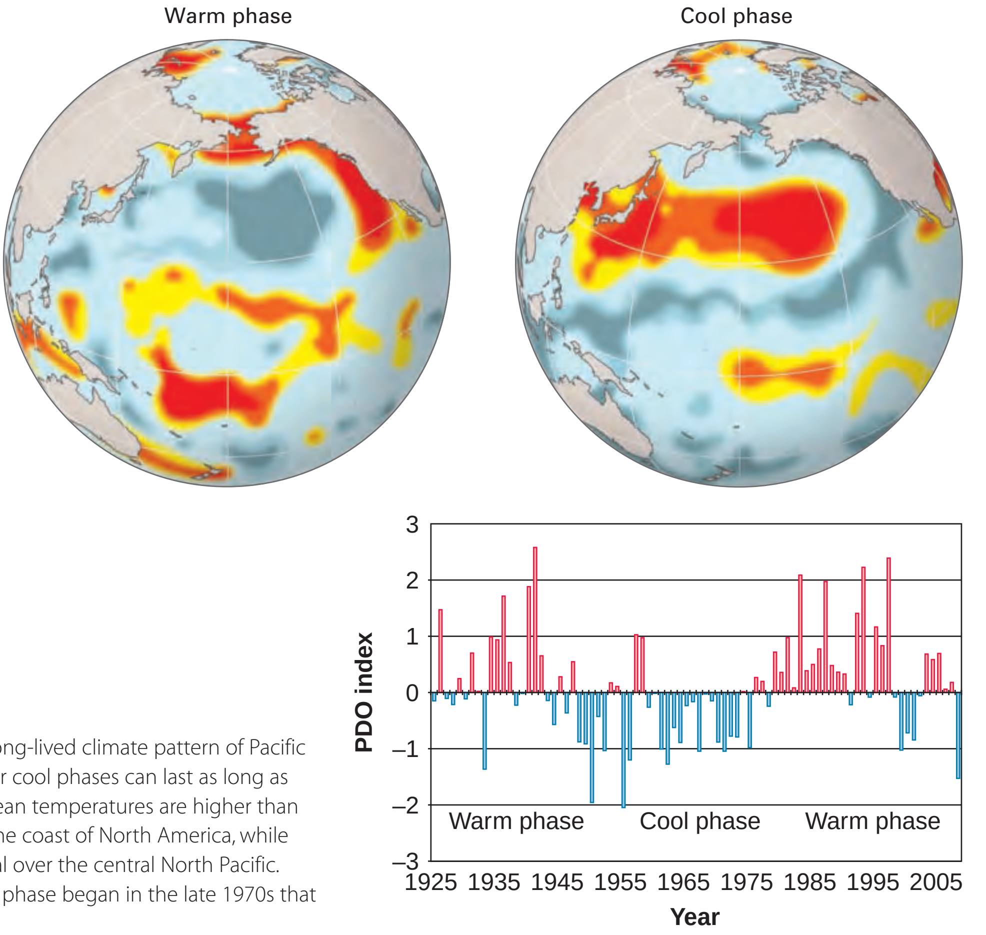
5.33 El Niño–ENSO



▲ El Niño–ENSO events drastically alter the climate, even in many areas far from the Pacific Ocean. As a result, some areas are drier, some wetter, some cooler, and some warmer than usual. Typically, northern areas of the contiguous United States are warmer during the winter, whereas southern areas are cooler and wetter.



▲ ENSO-driven warmer waters off western South America.



5.34 Pacific decadal oscillation

The Pacific decadal oscillation (PDO) is a long-lived climate pattern of Pacific Ocean temperatures. The extreme warm or cool phases can last as long as two decades. During warm conditions, ocean temperatures are higher than normal along the tropical Pacific and off the coast of North America, while ocean temperatures are lower than normal over the central North Pacific. Ocean temperatures suggest that a warm phase began in the late 1970s that has persisted until the present.

NORTH ATLANTIC OSCILLATION

Another ocean–atmosphere phenomenon affecting climate is the *North Atlantic oscillation (NAO)*, which is associated with changes in atmospheric pressures and sea-surface temperatures over the mid- and high latitudes of the Atlantic (Figure 5.35). The North Atlantic oscillation is predominantly an atmospheric phenomenon that is partly related to variations in the surface pressure gradient between the polar sea ice cap and the midlatitudes in both the Atlantic and Pacific Ocean basins. It may also be linked to changes in the ocean surface temperature and possibly snow and ice cover over Europe and Greenland.

Shifts in the North American oscillation can occur over the course of weeks, seasons, and even decades. Since about 1975, the positive phase has dominated, bringing wetter but milder conditions to northern Europe and dry conditions to southern Europe.

DEEP CURRENTS AND THERMOHALINE CIRCULATION

Deep currents move ocean waters in a slow circuit across the floors of the world's oceans. They are generated when surface waters become more dense and slowly sink downward. Coupled with these deep currents are very broad and slow surface currents on which the more rapid surface currents, described above, are superimposed. Figure 5.36 diagrams this slow flow pattern, which links all of the world's oceans. It is referred to as *thermohaline circulation*, since it depends on the sinking of cold, salty water along the northern edge of the Atlantic. The sinking leads eventually to upwelling at far distant locations, as described in the figure.

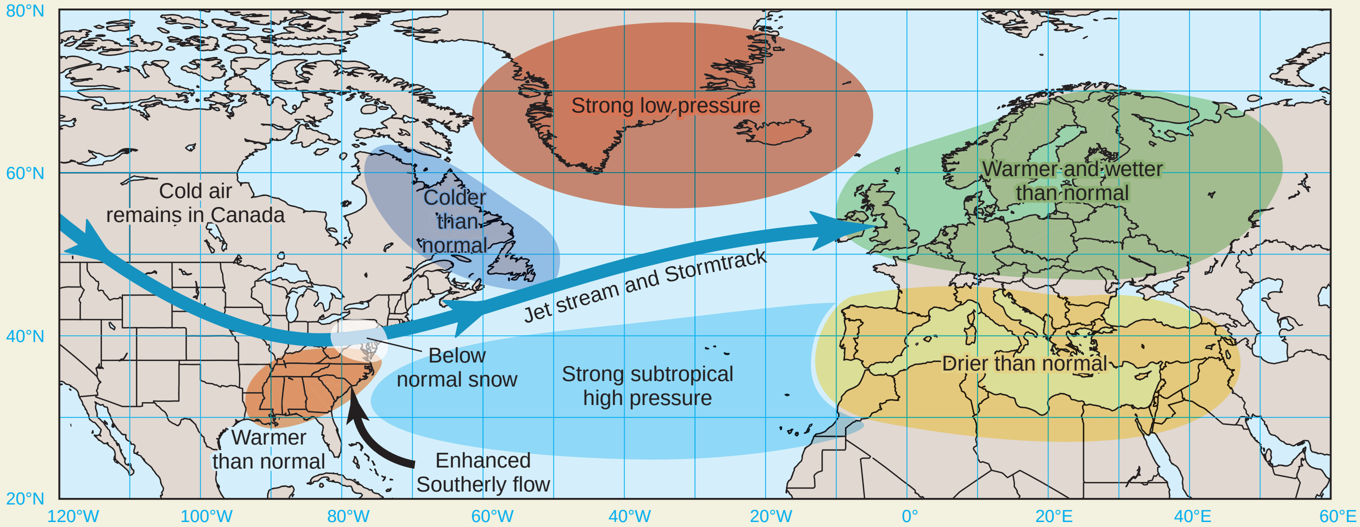
In the thermohaline circulation, dense, cold, salty surface water sinks in the northern Atlantic Ocean, generating slow bottom currents that in turn cause slow upwelling in the Indian Ocean, western Pacific Ocean, and along the coast of Antarctica.

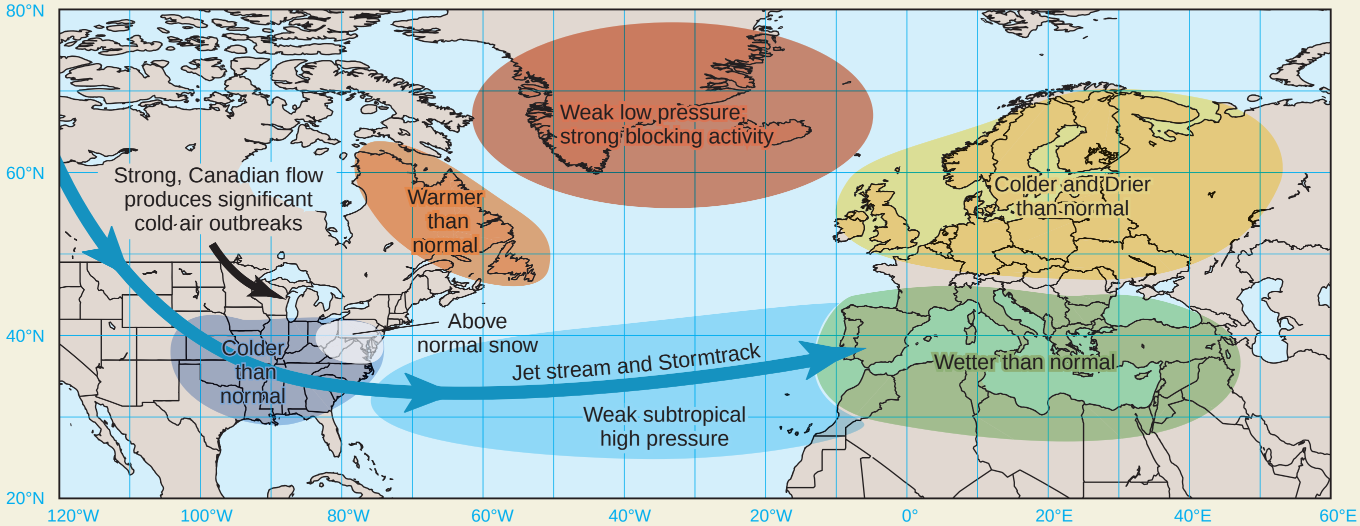
Thermohaline circulation plays an important role in the carbon cycle by moving CO_2-rich surface waters into the ocean depths. As noted in Chapter 3 in *Eye on the Environment 3.1 • Carbon Dioxide—On the Increase*, deep ocean circulation provides a conveyor belt for storage and release of CO_2 in a cycle of about 1500 years' duration. This allows the ocean to moderate rapid changes in atmospheric CO_2 concentration, such as those produced by human activity through fossil fuel burning.

5.35 North Atlantic oscillation (NAO)

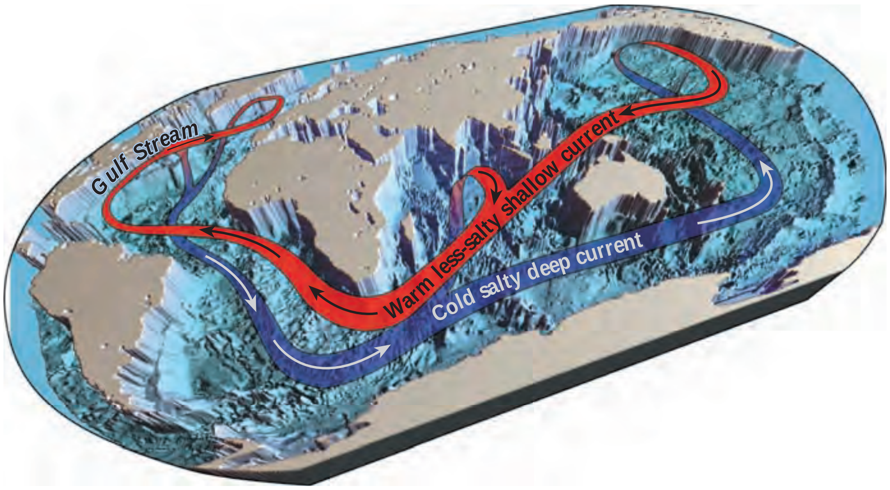
The NAO has two contrasting phases that are related to the strength of the pressure gradient between the North Pole and the tropical Atlantic.

▼ **Positive phase** Here, a strong pressure gradient generates strong low- and high-pressure fields that steer the polar jet stream and Atlantic storms toward northern Europe. In the United States, the southeast is warmer and cold air remains in Canada.





▲ **Negative phase** In this phase, the pressure gradient is weak and Atlantic storms track to the south, bringing more rainfall to the Mediterranean region. In America, cold air invades the eastern and central states, with more snow in the northeast.



5.36 Thermohaline circulation

This three-dimensional figure shows the "conveyor belt" of deep ocean currents. Warm surface waters in the tropics move poleward, losing heat to the atmosphere en route. The cooler waters sink at higher latitudes, flow equatorward, and eventually upwell to the surface in the tropics, cooling these regions significantly.

Some scientists have observed that thermohaline circulation could be slowed or stopped by inputs of fresh water into the North Atlantic. Such freshwater inputs could come from the sudden drainage of large lakes formed by melting ice at the close of the last Ice Age. The fresh water would decrease the density of the ocean water, keeping the water from becoming dense enough to sink. Without sinking, circulation would stop. In turn, this would interrupt a major flow pathway for the transfer of heat from equatorial regions to the northern midlatitudes. This mechanism could result in relatively rapid climatic change and is one explanation for the periodic cycles of warm and cold temperatures experienced since the melting of continental ice sheets about 12,000 years ago.

GEODISCOVERIES Web Quiz
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

This chapter has examined atmospheric and oceanic circulation processes at several scales, including local winds at the local scale, cyclones and anticyclones at the regional scale, and whole-Earth surface and upper atmosphere circulations at the global scale. We have seen how the pattern of pressure and wind is determined by the basic process of unequal heating of the air, which is largely the result of unequal solar heating of the land and ocean surface. In the oceans, the global pattern of surface currents is largely driven by the wind, while deep currents are caused by sinking and rising motions resulting from differences in water temperature and density. In both cases, the flows of water and air are strongly affected by the Earth's rotation as it is felt in the Coriolis force.

The global circulation of winds and currents paves the way for our next subject—weather systems. Recall from Chapter 4 that when warm, moist air rises, precipitation can occur. This happens in the centers of cyclones, where air converges. Although cyclones and anticyclones are generally large surface features, they move from day to day and are steered by the global pattern of winds. Thus, your knowledge of global winds and pressures will help you to understand how weather systems and storms develop and migrate. Your knowledge will also be very useful for the study of climate, which we take up in Chapter 7.

GEODISCOVERIES Web Links
Wind, the Coriolis effect, El Niños, jet streams, and ocean currents are all subjects you can investigate further on web links. Have a look!

IN REVIEW WINDS AND GLOBAL CIRCULATION

- **El Niño** is a major disturbance of the equatorial Pacific Ocean and atmosphere. It occurs when cold, upwelling surface water along the Peruvian coast is replaced by warm surface water flowing eastward from the equatorial Pacific. In contrast is *La Niña*, in which upwelling is enhanced and cold surface water is carried westward along the Equator.
- El Niño–La Niña can shift weather patterns around the world, bringing unexpected drought, floods, heat, and cold. The El Niño of 1997–1998 was particularly severe, with climate changes occurring across the globe.
- The term **atmospheric pressure** describes the weight of air pressing on a unit of surface area. Atmospheric pressure is measured by a **barometer**. Atmospheric pressure decreases rapidly as altitude increases.
- **Wind** occurs when air moves with respect to the Earth's surface. Air motion is produced by **pressure gradients** that are formed when air in one location is heated to a temperature that is warmer than another. Heating creates high pressure aloft, which moves high-level air away from the area of heating. This motion induces low pressure at the surface, pulling surface air toward the area of heating, and a **thermal circulation** loop is formed.
- *Local winds* are generated by local pressure gradients. *Sea* and *land breezes*, as well as *mountain* and *valley breezes*, are examples caused by local surface heating. Other local winds include *Santa Ana*, *chinook*, and *mistral winds*.
- *Wind power* is a widely available power source that is largely unutilized.
- The Earth's rotation strongly influences atmospheric circulation through the **Coriolis effect**, which is the result of the Earth's rotation. The *Coriolis force* deflects wind motion, producing circular or spiraling flow paths around **cyclones** (centers of low pressure and convergence) and **anticyclones** (centers of high pressure and divergence).
- Because the equatorial and tropical regions are heated more intensely than the higher latitudes, a vast thermal circulation develops—the **Hadley cells**. This circulation drives the *northeast* and *southeast trade winds*, the convergence and lifting of air at the **intertropical convergence zone (ITCZ)**, and the sinking and divergence of air in the **subtropical high-pressure belts**.
- The most persistent features of the global pattern of atmospheric pressure are the subtropical high-pressure belts, which are generated by the Hadley cell circulation. They intensify and move poleward during their high-Sun season, affecting the climate of adjacent coasts and continents.
- The **monsoon** circulation of Asia responds to a reversal of atmospheric pressure over the continent with the seasons. A *winter monsoon* flow of cool, dry air from the northeast alternates with a *summer monsoon* flow of warm, moist air from the southwest.
- In the midlatitudes and poleward, westerly winds prevail. In winter, continents develop high pressure, and intense oceanic low-pressure centers are found off the Aleutian Islands and near Iceland in the northern hemisphere. In the summer, the continents develop low pressure as oceanic subtropical high-pressure cells intensify and move poleward.
- Winds aloft are dominated by a global pressure gradient force between the tropics and pole in each hemisphere that is generated by the hemispheric temperature gradient from warm to cold. Coupled with the Coriolis force, the gradient generates strong westerly **geostrophic winds** in the upper air. In the equatorial region, weak easterlies dominate the upper-level wind pattern. Poleward of the Hadley cells, *upper-air westerlies* circle the Earth in an undulating pattern.
- The *polar-front* and *subtropical* **jet streams** are concentrated westerly wind streams with high wind speeds. The *tropical easterly jet stream* is weaker and limited to Southeast Asia, India, and Africa in summer.
- **Jet-stream disturbances** are large undulating patterns that develop in jet streams. Once formed, they tend to grow larger because of *baroclinic instability*. The undulations bring tongues of cold polar air equatorward and warm tropical air poleward that can last for some days or weeks.
- Oceans show a surface warm layer, a *thermocline*, and a deep cold layer. Near the poles, the warm layer and thermocline are absent.
- *Ocean* surface *currents* are dominated by huge **gyres** that are driven by the global surface wind pattern. *Equatorial currents* move warm water westward and then poleward along the east coasts of continents. Return flows bring cold water equatorward along the west coasts of continents.
- *El Niño* events are associated with changes in barometric pressure across the equatorial Pacific that are known as the *Southern Oscillation*, giving rise to the term *El Niño-Southern Oscillation* or *ENSO*.

- The *Pacific decadal oscillation (PDO)* in sea-surface temperature steers the polar jet stream over the Pacific, which alters winter storm tracks to create 20- to 30-year cycles of wet and dry years along the Pacific coast and arid interior western states.
- The *North Atlantic oscillation (NAO)* affects weather on both sides of the Atlantic. In the positive phase, the polar jet keeps to the north, bringing warm conditions to the southeast and more storms to northern Europe. In the negative phase, the polar jet is farther south, bringing cold conditions in the eastern United States and more precipitation in the Mediterranean region.
- Slow, deep ocean currents are driven by the sinking of cold, salty water in the northern Atlantic that ultimately causes upwelling in the Pacific and Indian oceans. This *thermohaline circulation* pattern involves nearly all the Earth's ocean basins, and also acts to moderate the buildup of atmospheric CO_2 by moving CO_2-rich surface waters to ocean depths.

KEY TERMS

El Niño, p. 150
atmospheric pressure, p. 150
barometer, p. 151
wind, p. 153
isobar, p. 154
pressure gradient, p. 154
thermal circulation, p. 154
Coriolis effect, p. 157
cyclone, p. 157
anticyclone, p. 158
Hadley cell, p. 158
intertropical convergence zone (ITCZ), p. 159
subtropical high-pressure belts, p. 159
polar front, p. 159
monsoon, p. 162
geostrophic wind, p. 165
jet stream, p. 167
jet stream disturbance, p. 167
ocean current, p. 171
gyre, p. 171

REVIEW QUESTIONS

1. Describe the change in sea-surface temperatures that occurs with *El Niño*. What were some of the effects of the severe El Niño of 1997–1998?
2. Explain *atmospheric pressure*. Why does it occur? How is atmospheric pressure measured and in what units? What is the normal value of atmospheric pressure at sea level?
3. How does atmospheric pressure change with altitude?
4. What is *wind*? How do we define wind direction? What instrument is commonly used to measure wind speed and direction?
5. What is a *pressure gradient*? How is it related to atmospheric heating?
6. Describe a simple *thermal circulation system*, explaining how air motion arises from a pressure gradient force induced by heating.
7. Describe *land* and *sea breezes* and *mountain* and *valley winds*. Identify two other types of local winds.
8. Briefly discuss wind power as a source of energy.
9. What is the *Coriolis effect*, and why is it important? What produces it? How does it influence the motion of wind and ocean currents in the northern hemisphere? in the southern hemisphere?
10. Define *cyclone* and *anticyclone*. How does air move within each? What is the direction of circulation of each in the northern and southern hemispheres? What type of weather is associated with each and why?
11. What is a *Hadley cell*? Describe the circulation in a Hadley cell using the terms *intertropical convergence zone* and *subtropical high pressure belt*.
12. What is meant by the term *polar front*?
13. Identify two atmospheric features of the subtropical high-pressure belt in the northern hemisphere. How do these features change with the seasons?
14. What is the Asian *monsoon*? Describe the features of this circulation in summer and winter. How is the ITCZ involved? How is the monsoon circulation related to the high- and low-pressure centers that develop seasonally in Asia?
15. Compare the winter and summer patterns of high and low pressure that develop in the northern hemisphere.
16. Describe the surface wind pattern of the south polar region and Southern Ocean. Does it change with the seasons?
17. How does global-scale heating of the atmosphere create a *pressure gradient force* that increases with altitude?
18. What is the *geostrophic wind*, and what is its direction with respect to the pressure gradient force?
19. Describe the basic pattern of global atmospheric circulation at upper levels.
20. Identify five *jet streams*. Where do they occur? In which direction do they flow?
21. What are *jet stream disturbances*? Describe how *baroclinic instability* causes jet streams to grow. Why are they important?

22. Describe the layered temperature structure of the ocean.
23. What is meant by the term *gyre*?
24. What is the general pattern of ocean surface current circulation? How is it related to global wind patterns?
25. How does the normal pattern of wind, pressure, and ocean currents in the equatorial Pacific change during an El Niño event? a La Niña event?
26. What is the *Pacific decadal oscillation*? On what time scale does it operate? What are its effects?
27. Describe the *North Atlantic oscillation*. How does it affect North American weather?
28. How does the *thermohaline circulation* induce deep ocean currents?

VISUALIZING EXERCISES

1. Sketch an ideal Earth (without seasons or ocean–continent features) and its global wind system. Label the following on your sketch: doldrums, equatorial trough, Hadley cell, ITCZ, northeast trades, polar easterlies, polar front, polar outbreak, southeast trades, subtropical high-pressure belts, and westerlies.
2. Draw four spiral patterns showing outward and inward flow in clockwise and counterclockwise directions. Label each as appropriate to cyclonic or anticyclonic circulation in the northern or southern hemisphere.
3. Draw a simplified sketch of the global map of ocean currents showing the larger gyres. Identify at least five currents by name.

ESSAY QUESTIONS

1. An airline pilot is planning a nonstop flight from Los Angeles to Sydney, Australia. What general wind conditions can the pilot expect to find in the upper atmosphere as the airplane travels? What jet streams will be encountered? Will they slow or speed the aircraft on its way?
2. You are planning to take a round-the-world cruise, leaving New York in October. Your vessel's route will take you through the Mediterranean Sea to Cairo, Egypt, in early December. Then you will pass through the Suez Canal and Red Sea to the Indian Ocean, calling at Mumbai, India, in January. From Mumbai, you will sail to Djakarta, Indonesia, and then go directly to Perth, Australia, arriving in March. Rounding the southern coast of Australia, your next port of call is Auckland, New Zealand, which you will reach in April. From Auckland, you head directly to San Francisco, your final destination, arriving in June. Describe the general wind and weather conditions you will experience on each leg of your journey.

Chapter 6
Weather Systems

The near-total destruction of this small village, located on an island about 60 km (37 mi) north of the Honduran coast, was caused by Hurricane Mitch in October of 1998. Mitch was one of the deadliest Atlantic tropical cyclones in history. It struck the heart of Central America, crossing its mountainous spine in a week-long odyssey of destruction. The economies of Honduras and Nicaragua were devastated, losing half of their annual gross national products. Guatemala and El Salvador were also hard hit.

The monster category 5 storm attained winds of 77.2 m/s (172 mph) before coming onshore near the coastal city of Trujillo, Honduras. Laden with tropical moisture, Mitch crossed the coastal mountains and the central ranges, reaching Tegucigalpa, the capital, two days later. As the saturated air moved up and over the mountains, adiabatic cooling produced huge raindrops that descended at a furious rate. A broad band along the coast received more than 500 mm (20 in.) of rain, with 250–375 mm (10–15 in.) falling near Tegucigalpa. Whole mountainsides gave way in debris avalanches of rocks, trees, and houses that cascaded through towns and villages below. More than 11,00 dead were left in Mitch's wake.

Village on Guanaja, Islas de la Bahía, Honduras, destroyed by Hurricane Mitch

Weather Systems

Many locations experience changeable weather brought about by weather systems moving through a region. What is a weather system? How do air masses interact in weather system? Why and where in a weather system is precipitation likely to occur? Weather systems include hurricanes and typhoons. How do these destructive storms develop? How and why do they move? How is their intensity measured, and what kinds of damage can they do? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Cloud Cover, Precipitation, and Global Warming

Clouds are so common we don't think much about them. But they can have a large impact on climate. How would global climate be influenced by an increase in clouds and precipitation (Figure 6.1)?

Global temperatures have been rising over the last 20 years. Satellite data show a rise in temperature of the global ocean surface of about 1°C (1.8°F) over the past decade. Any rise in sea-surface temperature will increase the rate of evaporation, and an increase in evaporation will raise the average atmospheric content of water vapor.

Water has several roles in global climate. First, in its vapor state it is one of the greenhouse gases that absorb and emit longwave radiation, enhancing the warming effect of the atmosphere above the Earth's surface. In fact, water is a more powerful greenhouse gas than CO_2. So we can predict that an increase in global water vapor in the atmosphere should enhance warming.

Second, water vapor, when cooled, can form clouds. Will more clouds increase or decrease global temperatures? Cloud droplets and ice crystals reflect a large proportion of incoming shortwave radiation back to space, cooling global temperatures. But cloud particles also absorb longwave radiation from the ground and return that emission as counterradiation. This absorption is an important part of the greenhouse effect, and it is even stronger for water as cloud droplets or ice particles than as water vapor. Which effect, shortwave cooling or longwave warming, will dominate?

Low, thick clouds tend to cool the Earth, and high, thin clouds tend to warm it. On balance, clouds presently act to cool the Earth.

The best estimate, at present, is that the average flow of shortwave energy reflected by clouds back to space is about 50 W/m^2 (loss), while the longwave warming effect of clouds amounts to about 30 W/m^2 (gain). So, at the moment, the net effect of clouds is to cool the planet by about 20 W/m^2. But computer models predict that with more clouds, the cooling effect will be reduced somewhat, making temperatures rise even higher.

Precipitation is the third role of water in global climate. With more water vapor and more clouds in the air, more precipitation should result. But what if precipitation increases in arctic and subarctic zones? More snow would increase the Earth's albedo, thus tending to reduce global temperatures. That could reduce ocean evaporation. More snow could also tie up more water in snow packs and glaciers, reducing runoff to the oceans and reducing the rate at which sea level rises.

So the situation is quite complicated. At this time, scientists are unsure exactly how the global climate system will respond to global warming induced by the CO_2 increases predicted by the end of the century. But models are beginning to converge on common predictions that show the changes will be significant and important to many regions and human activities.

Air Masses

We know that the Earth's atmosphere is in constant motion, driven by the planet's rotation and its uneven heating by the Sun. The horizontal motion of the wind moves air from one place to another, allowing air to acquire characteristics of temperature and humidity in one region and then carry those characteristics into another region. In addition, as winds at the surface converge and diverge, they produce vertical motions that affect clouds and precipitation. When air is lifted, it is cooled, enabling clouds and precipitation to form. When air descends, it is warmed, inhibiting the formation of clouds and precipitation. In this

6.1 Clouds and global climate

▶ **Earth mantled by clouds** This image, acquired by the European Space Agency's Meteosat-5, shows the Earth's full disk, centered over the Indian ocean. Cloud height and cloud cover are important factors in determining global climate.

▼ **High clouds** High clouds tend to absorb more solar radiation, warming the planet. These wispy cirrus clouds decorate the sky above Denali National Park, Alaska (National Geographic Image Collection).

▲ **Low clouds** If higher surface temperatures evaporate more ocean water, more clouds should result. Low clouds, like these over Miami, act to reflect sunlight back to space, cooling the planet (National Geographic Image Collection).

way, the Earth's wind systems influence the weather we experience from day to day—the temperature and humidity of the air, cloudiness, and the amount of precipitation.

Some patterns of wind circulation occur commonly and so present recurring patterns of weather. For example, traveling low-pressure centers (*cyclones*) of converging, inspiraling air often bring warm, moist air in contact with cooler, drier air, and clouds and precipitation are typically the result. We recognize these recurring circulation patterns and their associated weather as **weather systems**.

In the midlatitudes, weather systems are often associated with the motion of **air masses**—large bodies of air with fairly uniform temperature and moisture characteristics. An air mass can be several thousand kilometers or miles across and can extend upward to the top of the troposphere. We characterize each air mass by its surface temperature, environmental lapse rate, and surface specific humidity. Air masses can be searing hot, icy cold, or any temperature in between. Moisture content can also vary widely between different air masses.

Air masses acquire their characteristics in *source regions.* In a source region, air moves slowly or not at all, which allows the air to acquire temperature and moisture characteristics from the region's land or ocean surface (Figure 6.2). For example, a warm, moist air mass develops over warm equatorial oceans. In contrast, a hot, dry air mass forms over a large subtropical desert. Over cold, snow-covered land surfaces in the arctic zone in winter, a very cold air mass with very low water vapor content is found.

Air masses have fairly uniform temperature and moisture characteristics that are acquired from a source region. They are classified by latitudinal position (e.g., arctic, tropical), and by surface type (maritime, continental).

Pressure gradients and upper-level wind patterns drive air masses from one region to another. When an air mass moves to a new area, it can retain its initial temperature and moisture characteristics for weeks before it comes to fully reflect the new surrounding environment. This is one of the most important properties of air masses—they have the temperature and moisture characteristics of their original source regions, even as they move away from those regions.

We classify air masses by the latitude zone (arctic, polar, tropical, equatorial) and surface type (maritime, continental) of their source regions. Combining these labels produces a list of six important types of air masses (Figure 6.3). Latitudinal position is important

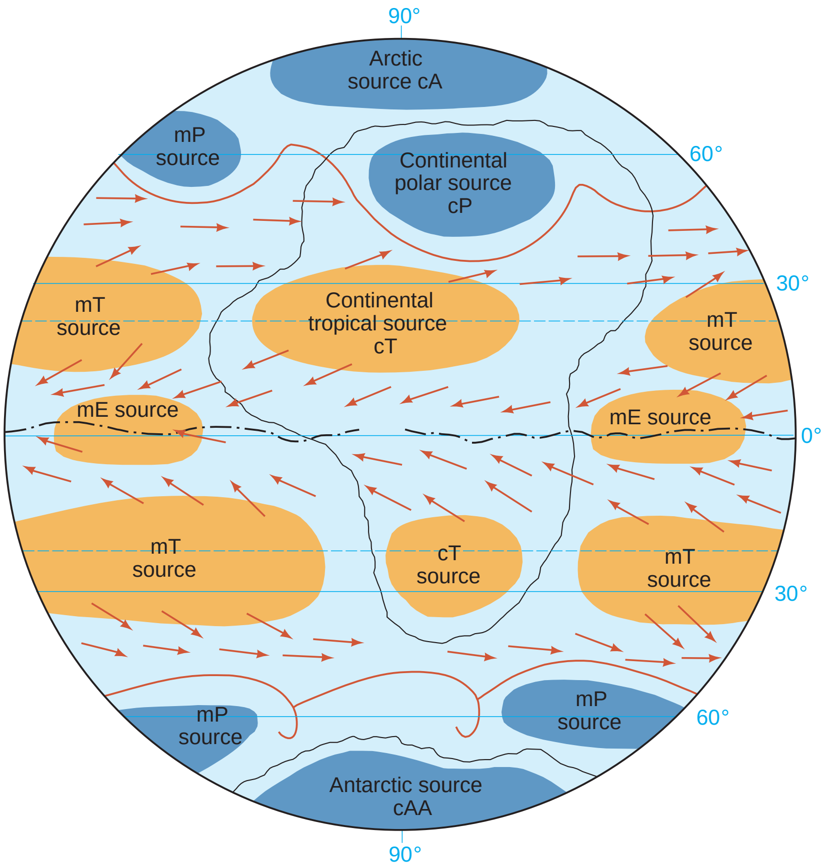
6.2 Source regions

Air masses form when large bodies of air acquire the temperature and moisture characteristics of the underlying surface conditions.

▼ **Subtropical deserts** Over a large subtropical desert, slowly subsiding air forms a hot air mass with low humidity (National Geographic Image Collection).

▲ **Tropical oceans** An air mass with warm temperatures and high water vapor content develops over a warm equatorial ocean (National Geographic Image Collection).

▼ **Arctic land masses** A very cold air mass with low water vapor content is generated over cold, snow-covered land surfaces in the arctic zone in winter (National Geographic Image Collection).



Source regions

Air mass	Symbol	Source region
Arctic	A	Arctic Ocean and fringing lands
Antarctic	AA	Antarctica
Polar	P	Continents and oceans, lat. 50–60° N and S
Tropical	T	Continents and oceans, lat. 20–35° N and S
Equatorial	E	Oceans close to Equator

Surface types

Air mass	Symbol	Surface type
Maritime	m	Oceans
Continental	c	Continents

6.3 Global air masses and source regions

In the center of the figure is an idealized continent, which produces continental (c) air masses. It is surrounded by oceans, producing maritime air masses (m). Tropical (T) and equatorial (E) source regions provide warm- or hot-air masses, while polar (P), arctic (A), and antarctic (AA) source regions provide colder air masses of low specific humidity. Polar air masses (mP, cP) originate in the subarctic latitude zone, not in the polar latitude zone. Meteorologists use the word "polar" to describe air masses from the subarctic and subantarctic zones, and we will follow their usage when referring to air masses.

because it determines the surface temperature and the environmental temperature lapse rate of the air mass. For example, air-mass temperature can range from –46°C (–51°F) for arctic air masses to 27°C (81°F) for equatorial air masses. The nature of the underlying surface—maritime or continental—usually determines the moisture content of an air mass given a latitudinal zone. Specific humidity of an air mass can range from 0.1 g/kg over the frozen ground of the arctic to as much as 19 g/kg over a warm ocean. In other words, maritime equatorial air can contain about 200 times as much moisture as continental arctic air.

The air masses that form near North America and their source regions have a strong influence on the weather. Figure 6.4 shows the air masses and source regions that influence North American weather.

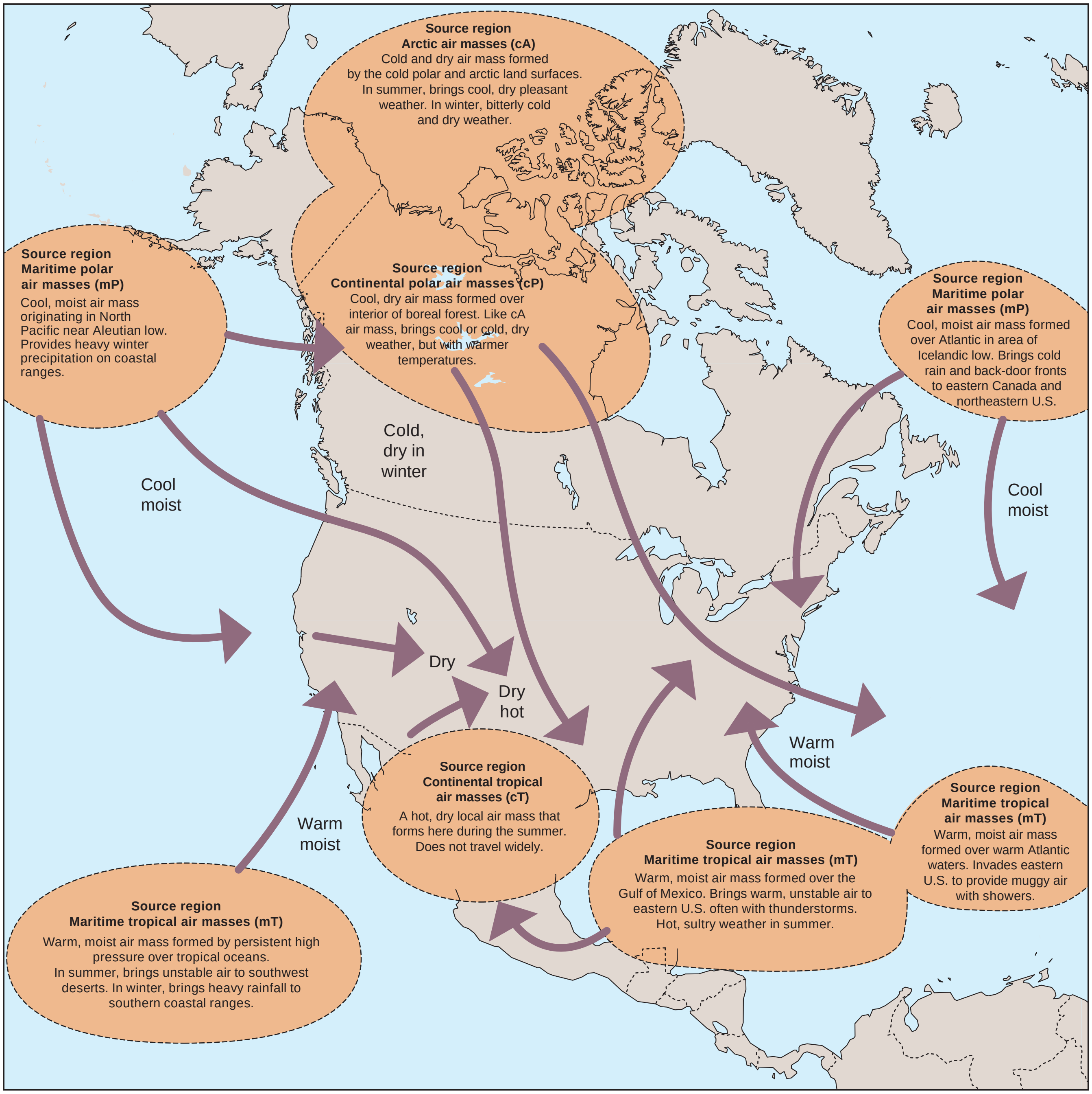
COLD, WARM, AND OCCLUDED FRONTS

A given air mass usually has a sharply defined boundary between itself and a neighboring air mass. This boundary is termed a **front**. An example we saw in Chapter 5 is the *polar front*, where polar and tropical air masses are in contact.

Fronts are boundaries between air masses. When cold air invades warmer air, the boundary is a cold front. When warm air invades colder air, the boundary is a warm front.

In addition to this polar front, we can also have situations in which a cold-air mass temporarily invades a zone occupied by a warm air mass during the passage of a weather system. The result is a **cold front**, shown in Figure 6.5. Because the cold air mass is colder and therefore more dense than the warmer air mass, it remains in contact with the ground. As it moves forward, it forces the warmer air mass to rise above it. As the warm air mass rises, it cools adiabatically, water vapor condenses, and clouds form. If the warm, moist air is unstable, severe convection may develop. A cold front often forms a long line of massive cumulus clouds stretching for tens of kilometers.

In contrast to a cold front, a **warm front** is a front in which warm air moves into a region of colder air, as the cold air retreats (Figure 6.6). Again, the cold air

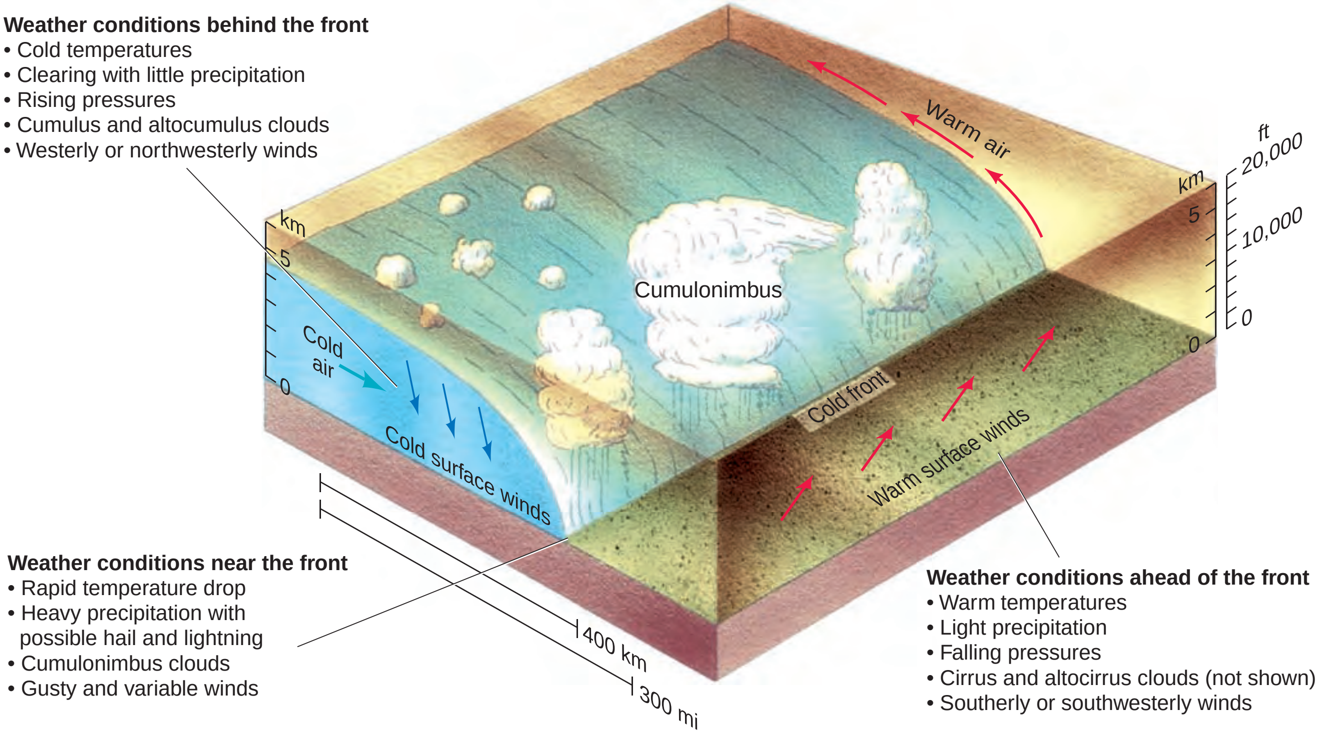


6.4 North American air-mass source regions and trajectories

Air masses acquire temperature and moisture characteristics in their source regions, then move across the North American continent.

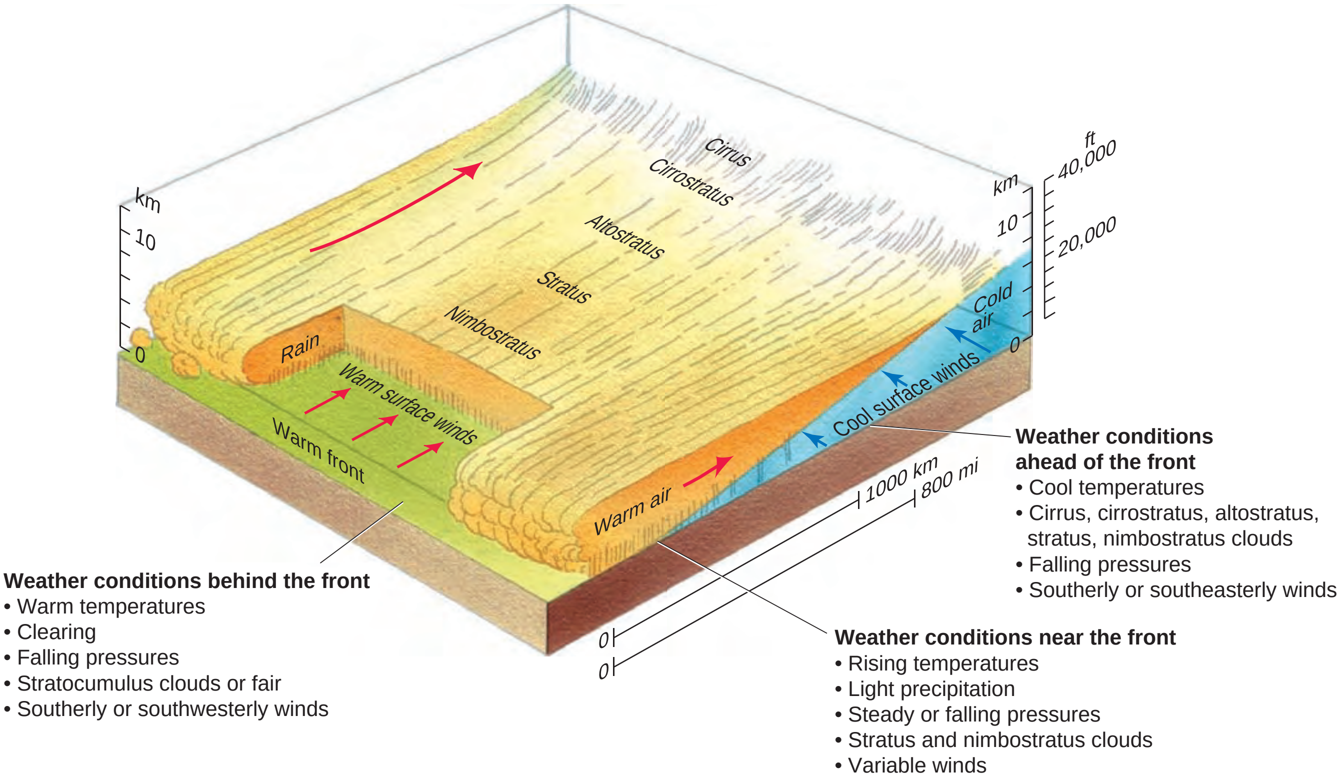
mass remains in contact with the ground because it is denser. As before, the warm-air mass is forced aloft, but this time it rises up on a long ramp over the cold air below. This rising motion, called *overrunning,* creates stratus—large, dense, blanket-like clouds that often produce precipitation ahead of the warm front. If the warm air is stable, the precipitation will be steady. If the warm air is unstable, convection cells can develop, producing cumulonimbus clouds with heavy showers or thunderstorms.

Cold fronts normally move along the ground at a faster rate than warm fronts because the cold, dense air behind the cold front can more easily push through the warm, less dense air ahead of it. The motion of the warm front, which depends on the retreat of the cooler air ahead of it, is slower. Thus, when a cold front and a warm front are in the same region, the cold front can eventually overtake the warm front. The result is an **occluded front**. (“Occluded” means closed or shut off.) The colder air of the fast-moving cold front remains



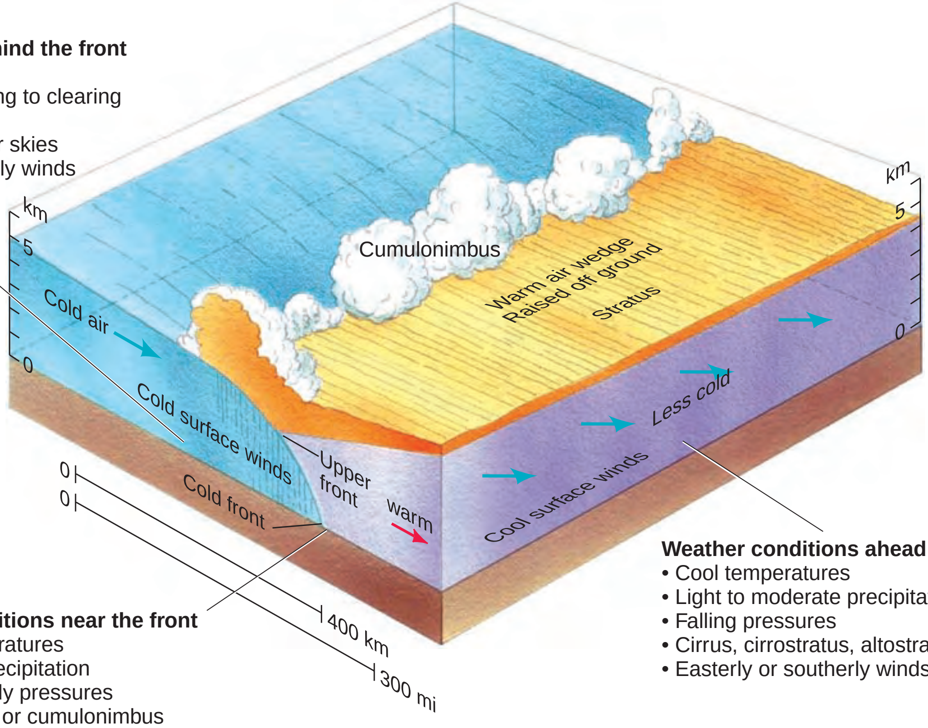
6.5 Cold front

In a cold front, a cold air mass lifts a warm air mass aloft. The upward motion can set off a line of showers or thunderstorms. The frontal boundary is actually much less steep than is shown in this schematic drawing.



6.6 Warm front

In a warm front, warm air advances toward cold air and rides up and over the cold air, called *overrunning*. A notch of cloud is cut away to show rain falling from the dense stratus cloud layer.



6.7 Occluded front

In an occluded front, a cold front overtakes a warm front. The warm air is pushed aloft, so that it no longer touches the ground. This abrupt lifting by the denser cold air produces precipitation.

next to the ground, forcing both the warm air and the less cold air ahead to rise over it, as shown in Figure 6.7. The warm air mass is lifted completely free of the ground.

> **In an occluded front, a cold front overtakes a warm front, lifting a pool of warm, moist air upward. The result is a region of clouds and precipitation.**

A fourth type of front is known as the *stationary front*, in which two air masses are in contact but there is little or no relative motion between them. Stationary fronts often arise when a cold or warm front stalls and stops moving forward. Clouds and precipitation that were caused by earlier motion will often remain in the vicinity of the now stationary front.

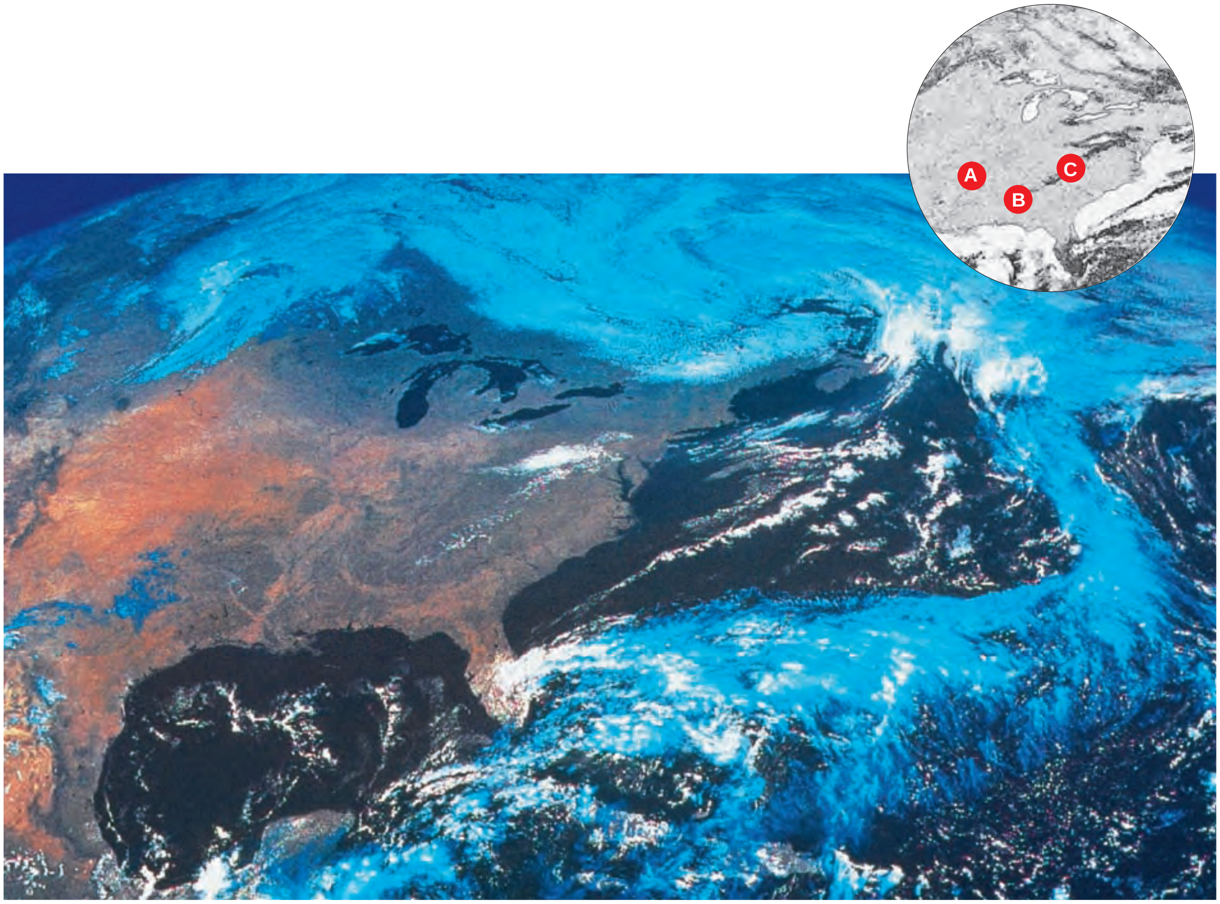
A final type of front—called a *dry line*—can form along the boundary between hot, dry, continental tropical (cT) air and warm, moist, marine tropical (mT) air. Dry lines are usually found out ahead of cold fronts where southerly and southwesterly winds bring subtropical air from the continental regions and marine regions into contact with one another. Very strong thunderstorms can form along these dry lines as the hot, dry air mass mixes with the warm, moist air mass, increasing its temperature and making it very unstable.

Midlatitude Anticyclones and Cyclones

Air masses are set in motion by wind systems—typically, masses of air moving in a spiral. Air can spiral inward and converge in a *cyclone*, or spiral outward and diverge in an *anticyclone*. Most types of cyclones and anticyclones are large features spanning hundreds to thousands of kilometers that move slowly across the Earth's surface, bringing changes in the weather as they move. These are referred to as *traveling cyclones* and *anticyclones*.

ANTICYCLONES

Anticyclones are associated with fair skies, except for occasional puffy cumulus clouds that sometimes develop in a moist surface air layer. For this reason, we often call anticyclones *fair-weather systems*. Within a traveling anticyclone, the air is warmed adiabatically as it descends and diverges, so condensation does not occur. Toward the center of an anticyclone, the pressure gradient is weak, so winds are light and variable. We find traveling anticyclones in the midlatitudes, typically associated with ridges or domes of clear, dry air that move eastward and equatorward. Figure 6.8 shows an example of a large anticyclone centered over



6.8 Picture of an anticyclone

This geostationary satellite image of eastern North America shows a large anticyclone centered over the area, bringing fair weather and cloudless skies. The boundary between clear sky and clouds running across the Gulf of Mexico and the Florida peninsula delineates the leading edge of the cool, dry air mass. The cloud edge at the top of the photo marks the cold fronts of two cold-air masses advancing eastward and southward.

EYE ON THE LANDSCAPE **What else would the geographer see?** On this clear satellite image, some of the major features of the eastern North American landscape stand out. At (A), note the difference in soil color along the Mississippi River. These are alluvial soils, deposited over millennia by the Mississippi during the Ice Ages. At (B), note the curving arc that marks the boundary between soft coastal plain sediments to the south (light color) and the weathered rocks and soils of the piedmont (dark color), to the north. This boundary can be traced all the way to New York City. Farther inland lie the Appalachians (C), showing puffy orographic cumulus clouds.

eastern North America, bringing fair weather and cloudless skies to the region.

In middle and higher latitudes, traveling cyclones and anticyclones bring changing weather systems. Convergence and uplift in cyclones cause condensation and precipitation. Subsidence in anticyclones warms the air, producing clear conditions.

CYCLONES

In a cyclone, the air converges and rises, cooling adiabatically as it does so. If the cooling air reaches saturation, this can cause condensation leading to precipitation. Many cyclones are weak and pass overhead with little more than a period of cloud cover and light precipitation. However, some cyclones have very intense pressure gradients associated with them that generate strong, intense winds. In addition, the inspiraling motion associated with these winds can result in significant convergence, and heavy rain or snow can accompany the cyclone. In that case, we call the disturbance a **cyclonic storm**, described in Figure 6.9.

There are three types of traveling cyclones. First is the *midlatitude cyclone* of the midlatitude, subarctic, and subantarctic zones, sometimes also called an *extratropical cyclone*. These cyclones range from weak disturbances to powerful storms. Second is the *tropical cyclone* found in the tropical and subtropical zones. Tropical cyclones range from mild disturbances to highly destructive hurricanes or *typhoons*. A third type is the **tornado**, a small, intense cyclone of enormously powerful winds. The tornado is much smaller in size than other cyclones and is related to strong, localized convective activity.

MIDLATITUDE CYCLONES

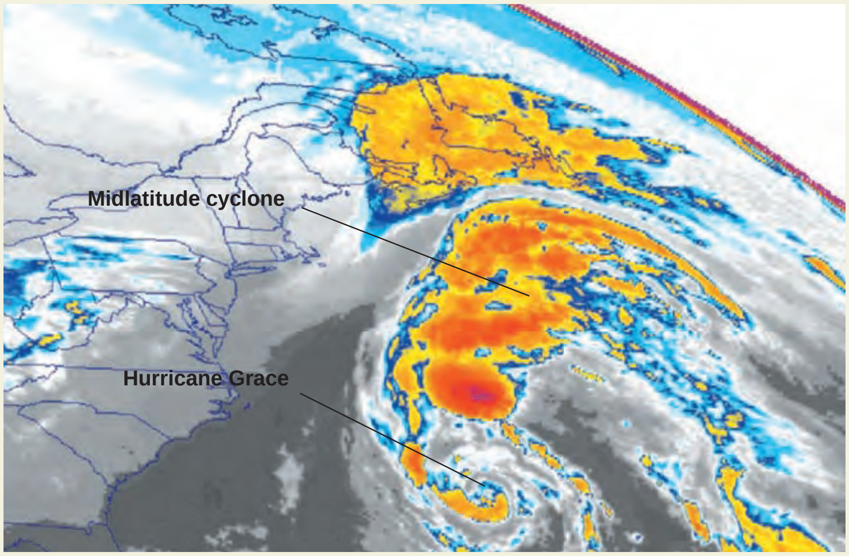
The **midlatitude cyclone** is the dominant weather system in middle and high latitudes. It is a large inspiraling of air that repeatedly forms, intensifies, and dissolves along the polar front.

The polar front sits between two large anticyclones—the polar high to the north, with its cold, dry air mass, and the subtropical high, with its warm, moist air mass, to the south. At the polar front, the airflow converges from opposite directions, with northeasterly winds to the north of the polar front and southwesterly winds to the south of the polar front.

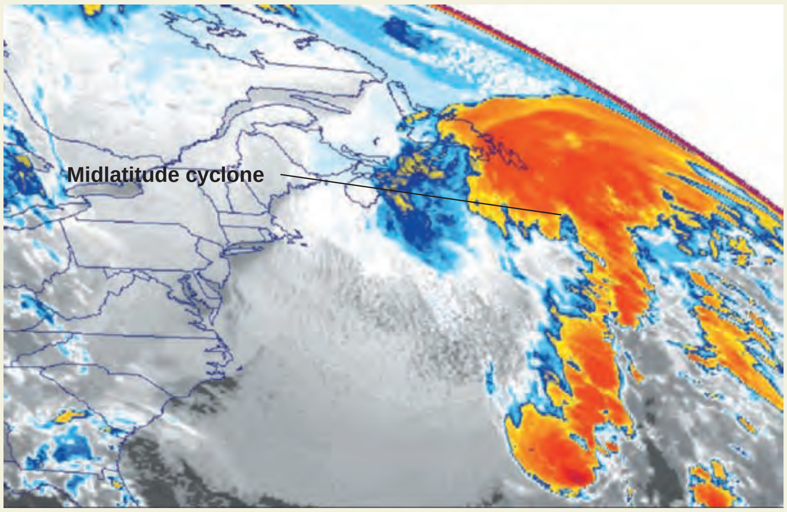
These wind motions lead to a counterclockwise, or cyclonic, circulation that creates a *low-pressure trough* between the two high-pressure cells. Midlatitude cyclones are local intensifications of cyclonic circulation that move along this low-pressure trough. The circular motion of air around the cyclone generates warm and cold fronts that sweep across large regions, creating weather changes. Figure 6.10 shows the life history of a midlatitude cyclone and associated warm and cold

6.9 The Perfect Storm

Cyclonic storms can be very dangerous. These satellite images show the development of the monster "Perfect Storm" of October 1991, which formed when a weakened tropical cyclone merged with a midlatitude cyclone. Generating 30-m (100-ft) waves and winds of 36 m/s (80 mph), it was perhaps the worst North Atlantic storm in a century.



◀ **October 28, 1991** As the remnants of Hurricane Grace approach from the south, a midlatitude cyclone moves over the eastern seaboard of the United States, setting the stage for a collision of the two cyclonic storms.



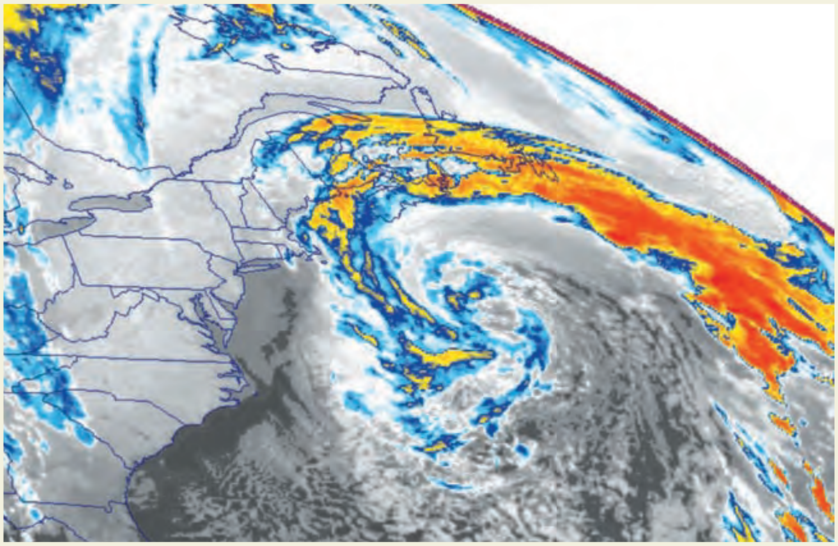
◀ **October 29, 1991** The moisture and low pressures of Hurricane Grace are incorporated into the midlatitude cyclone, adding latent heat to the system and intensifying the circulation. Now there is only one large storm system visible in the satellite image. Instead of moving out to sea, however, it begins to slowly drift to the southwest.

fronts and explains how a midlatitude cyclone forms, grows, and eventually dissolves.

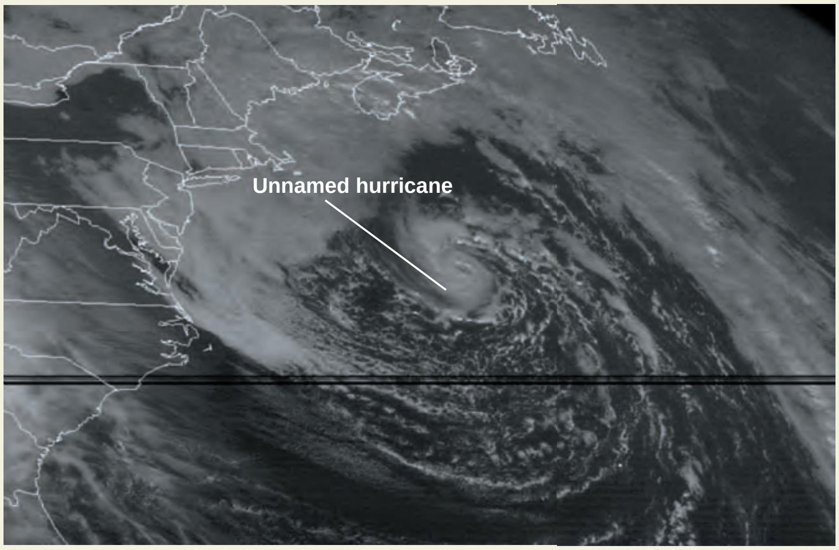
How does weather change as a midlatitude cyclone passes through a region? As the midlatitude cyclone and its accompanying fronts move eastward, a fixed location—like a point south of the Great Lakes—can experience weather ranging from warm, mild conditions with light winds to periods of heavy precipitation with gusty winds to cold, dry, breezy conditions with clear skies overhead. All of these can take place in a span of 24–36 hours as the fronts pass through. We can see these changes in Figure 6.11.

MIDLATITUDE CYCLONES AND UPPER-AIR DISTURBANCES

What causes midlatitude cyclones to grow over time? This growth is actually related to the growth of *jet stream disturbances,* which we explained in Chapter 5. To understand this process, look at the upper-level wind and pressure map in Figure 6.12. As the jet stream moves southward and eastward between the high-pressure disturbance—or *ridge*—and low-pressure disturbance—or *trough*—in the upper atmosphere, it tends to squeeze together or converge. As it does so, the winds around



◀ **October 30, 1991** The storm continues to intensify off the eastern seaboard of the United States. Winds generated by the storm reach hurricane strength. Devastating waves pound the shore from the Carolinas up to Nova Scotia. During this time, the storm continues to move southwest, back toward shore.



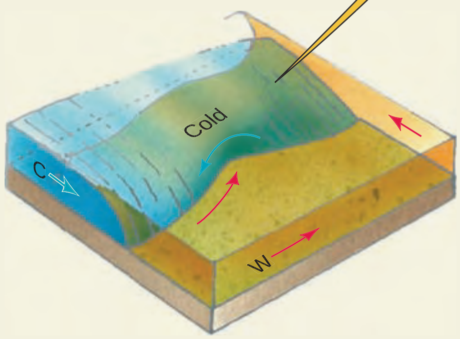
◀ **November 1, 1991** As the storm moves back toward shore, it drifts over the warm, subtropical waters of the Gulf Stream. The added sensible and latent heat feed convection within the storm, lowering the central pressure even farther. Eventually, a closed circulation forms around the central low pressure and an eye appears. A new, unnamed hurricane has formed. It eventually makes landfall in Nova Scotia on November 2.

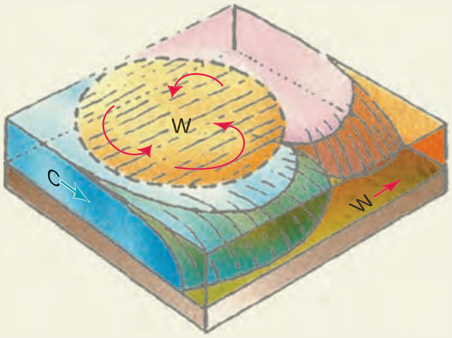
6.10 Life history of a midlatitude cyclone

Midlatitude cyclones are large features, spanning 1000 km (about 600 mi) or more. These are the "lows" that meteorologists show on weather maps. They typically last three to six days. In the midlatitudes, a cyclone normally moves eastward as it develops, propelled by prevailing westerly winds aloft. A–E show key stages in the life of a cyclone.

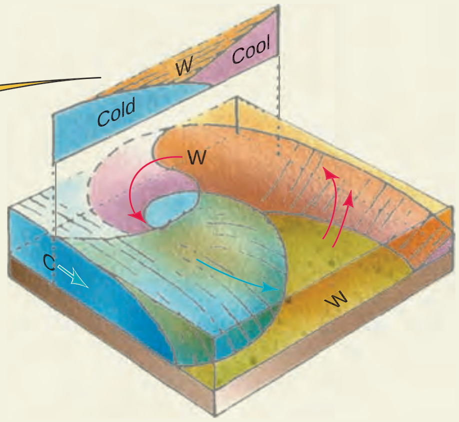
▶ Along the polar front, cold, dry polar air flowing from the northeast, meets warm, humid subtropical air flowing from the southwest.

▶ **Early stage** An undulation or disturbance begins at a point along the polar front. Cold air is turned in a southerly direction and warm air in a northerly direction, so that each advances on the other. This creates two fronts—a cold front indicated by a line with blue triangles and a warm front indicated by a line with red half-circles. As the fronts begin to move, the precipitation process begins.

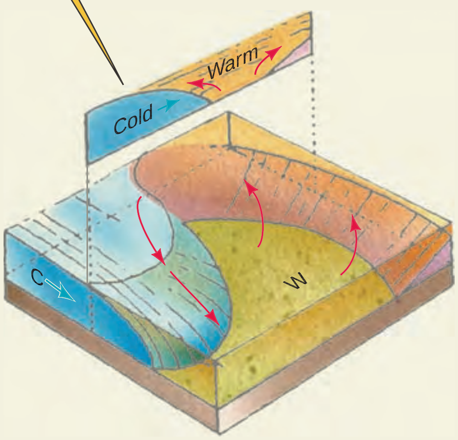




◀ **Dissolving stage** Eventually, the polar front is reestablished, but a pool of warm, moist air remains aloft and north of the polar front. As its moisture content reduces, precipitation dies out, and the clouds gradually dissolve. Soon, another midlatitude cyclone will form along the polar front and move across the continent.



▲ **Occluded stage** The faster-moving cold front overtakes the warm front, lifting the warm, moist air mass at the center completely off the ground. Because the warm air is shut off from the ground, this is called an occluded front and is indicated by a line with alternating triangles and half-circles. Precipitation continues to occur as warm air is lifted ahead of and behind the occluded front.

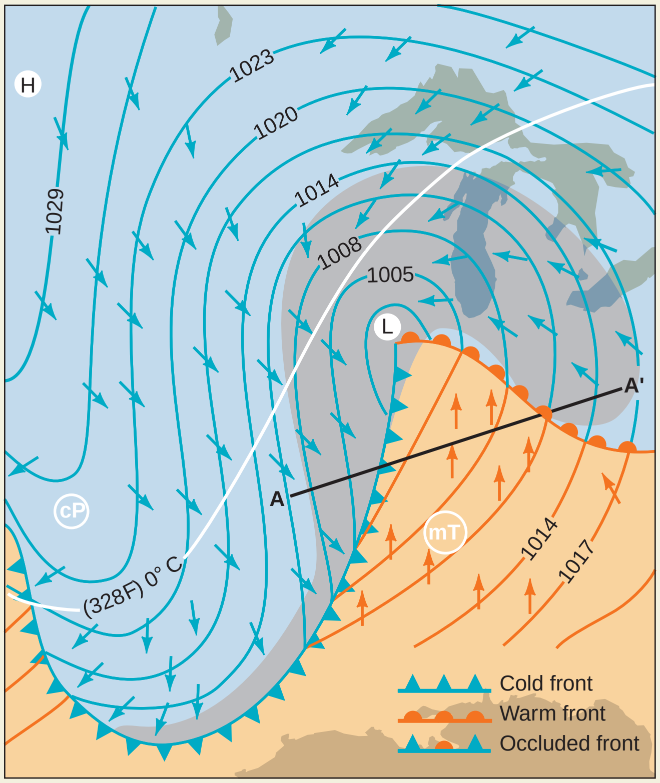


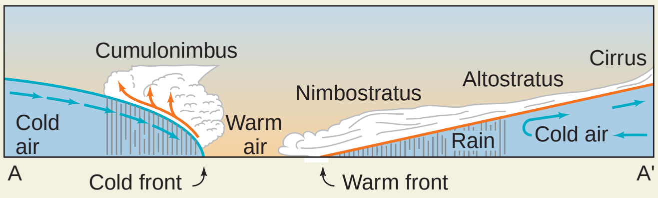
◀ **Open stage** The disturbance along the cold and warm fronts deepens and intensifies. Cold air actively pushes southeastward along the cold front, and warm air actively moves northward along the warm front. Precipitation zones along the two fronts are now strongly developed. The precipitation zone along the warm front is wider than the zone along the cold front.

6.11 Simplified surface weather maps and cross sections through a midlatitude cyclone

These maps show weather conditions on two successive days in the eastern United States. The three kinds of fronts are shown by special line symbols. Areas of precipitation are shown in gray. We can understand the movement of the respective air masses that generate the fronts by looking at the circulation around the surface low-pressure center, indicated by the isobars. The white line indicates the 0°C isotherm.

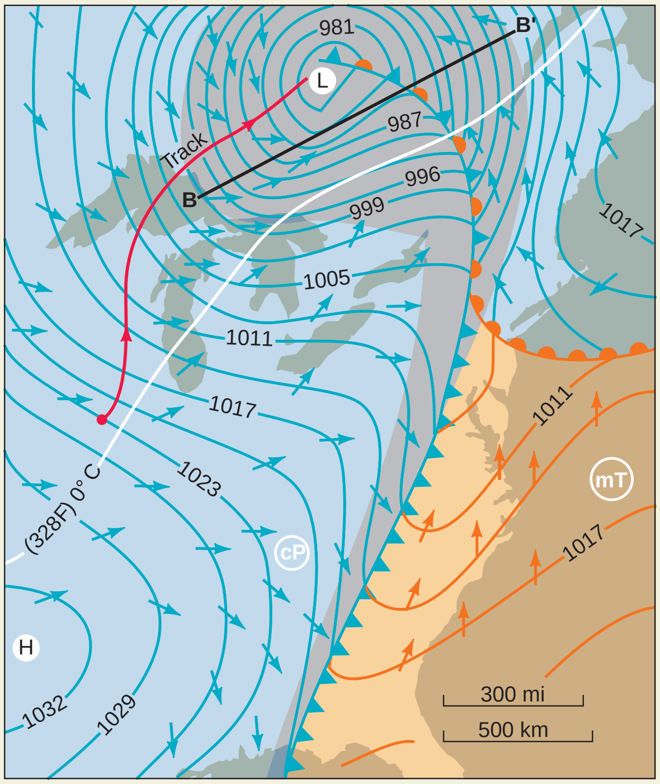
▼ **Open stage** The isobars show a surface low-pressure center with inspiraling winds. The cold front is pushing south and east, supported by a flow of cold, dry continental polar air circulating around the low-pressure center. Note that the wind direction changes abruptly ahead of the cold front, shifting from southerly to northwesterly. The temperature behind the cold front drops sharply as cP air moves into the region. The warm front is moving north and somewhat east, with warm, moist maritime tropical air circulating around the low pressure as well. The precipitation pattern includes a broad zone near the warm front and the central area of the cyclone. A thin band of intense precipitation extends down the length of the cold front. Generally, there is cloudiness over much of the cyclone.

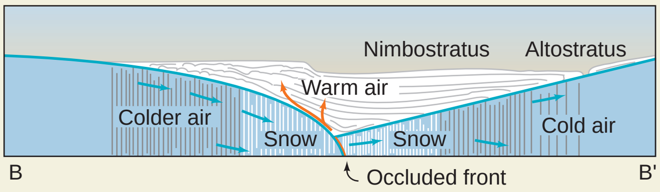




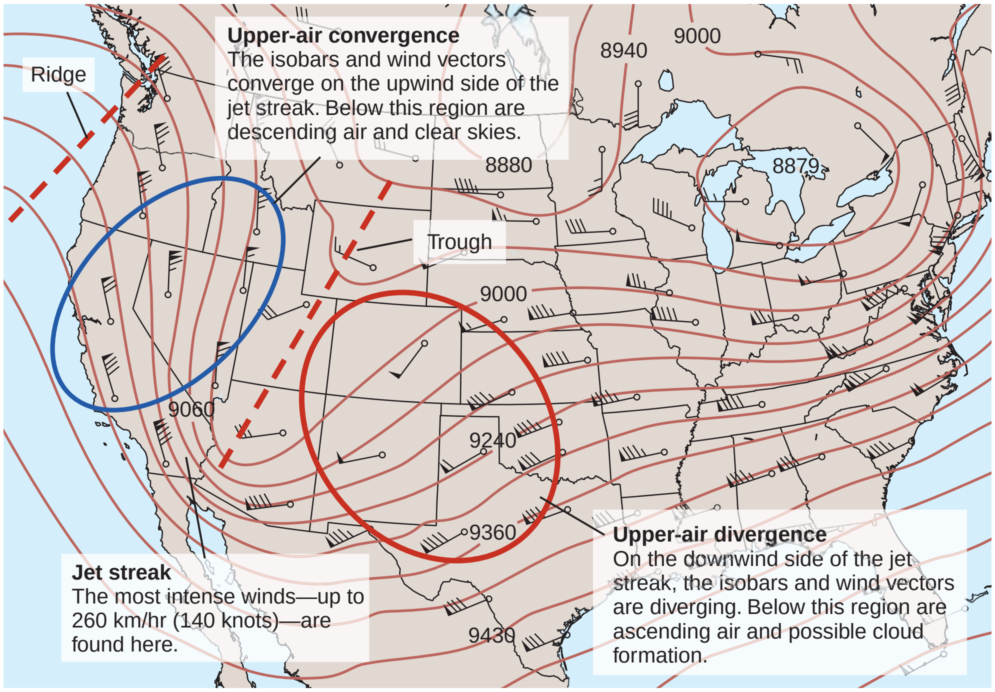
▲ **Cross section of open stage** A cross section along the line A–A′ shows how the fronts and clouds are related. A broad layer of stratus clouds ahead of the warm front takes the form of a wedge with a thin leading edge of cirrus. Westward, this wedge thickens to altostratus, then to stratus, and finally to nimbostratus with steady rain. Within the sector of warm air, the sky may partially clear with scattered cumulus. Along the cold front are cumulonimbus clouds associated with thunderstorms. These yield heavy rains but only along a narrow belt.

▼ **Occluded stage** This map shows conditions 24 hours later. The cyclone track is shown by the red line. The center has moved about 1600 km (1000 mi) in 24 hours—a speed of just over 65 km (40 mi) per hour. In this time, the cold front has overtaken the warm front, forming an occluded front in the central part of the disturbance. A high-pressure area, or tongue of cold polar air, has moved into the area west and south of the cyclone, and the cold front has pushed far south and east. Within the cold-air tongue, the skies are clear. Winds shift from southeasterly to westerly as the occluded front passes. Now precipitation is found in a broad region across the occluded front and throughout the central area of the cyclone. Behind the occluded front, conditions are clear and cold.





▲ **Cross section of occluded stage** A cross section shows conditions along the line B–B′, cutting through the occluded part of the storm. Note that the warm air mass is lifted well off the ground and yields heavy precipitation both ahead of and behind the occluded front.



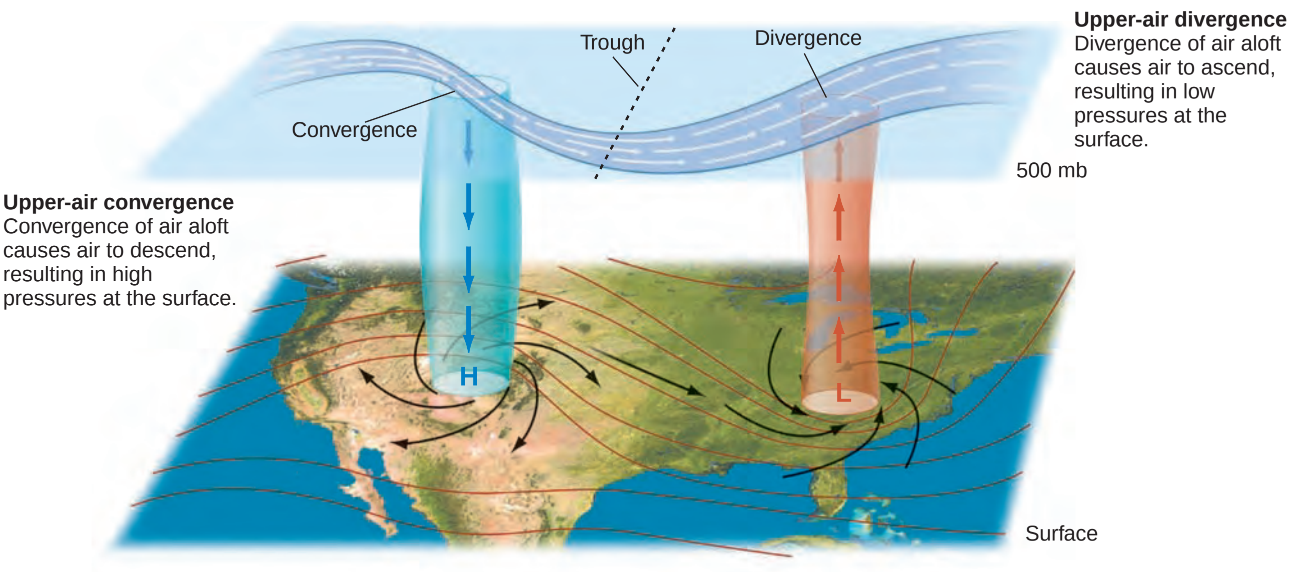
6.12 Upper-air jet streak

This upper-air pressure and wind map shows a jet streak over the southwestern portion of the United States.

the low-pressure accelerate, forming a *jet streak*. On the eastward side of the low pressure, the winds slow down as they spread apart or diverge.

As the air aloft converges on the upwind side of the jet streak, it produces a descent of air toward the surface. The descending air subsequently produces an anticyclone (or high-pressure center) at the surface, as seen in Figure 6.13. Conversely, as the air diverges on the downwind side of the jet streak, air ascends from below, resulting in a cyclone (or low-pressure center) at the surface.

Thus, the life history of the low-level midlatitude cyclone and its accompanying fronts follows the life history of the jet stream disturbance, as shown in Figure 6.14. As the upper-air circulation disturbance intensifies and moves eastward, the vertical circulations cause the midlatitude cyclones and anticyclones at the surface to intensify and move along with the disturbance. Eventually, the

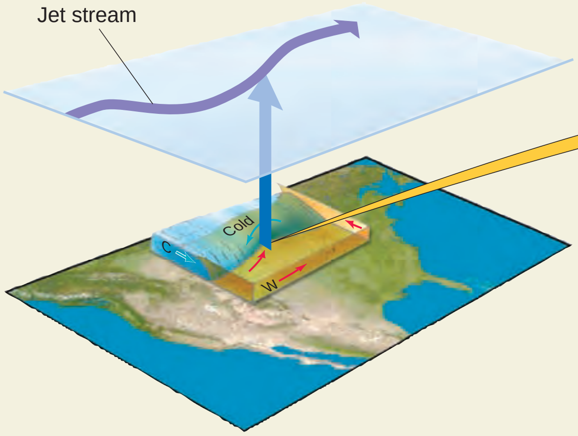


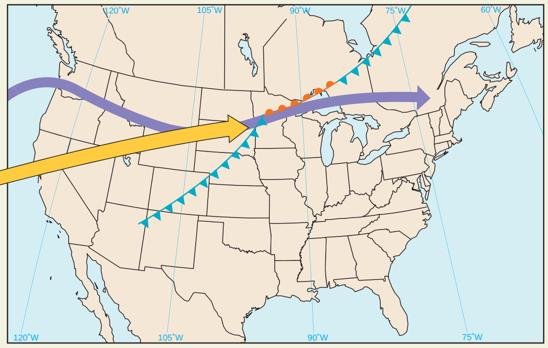
6.13 Upper-air and surface pressure patterns

As air diverges and converges around an upper-air low-pressure trough, surface highs and lows are generated.

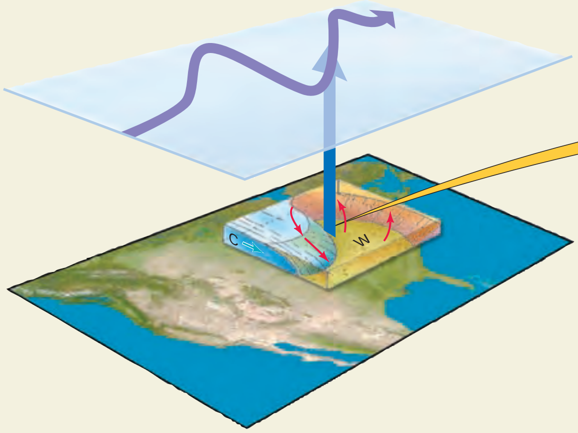
6.14 Life history of an upper-air disturbance and accompanying midlatitude cyclone

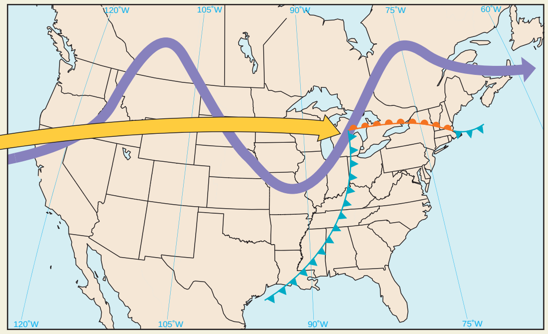
As an upper-air disturbance in the jet stream develops, vertical circulations in the regions of upper-air convergence and divergence produce changes in the surface pressures. As the upper-air disturbance moves and intensifies, so do the accompanying midlatitude cyclones and anticyclones.



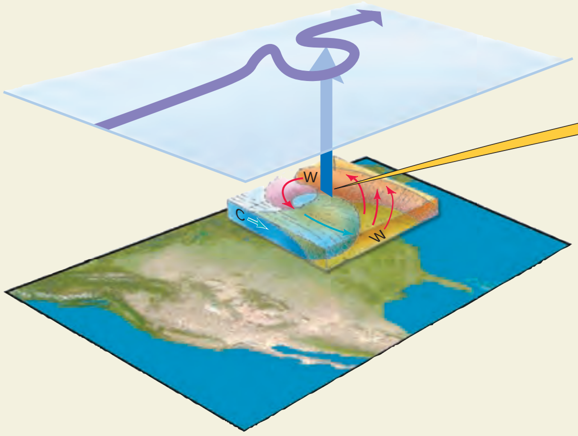


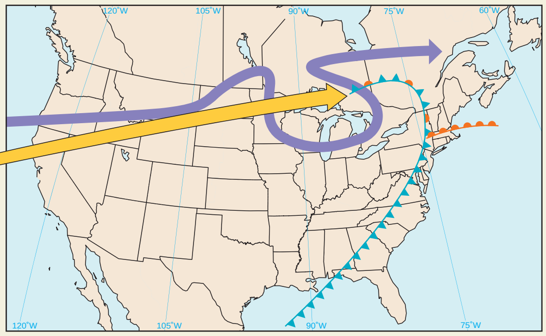
▲ **Early stage** A disturbance in the upper-air jet stream produces regions of upper-air convergence and divergence. Below the region of upper-air divergence, low pressure forms as air begins to ascend. Circulation around this low pressure moves warm air to the north and cool air south, initiating the formation of two fronts.





▲ **Open stage** As the upper-air disturbance strengthens, upper-air convergence and divergence increase. The intensified ascent below the region of upper-air divergence strengthens the surface cyclone. Cold air pushes south, while warmer air moves north around the intensified circulation.





▲ **Occluded stage** Eventually, the upper-air disturbance grows so large it forms a closed low-pressure center aloft. At this point, the storm has reached its maximum intensity and will begin to die out. Ascent continues in the region of upper air divergence. At the surface, the circulation around the low-pressure center causes the cold front to catch the warm front, producung an occluded front and a closed midlaitude cyclone.

upper-air jet stream disturbance gets so large it causes the jet stream to circle back on itself, pinching off the upper-air low-pressure center and reestablishing the east–west flow of the jet stream. At the surface, we recognize this as the point at which the midlatitude cyclone occludes and reestablishes the polar front.

GEODISCOVERIES **Midlatitude Cyclones**

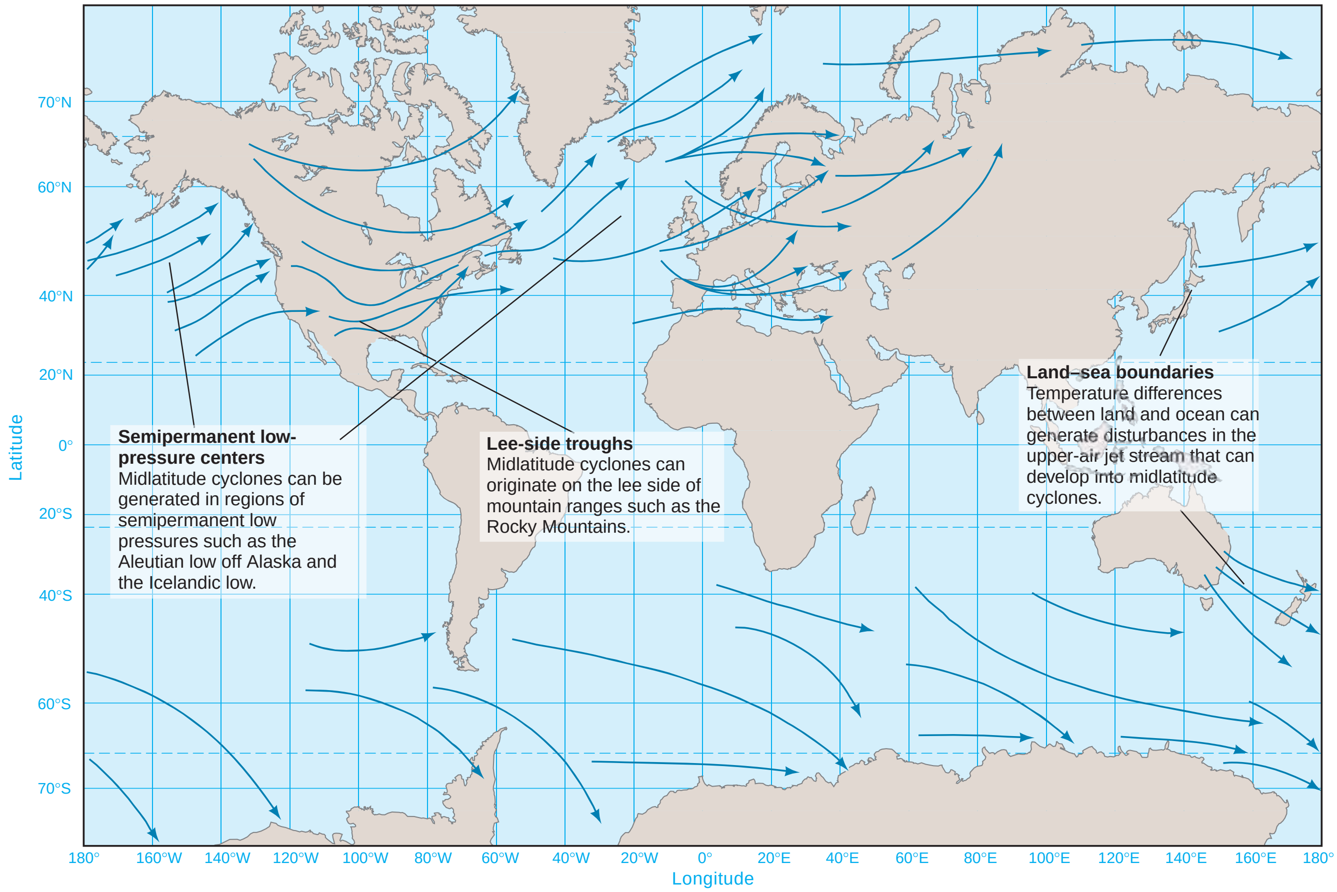
Watch an animation showing the life cycle of a midlatitude cyclone with cold, warm, and occluded fronts.

CYCLONE TRACKS AND CYCLONE FAMILIES

Several important processes can initiate traveling midlatitude cyclones, as seen in Figure 6.15. These processes link upper-air pressure patterns to surface patterns through vertical circulations induced by convergence and divergence, as explained above. The Aleutian and Icelandic lows are regions of frequent jet stream disturbances that spawn eastward-moving cyclones. Disturbances in the upper air flow caused by mountain chains produce *lee-side troughs* that also produce cyclones. Land–sea coastal boundaries are often regions of strong temperature contrast that can trigger disturbances and cyclones as well. As the disturbances propagate downwind, their cyclones move as well, and thus the surface storms are "dragged" along by the upper-air *steering winds*.

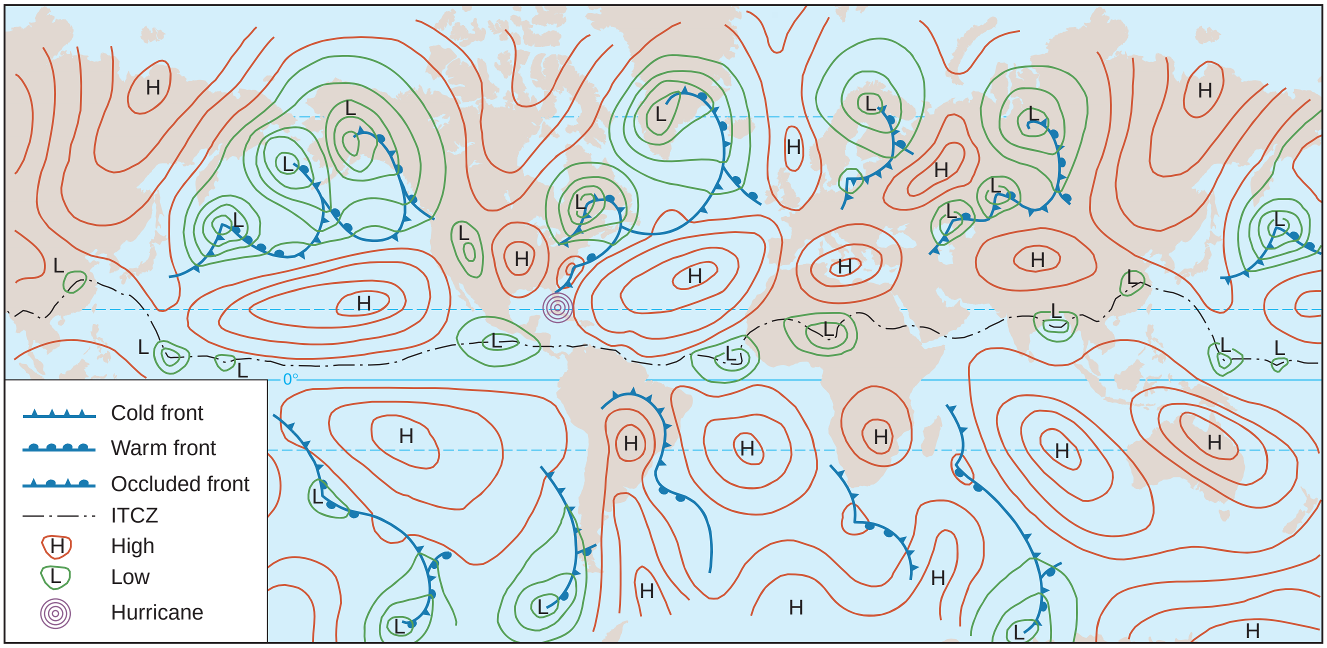
Because midlatitude cyclones tend to form in certain areas, they tend to travel common paths, called *storm tracks*, as they develop, mature, and dissolve. Cyclones of the Aleutian and Icelandic lows commonly form in succession, traveling as a chain across the North Atlantic and North Pacific oceans. A world weather map, such as in Figure 6.16, shows several such *cyclone families*. Each midlatitude cyclone moves northeastward along the storm track, deepening in low pressure and eventually occluding. For this reason, intense cyclones arriving at the western coasts of North America and Europe are usually occluded, while those arriving on the eastern seaboard after originating on the lee side of the Rocky Mountains are still intensifying.

In the southern hemisphere, storm tracks are more nearly along a single lane, following the parallels of latitude. Three such cyclones are shown in Figure 6.16. This track is more uniform because of the uniform pattern of ocean surface circling the globe at these latitudes. Only the southern tip of South America projects



6.15 Paths of midlatitude cyclones

This world map shows typical paths of midlatitude cyclones (blue).



6.16 Daily world weather map

A daily weather map of the world for a given day during July or August might look like this map, which is a composite of typical weather conditions.

southward to break the monotonous expanse of the Southern Ocean.

COLD-AIR OUTBREAKS

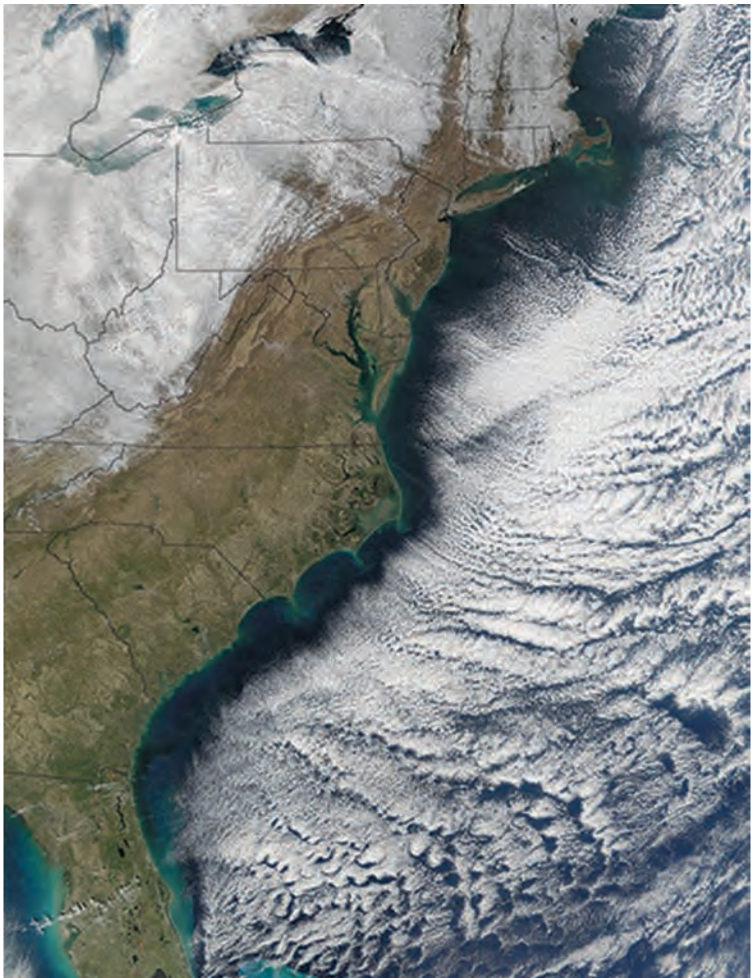
Another distinctive weather feature of midlatitude weather systems is the occasional penetration of powerful tongues of cold polar air from the midlatitudes into very low latitudes. These tongues are known as **cold-air outbreaks**. The leading edge of a cold-air outbreak is a cold front with squalls, which is followed by unusually cool, clear weather with strong, steady winds. The cold-air outbreak is best developed in the Americas. Outbreaks that move southward from the United States into the Caribbean Sea and Central America are called *northers* or *nortes*, whereas those that move north from Patagonia into tropical South America are called *pamperos*. Figure 6.17 shows one such outbreak over North America. A severe polar outbreak may bring subfreezing temperatures to the low latitudes of both regions and damage tropical crops such as citrus and coffee.

Tropical and Equatorial Weather Systems

So far, we have discussed weather systems of the midlatitudes and poleward. Weather systems of the tropical and equatorial zones show some basic differences from those of the midlatitudes. Upper-air winds are often weak, so

6.17 Cold-air outbreak

This satellite image shows the eastern seaboard during a cold-air outbreak on February 28, 2002. White regions over the central and northeastern portion of the United States are associated with snow cover. To the south, clear, cold conditions are found. This cold-air outbreak brought subfreezing cP air from Canada down into Florida.



air-mass movement is slow and gradual. Air masses are warm and moist, and different air masses tend to have similar characteristics, so fronts are not as clearly defined. Without the strong temperature gradients across unlike air masses, there are no large, intense upper-air disturbances. On the other hand, the high moisture content leads to intense convective activity in low-latitude maritime air masses. Because these air masses are very moist, only slight convergence and uplift are needed to trigger precipitation.

Tropical weather systems include easterly waves and weak equatorial lows. Precipitation results when moist air converges in these systems, triggering convective showers.

One of the simplest forms of tropical weather systems is an **easterly wave**—a slowly moving trough of low pressure within the belt of tropical easterlies (the trade winds). These waves occur in latitudes 5°–30° N and S over oceans, but not over the Equator itself. Figure 6.18 shows circulations and weather features associated with an easterly wave.

Another related weather system is the *weak equatorial low*—a disturbance that forms near the center of the equatorial trough. Moist equatorial air masses converge on the center of the low, causing rainfall from many individual convectional storms. Several such weak lows usually lie along the ITCZ.

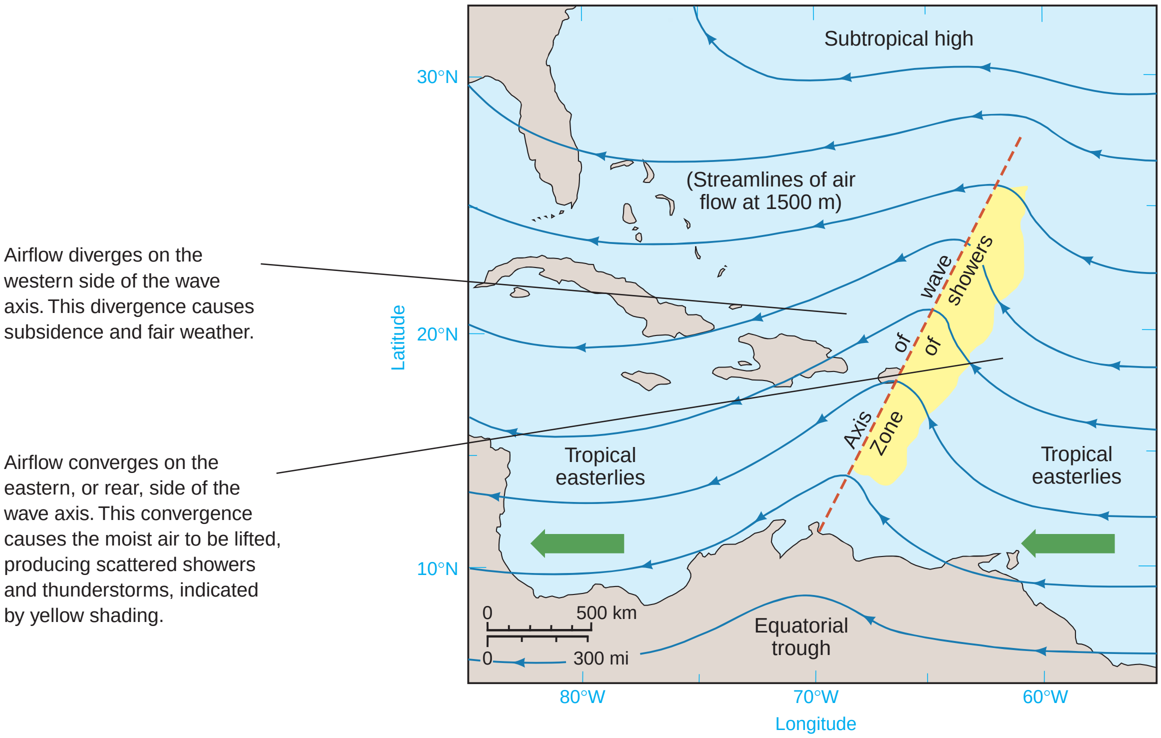
TROPICAL CYCLONES

The **tropical cyclone** is the most powerful and destructive type of cyclonic storm (Figure 6.19). It is known as a *hurricane* in the western hemisphere, a *typhoon* in the western Pacific off the coast of Asia, and a cyclone in the Indian Ocean. This type of storm typically develops over oceans between 10° and 20° N and S latitudes and no closer than 5° from the Equator.

Tropical cyclones (hurricanes or typhoons) are often powerful and destructive storms, with wind speeds of 30 to 50 m/s (about 65 to 135 mi/hr) and above.

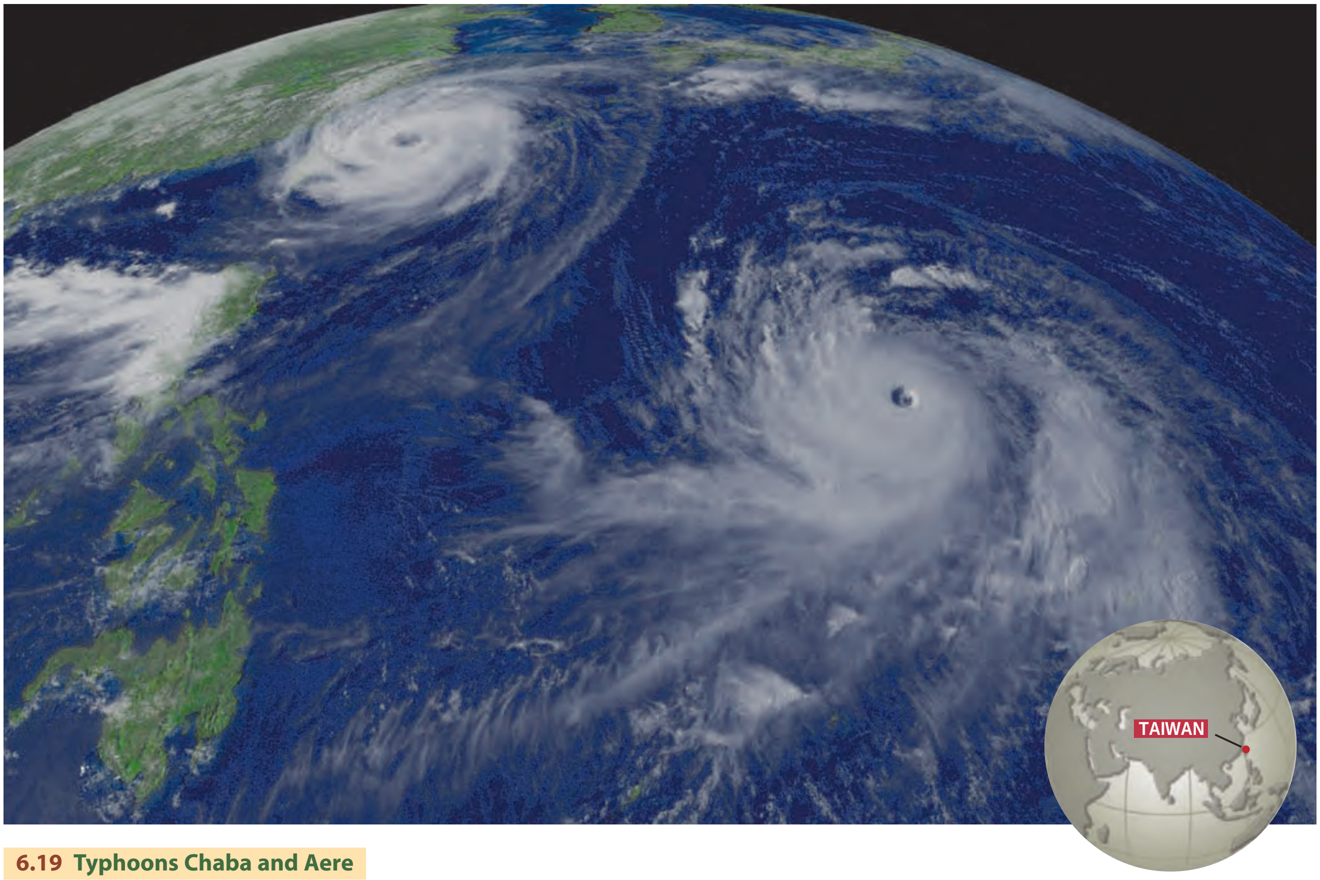
A tropical cyclone can originate as an easterly wave or weak low that intensifies and grows into a deep, circular low. It can also form as upper-air disturbances in the subtropical jet stream move south into the tropical regions. Once formed, the storm moves westward through the trade-wind belt, often intensifying as it travels. It can then curve poleward and eastward, steered by winds aloft. Tropical cyclones can penetrate well into the midlatitudes, as many residents of the southern and eastern coasts of the United States have experienced.

Tropical cyclones grow from *tropical depressions*, which are cyclones with winds below 17 m/s (39 mph). They



6.18 An easterly wave passing over the West Indies

A zone of weak low pressure is at the surface, under the axis of the wave. The wave travels westward at a rate of 300–500 km (about 200–300 mi) per day. Rainy weather associated with the passage of the wave may last a day or two.



6.19 Typhoons Chaba and Aere

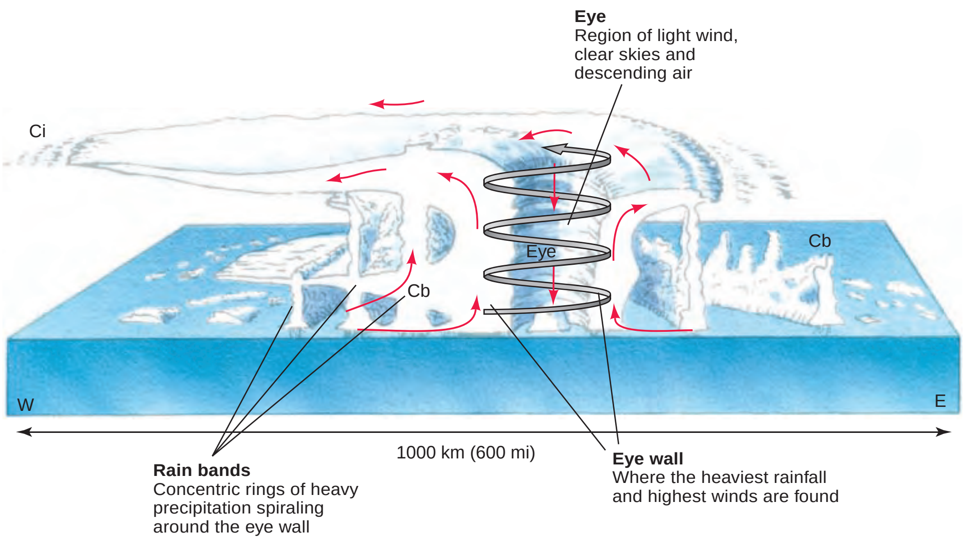
This satellite image shows Typhoon Aere, situated over Taiwan (upper left), and Typhoon Chaba, situated over the western Pacific (right center), on August 24, 2004. Typhoon Chaba became one of the 15 most intense tropical cyclones on record and surpassed any hurricane in the Atlantic.

intensify into *tropical storms* with winds of 18–33 m/s (40–74 mph). When winds exceed 33 m/s (74 mph), a tropical storm becomes a tropical cyclone.

An intense tropical cyclone is an almost-circular storm center of extremely low pressure (Figure 6.20). Because of the very strong pressure gradient, winds spiral inward at high speed. Convergence and uplift are intense, producing very heavy rainfall. The storm gains its energy through the release of latent heat as the intense precipitation forms. The storm's diameter may be 150–500 km (about 100–300 mi). Wind speeds can range from 30 to 50 m/s (about 65 to 135 mi/hr) and sometimes much

6.20 Structure of a tropical cyclone

In this schematic diagram, cumulonimbus (Cb) clouds in concentric rings rise through dense stratiform clouds. Cirrus clouds (Ci) fringe out ahead of the storm.



higher. Barometric pressure in the storm center commonly falls to 950 mb (28.1 in. Hg) or lower.

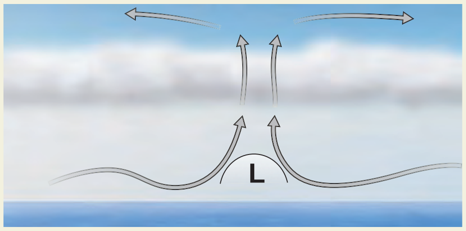
Another characteristic feature of a well-developed tropical cyclone is its central *eye*, in which clear skies and calm winds prevail. The eye is a cloud-free vortex produced by the intense spiraling of the storm. Around the eye, the wind is spinning so fast that it cannot converge into the center. Here in the eye, air descends from high altitudes and is adiabatically warmed, causing reevaporation of cloud droplets. As the eye passes over a site, calm prevails, and the sky is clear. It may take about half an hour for the eye to pass, after which the storm strikes with renewed ferocity but with winds in the opposite direction. Wind speeds and precipitation are highest along the cloud wall surrounding the eye. However, precipitation can also be intense in the rain bands that extend in concentric circles away from the hurricane.

TROPICAL CYCLONE DEVELOPMENT

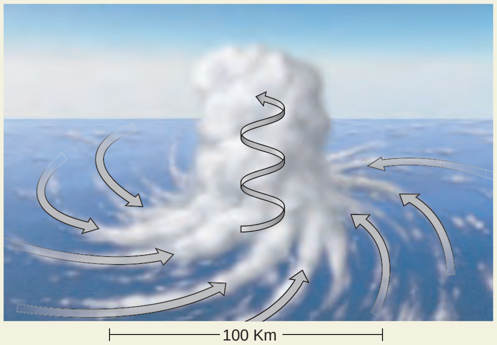
Why do tropical cyclones become so intense? The intensification is due to positive feedback between the ocean and atmosphere, described in Figure 6.21, that allows the atmosphere to draw in massive amounts of energy stored in the ocean.

6.21 Development and intensification of tropical cyclones

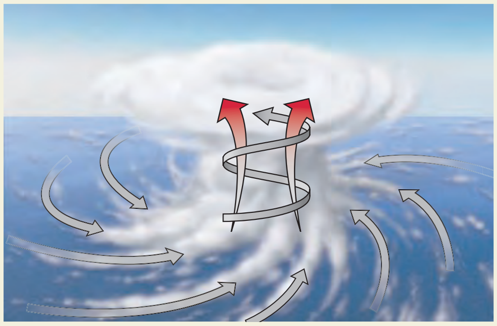
Tropical cyclones are intense wind and rain events. The intensification of these tropical cyclones involves positive feedback loops between the ocean and the atmosphere.



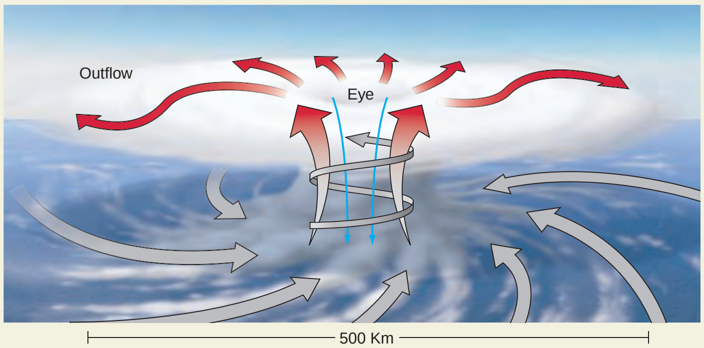
◀ **Starting the engine** Tropical cyclones begin when low-level air flow is disturbed—by an easterly wave or the equatorward intrusion of an upper-air disturbance. Either can initiate the convection needed to start a hurricane. Once convection begins, a low-pressure center forms near the surface.



▲ **Feeding it some fuel** The low-pressure center produces inspiraling air from the tropical ocean. This warm, moist air converges.



▲ **Feeding it more** As warm, moist air rises, it expands and cools adiabatically. Once the air cools to the dew point temperature, condensation begins, releasing tremendous latent heat into the surrounding air. This heating accelerates the upward flow of air.



◀ **Running it wide open** Convection grows "explosively," accelerating air flow vertically and lowering surface pressures even more. The lowering pressure induces stronger inspiraling of warm, moist air. As this air rises, its water vapor condenses, releasing more latent heat. This enhances convection further, leading to even lower pressures. Around the center of the hurricane, convection and winds are most intense. However, because the air is spinning so fast, it never reaches the center. Here, calm prevails with descending air producing a clearing of clouds characteristic of the hurricane eye.

As an easterly wave moves over the warm ocean waters of the low latitudes, the convergence at the surface results in convective lifting. This lifting subsequently results in condensation, which releases latent heat that warms the surrounding air and produces even greater convection. As the convection intensifies, it further lowers the pressure at the surface. The result is enhanced convergence of warm, moist air, which supplies even more latent heat to the system as the air is lifted. As the low pressure at the surface continues to drop, the inspiraling winds intensify, producing the ferocious winds described in the chapter opening.

Another reason for the very intense winds is weakness of the Coriolis force at the latitudes at which tropical cyclones are located. Looking at Figure 6.21, the pressure gradient force on a moving parcel of air has to be balanced by the Coriolis force, which depends on the parcel's speed. Because the force is weaker at low latitudes, the parcel has to go faster to generate a force that balances the same amount of pressure gradient force. Thus, wind speeds in tropical cyclones can become much higher than in traveling cyclones of the midlatitudes.

GEODISCOVERIES Hurricanes
A video shows how a hurricane, fueled by warm ocean water, develops extreme winds in its eye wall.

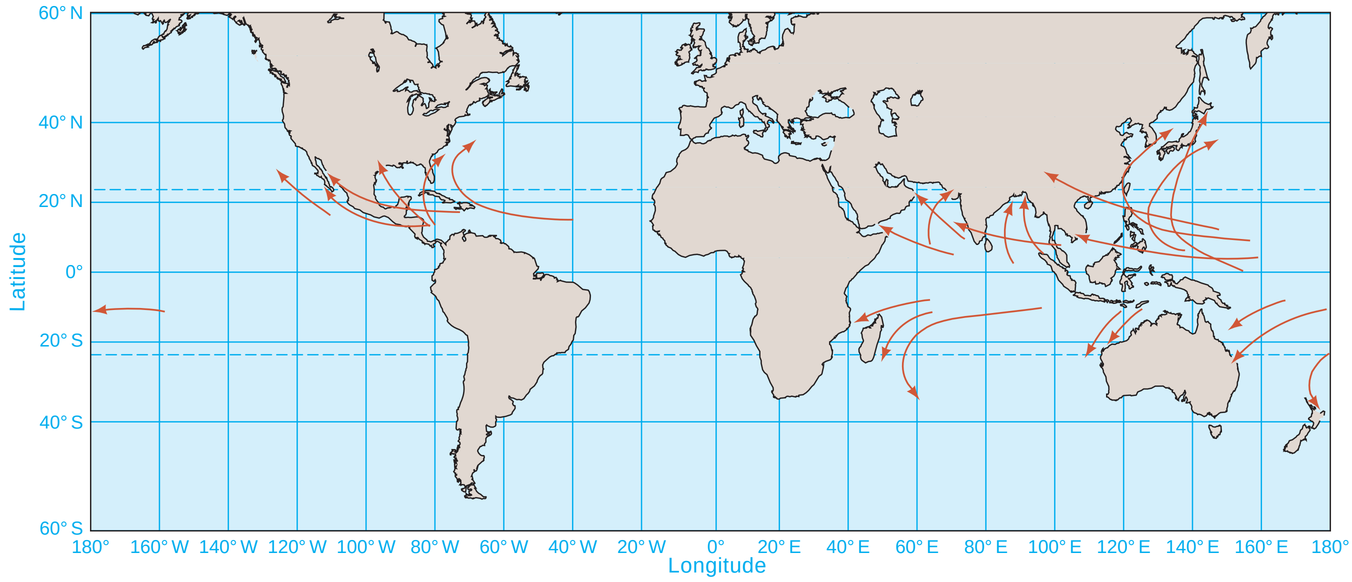
TROPICAL CYCLONE TRACKS

Tropical cyclones occur only during certain seasons. For hurricanes of the North Atlantic, the season typically runs from June through November, with maximum frequency in late summer or early autumn. In the southern hemisphere, the season is roughly the opposite. These periods follow the annual migrations of the ITCZ to the north and south with the seasons, and correspond to periods when ocean temperatures are warmest.

Most of the storms originate at 10°–20° N and S latitude and tend to follow known *tropical cyclone tracks* (Figure 6.22). In the northern hemisphere, they most often travel westward and northwestward through the trade winds, and then turn northeast at about 30°–35° N latitude into the zone of the westerlies. Here their intensity lessens, especially if they move over land. In the trade-wind belt, the cyclones typically travel at 10–20 km (6–12 mi) per hour. In the zone of the westerlies, their speed is more variable.

What factors are required for tropical cyclone development? As shown in Figure 6.22, tropical cyclones form over ocean regions in the low latitudes, but not within 5° of the Equator. Here, we find the warm ocean waters, greater than 26.5° C (80° F), that supply the latent and sensible heat needed to drive the tropical cyclone. Also required is an unstable environmental lapse rate, so that convection can easily be initiated by passing easterly waves or upper-air disturbances.

Weak winds with little change in wind speed or direction with height are also needed, so that the large uniform vertical structure of the tropical cyclone can develop. If this uniform structure is disrupted, the tropical cyclone will quickly die out. Finally, the atmosphere must have a high water content through the bottom 5 km (16,000 ft) of the atmosphere. If warm, moist surface air mixes with dry air above, the relative humidity of the air will decrease and the latent heat release needed to sustain the tropical cyclone will be shut down.



6.22 Paths of tropical cyclones

This world map shows typical paths of tropical cyclones. They develop over warm oceans to the north and south of the Equator, are steered westward on tropical easterlies, and then often turn poleward and eastward into the zone of prevailing westerlies.

What factors prevent the formation of tropical cyclones? Because weak winds are needed, moderate to strong winds above the surface will tend to disrupt the uniform structure of the tropical cyclone. Also, descent of air from above will inhibit convection and the vertical circulations necessary to release latent heat. Finally, if the low is too close to the Equator, the Coriolis force will be too weak to deflect the air motion, and it will rapidly converge into the low-pressure center, evening out the pressure at the surface.

In the western hemisphere, hurricanes originate in the Atlantic off the west coast of Africa, in the Caribbean Sea, or off the west coast of Mexico. In the Indian Ocean, cyclones originate both north and south of the Equator, moving north and west to strike India, Pakistan, and Bangladesh, as well as south and west to strike the eastern coasts of Africa and Madagascar. *Typhoons* of the western Pacific also form both north and south of the Equator, moving into northern Australia, Southeast Asia, China, and Japan. Curiously, tropical cyclones almost never form in the South Atlantic or southeast Pacific regions. As a result, South America is not threatened by these severe storms.

Once formed, tropical cyclones are given names for convenience as they are tracked by weather forecasters. Male and female names are alternated in an alphabetical sequence that is renewed each season. Different sets of names are used within distinct regions, such as the western Atlantic, western Pacific, or Australian regions. Names are reused, but the names of storms that cause significant damage or destruction are retired from further use.

To track tropical cyclones, we now use satellite images. Within these images, tropical cyclones are often easy to identify by their distinctive pattern of inspiraling bands of clouds and a clear central eye. Figure 6.23 shows a gallery of satellite images of the Atlantic tropical cyclones from 2005.

GEODISCOVERIES **Remote Sensing and Climate Interactivity**

Examine satellite images of Hurricanes Hugo and Andrew and watch the storms develop. Learn how cloud types are organized in the hurricane structure.

IMPACTS OF TROPICAL CYCLONES

Tropical cyclones can be tremendously destructive storms, with intense rainfall and very strong winds. The effects of wind, sea-level rise, and rain can cause devastation across very large areas. This devastation can occur along the coasts and farther inland along waterways and over mountain ranges, affecting thousands as the tropical cyclone moves along its track.

The intensity of a tropical cyclone is based on the central pressure of the storm, mean wind speed, and height of the accompanying sea-level rise. Storms are ranked from category 1 (weak) to category 5 (devastating) on the Saffir-Simpson scale, shown in Figure 6.24.

To be classified as a hurricane, a tropical cyclone must have sustained winds of over 33 m/s (74 mph). However, sustained winds in the strongest storms can exceed 70 m/s (about 150 mph) with wind gusts of 90 m/s (about 200 mph) at times.

In addition, rainfall rates can be extremely high. During the passage of some tropical cyclones, 600 mm (2 ft) of rain or more can fall at a location. In some coastal regions, these storms provide much of the summer rainfall. Although this rainfall is a valuable water resource, it can also produce freshwater flooding, raising rivers and streams from their banks. On steep slopes, soil saturation and high winds can topple trees and produce disastrous earthflows.

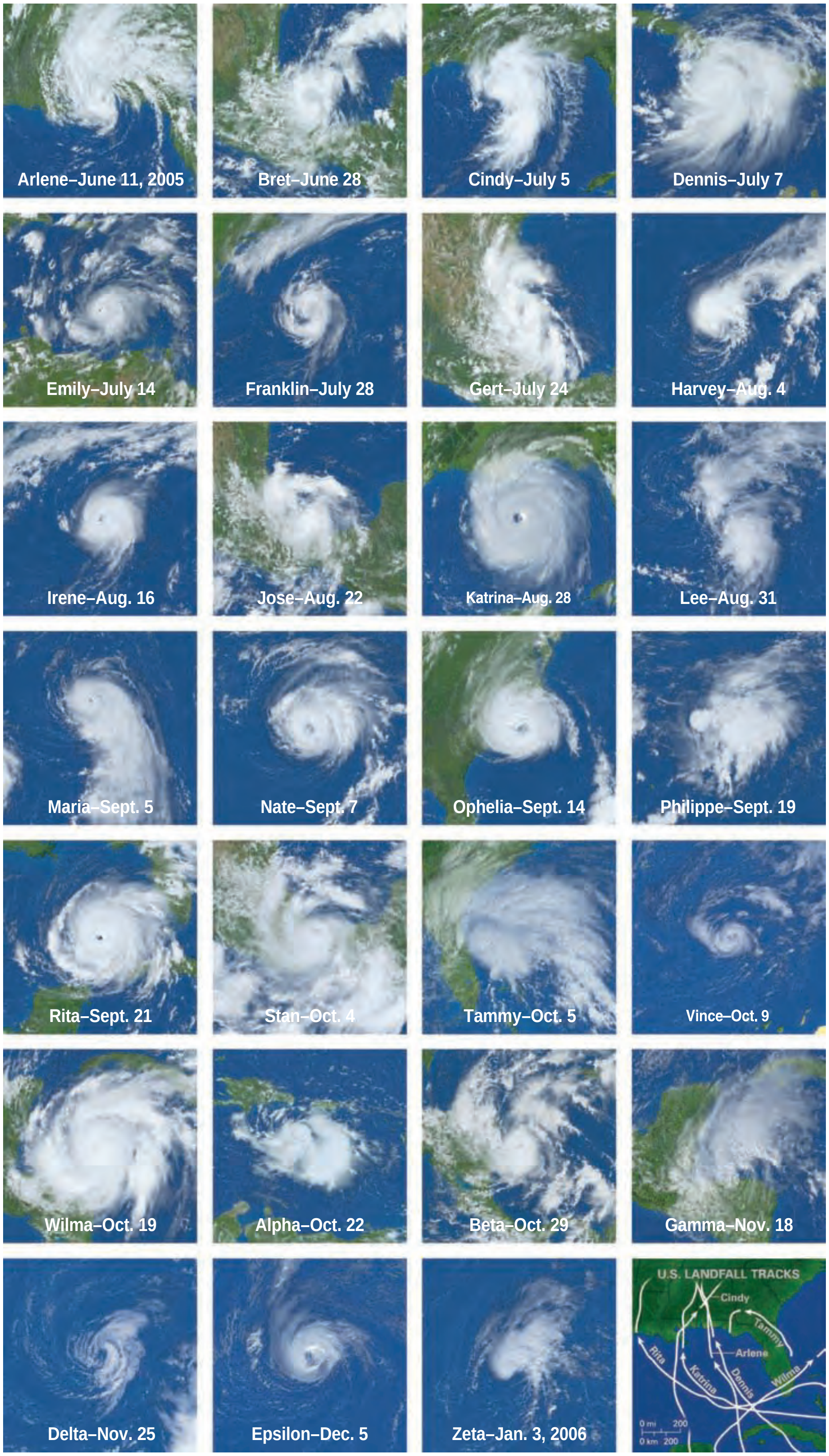
The strong onshore winds of a tropical cyclone, coupled with high tides and a favorable offshore sea-bottom configuration, can create a devastating storm surge that inundates wide areas near the coast. Heavy rains, while recharging water supplies, can also produce damaging floods.

However, the most serious effect of tropical cyclones is usually coastal destruction by storm waves and very high tides, seen in Figure 6.25. Since atmospheric pressure at the center of the cyclone is so low, the sea level rises within the center of the storm. In addition, high winds create damaging surf and push water toward the coast on the side of the storm with onshore winds, raising the sea level even higher. Waves attack the shore at points far inland of the normal tidal range. Low pressure, winds, and the underwater shape of a bay floor can combine to produce a sudden rise of water level known as a **storm surge**, which carries ocean water and surf far inland. If high tide accompanies the storm, waters will be even higher. For example, low-lying coral atolls of the western Pacific may be entirely swept over by wind-driven sea water, washing away palm trees and houses and drowning the inhabitants.

IMPACTS ON COASTAL COMMUNITIES

Coastal residents of South Florida are particularly aware of the damage hurricanes can cause. In 1992, Hurricane Andrew struck the east coast of Florida near Miami. The second most damaging storm to occur in the United States, it claimed 26 lives and caused more than $35 billion in property damage, measured in today's dollars. In 2004, four major hurricanes crossed Florida—Charley, Frances, Ivan, and Jeanne. Taken together, the storms destroyed over 25,000 homes in Florida, with another 40,000 homes sustaining major damage.

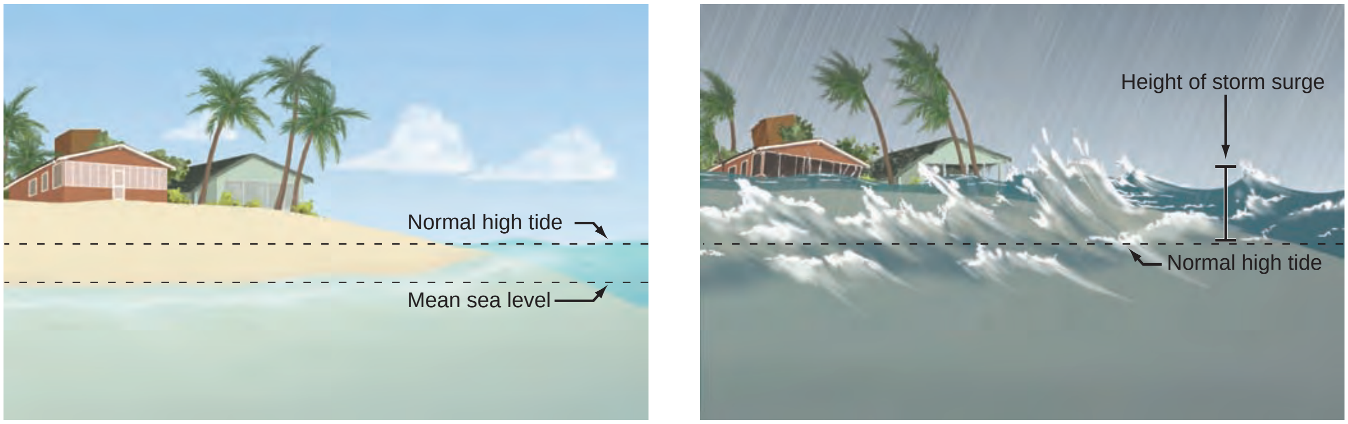
South Florida is not the only coastal region to suffer the devastating effects of hurricanes. In 2005, Hurricane Katrina laid waste to the city of New Orleans and much of



6.23 Atlantic tropical cyclone gallery for 2005

The year 2005 was the most active on record for Atlantic hurricanes. Shown here are the 27 named storms that occurred during the official season of June 1 to November 30. Katrina was the costliest Atlantic storm on record. Wilma was the most intense, at one point observed with a central pressure of 882 mb (26.05 in. Hg) and winds of 83 m/s (185 mph) (National Geographic Image Collection).

6.24 Saffir-Simpson scale of tropical cyclone intensity



Normal conditions
Structures above normal high tide are not subject to damage from continuously breaking waves.

Storm surge
A storm surge combined with a high tide can lift the sea level so that structures are subjected to continuous pounding of heavy surf.

6.25 Storm surge and its effect on coastal areas

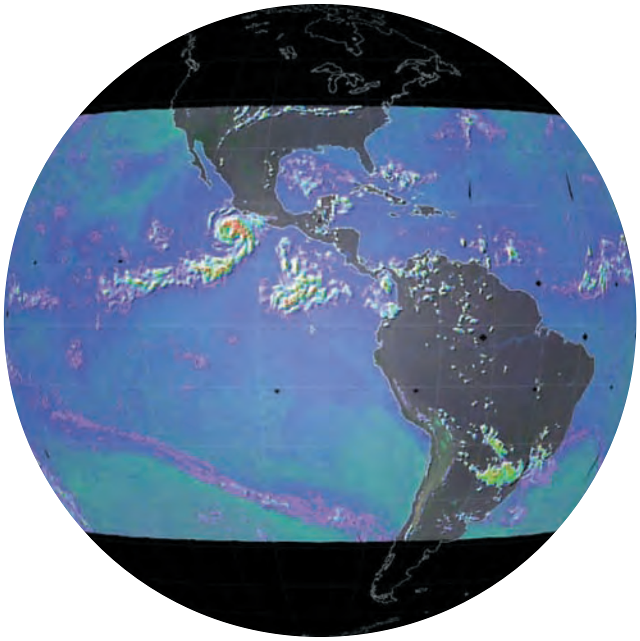
As a tropical cyclone moves onshore, it can bring with it a devastating storm surge. By raising the sea level through a combination of high winds and low surface pressures, the storm surge can inundate low-lying areas and subject them to heavy surf.

FOCUS ON REMOTE SENSING

The Tropical Rainfall Monitoring Mission

In November of 1997, NASA and the Japanese Space Agency launched a joint satellite mission with the goal of monitoring rainfall in the tropical and equatorial regions of the world—the Tropical Rainfall Monitoring Mission (TRMM). Its operational objective is to provide more information about where and when intertropical convective precipitation occurs, particularly over oceans, which are not monitored by weather stations and rain gauges. The mission is also designed to document how rainfall formation occurs within rain clouds in the intertropical region. Still in operation in 2009, the mission has successfully provided large volumes of information on rainfall amounts and locations as well as the structure of storms and cyclones over its long lifetime. Figure 6.26 shows an example of how TRMM measures precipitation.

The TRMM satellite has a unique orbit, covering only the region from 35° N to 35° S latitudes. With a low altitude and a short orbital period, the platform's instruments sample the complete day-night precipitation cycle over land and ocean surfaces in this region. In this way, scientists have accumulated accurate statistics about rainfall frequency,



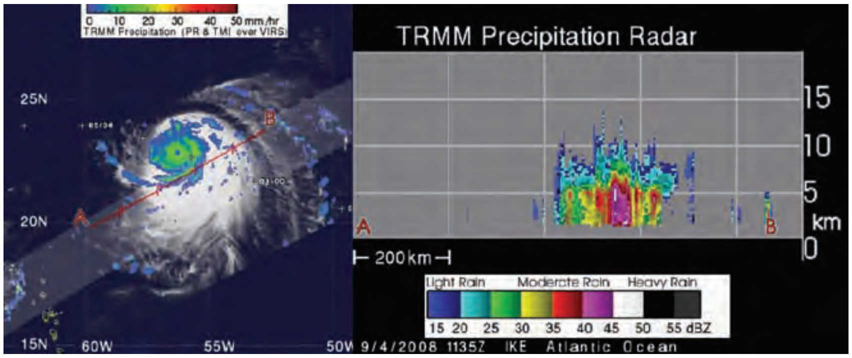
6.26 Intertropical rainfall measured by TRMM

This image shows precipitation as observed over a two-day period by TRMM instruments. A tropical cyclone lies off the Pacific coast of Mexico. Also visible is a line of frontal precipitation across the United States at the top of the image and a band of rainfall across the southern Pacific from the Equator southeast to southern Chile.

the Louisiana and Mississippi Gulf coasts (Figure 6.28). Originating southeast of the Bahamas, the hurricane first crossed the South Florida peninsula as a category 1 storm, then moved into the Gulf of Mexico, where it intensified to a category 5 storm. Weakening somewhat as it approached the Gulf Coast, its eye came ashore at Grand Isle, Louisiana, with sustained winds of 56 m/s (125 mph) early on August 29.

The city of New Orleans is particularly vulnerable to hurricane flooding. Built largely on the floodplain of the Mississippi River, most of its land area has slowly sunk below sea level as underlying river sediments have compacted through time. In addition, it is a city surrounded by water. Levees protect the city from Mississippi River floods on the south, as well as from ocean waters along the saline Lakes Borgne on the east and Pontchartrain on the north, which are both connected to the Gulf of Mexico. Rainwater falling into the sunken basin is pumped up and out of the city by discharge canals that run through the city itself and out to Lake Pontchartrain. There are also several canals and shipping channels connecting the river with the lakes and the Gulf.

Katrina's first assault was mounted from the east along one of these shipping channels, as a storm surge swept westward from Lake Borgne, overtopping and eroding levees and flooding east New Orleans and St. Barnard Parish. Penetrating deep into the city along the Intracoastal Waterway, the surge also overtopped and breached floodwalls and levees along the main canal connecting the Mississippi River with Lake Pontchartrain. To the north, water levels rose in Lake Pontchartrain, overtopping dikes and levees and filling the discharge canals to dangerously high levels. Eventually, large sections of the canal walls failed, allowing water to pour into the central portion of the city (Figure 6.29). Over the next two days, the water level rose until it equalized with the level of Lake Pontchartrain. Eighty percent of the city was covered with water at depths of up to 6 m (20 ft).



6.27 TRMM observes Hurricane Ike

This data swath from TRMM instruments shows Hurricane Ike in the Atlantic on September 4, 2008, located about 1000 km (620 mi) east-northeast of San Juan, Puerto Rico. The category 4 storm had sustained winds of 60 m/s (132 mi/hr) with gusts of 72 m/s (161 mi/hr). The image on the left shows the cloud pattern with a rainfall rate map superimposed. The eye is clearly visible. It is obtained from the TRMM visible/infrared scanner and the microwave imager. The transect A–B, acquired by the platform's precipitation radar, shows a cross section through a rain band to the southeast of the storm's center.

intensity, duration, and latent heat energy released. This, in turn, has allowed mathematical models of atmospheric circulation to predict global energy transport, winds, and precipitation with much better accuracy.

The TRMM satellite platform has three principal instruments: the precipitation radar, the passive microwave imager, and the visible and infrared scanner. The precipitation radar provides three-dimensional images of storm clouds, including the intensity and distribution of rain, precipitation type, cloud height, and height at which snow melts into rain. The passive microwave imager monitors water vapor, cloud water, and rainfall intensity by measuring the intensity of microwave radiation emitted by liquid water droplets. The visible and infrared scanner tracks clouds as bright objects at visible wavelengths, while its thermal bands measure cloud-top temperature, which indicates cloud height.

Figure 6.27 shows data obtained as TRMM passed near the center of Hurricane Ike on September 4, 2008. The inward-spiraling cloud pattern of this tropical cyclone is clearly shown on the wide track of the instrument, which combines the two imagers (left). The radar transect (right) shows the three-dimensional structure of the storm along a slice through one of its rain bands. Hurricane Ike later crossed Cuba as a category 3 storm, then hit the Texas coast near Galveston as a very large category 2 storm. Its winds brought storm surges of 1.5–4 m (5–13 ft) to the coast that leveled the towns of Crystal Beach, Caplen, and Gilchrist, Texas, and destroyed about 13,000 homes in Terrebone Parish, Louisiana.

The result was devastation. Total losses were estimated at more than $100 billion. The official death toll exceeded 1300. The Gulf coasts of Mississippi and Louisiana were also hard hit, with a coastal storm surge as high as 8 m (25 ft) penetrating from 10 to 20 km (6–12 mi) inland. Adding insult to injury, much of New Orleans reflooded three weeks later because of Hurricane Rita, a category 3 storm that made landfall on September 24 at the Louisiana–Texas border.

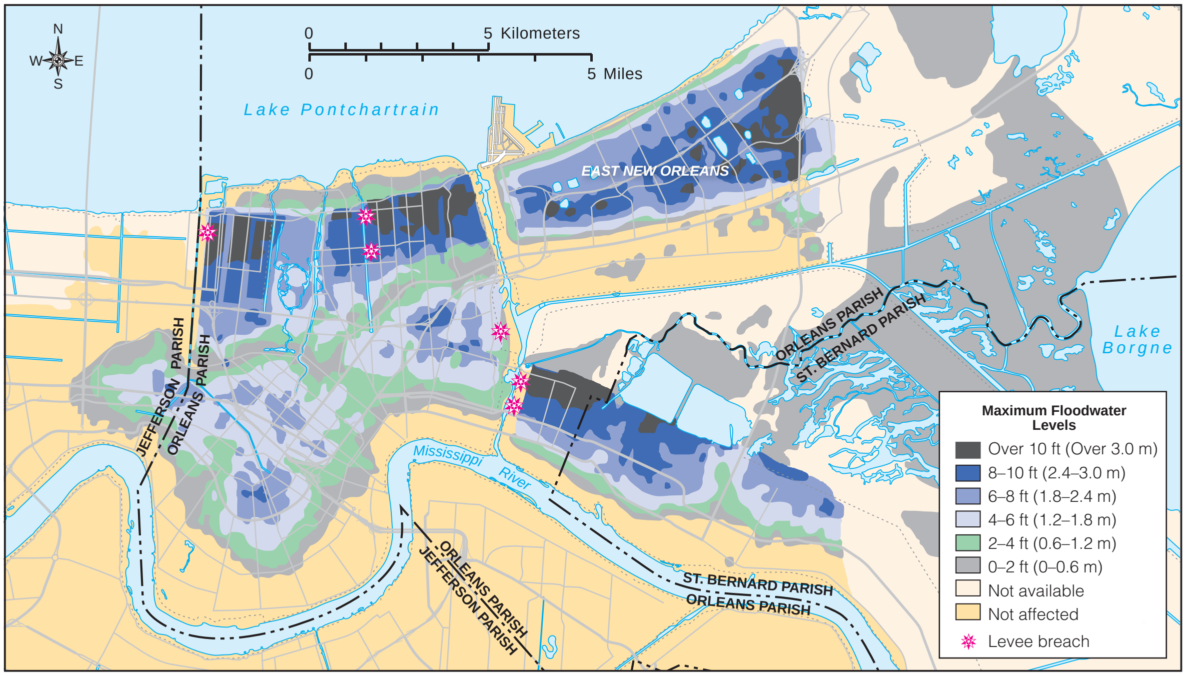
Poleward Transport of Heat and Moisture

As we saw in Chapter 5, the general circulation of the atmosphere and oceans is driven by the difference in solar heating between low and high latitudes. This general circulation, combined with jet stream disturbances in the midlatitudes, serves to redistribute heat and moisture from the Equator to the poles in the process of *poleward heat transport*. Figure 6.30 shows the various mechanisms by which this heat and moisture redistribution takes place.

Mechanisms of poleward heat transport include the Hadley cells, jet stream disturbances, and the Atlantic thermohaline circulation.

An important feature of this redistribution is the Hadley cell circulation—a global convection loop in which moist air converges and rises in the intertropical convergence zone (ITCZ) while subsiding and diverging in the subtropical high-pressure belts.

The Hadley cell convection loop acts to pump heat from warm equatorial oceans poleward to the subtropical zone. Near the surface, air flowing toward the ITCZ picks up water vapor evaporated by sunlight from warm ocean surfaces, increasing the moisture



6.28 Flooding in New Orleans

This sketch map, based on data compiled by the *New Orleans Times-Picayune* newspaper, shows the extent of flooding during and following the passage of Hurricane Katrina.

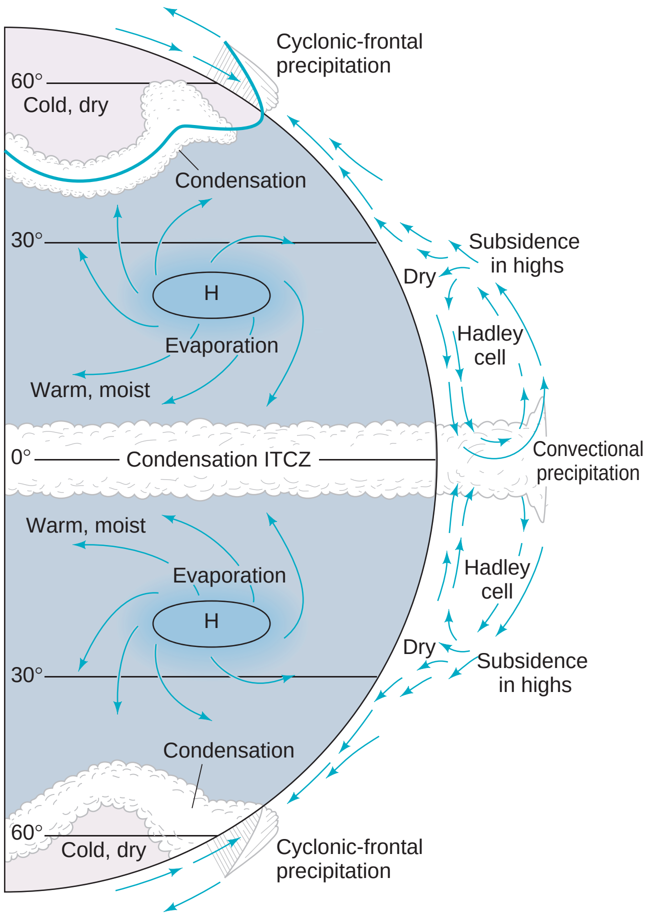
6.29 Hurricane Katrina floods New Orleans

In the aftermath of Hurricane Katrina, entire neighborhoods in New Orleans lay in ruins for months. Two weeks after the hurricane, the devastation is nearly complete. The red object in the foreground is a barge.

and latent heat content of the air. With convergence and uplift of the air at the ITCZ, the latent heat is converted to sensible heat as condensation occurs. Air traveling poleward in the return circulation aloft retains much of this heat, although some is lost to space by radiant cooling. When the air descends in the subtropical high-pressure belts, the sensible heat becomes available at the surface. The net effect is to gather heat from tropical and equatorial zones and release the heat in the subtropical zone, where it can be conveyed farther poleward by jet stream disturbances into the midlatitudes.

In the mid- and high latitudes, poleward heat transport is produced almost exclusively by jet stream disturbances (Figure 6.31). Because the jet streams flow west to east, there can be no direct poleward transport of heat as in the Hadley cells. Instead, lobes of cold, dry polar or arctic air associated with growing jet stream disturbances plunge toward the Equator, while tongues of warmer, moister air originating in the subtropics flow toward the poles. Within these disturbances, cyclones also develop along the polar front, producing convergence of air at the surface. The subsequent uplift releases latent heat by condensation. Both of these processes provide a heat flow that warms the mid- and higher latitudes well beyond the insolation they receive.

Just as atmospheric circulation plays a role in moving heat from one region of the globe to another, so do oceanic circulations. How is this heat transported? Near the surface, the water in the low latitudes is exposed to



6.30 Global atmospheric transport of heat and moisture

◀ **High latitudes** Disturbances along the polar front allow warm, moist subtropical air to reach far into the high latitudes while also moving cold, dry air from these regions toward lower latitudes. This warms the polar regions.

◀ **Midlatitudes** Warm, moist air flows north along the surface. Disturbances along the polar front cause this air to lift over the cooler polar air, producing condensation and latent heat release.

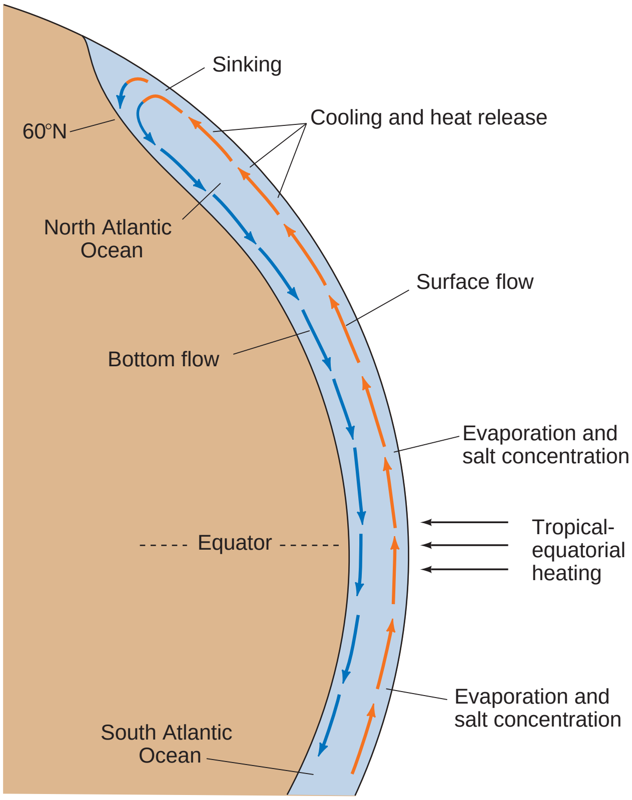
◀ **Low latitudes** As surface winds blow over warm tropical waters, they acquire sensible heat and latent heat. As the air rises in the intertropical convergence zone, latent heat is released, further warming the air. This air flows north, eventually subsiding and warming the subtropics.

6.31 Transport of moisture by storm systems

This satellite image tracks water vapor (in shades of white) as it moves through the atmosphere. Trails of water vapor—also called precipitable water—stretch from the tropical Pacific across the eastern United States and into the high latitudes of the Atlantic, marking the poleward transport of water and energy. The release of latent heat as this water vapor condenses drives tropical cyclones, like the one seen over the Gulf of Mexico, and midlatitude cyclones, pictured here as swirling bands of white over the North Atlantic and North Pacific.

intense insolation in the equatorial and tropical zones and is subsequently warmed. It is then transported by the western boundary currents, which bring warm, tropical waters to higher latitudes. As the water travels northward, it cools, losing heat and warming the atmosphere above it. The cooler waters then return south as part of the gyre circulation, where they cool the overlying atmosphere in the tropics.

Heat is also transported by the thermohaline circulation (Figure 6.32). By carrying warm surface water poleward, this loop acts like a heat pump in which sensible heat is acquired in tropical and equatorial regions and is moved northward into the North Atlantic, where it is transferred to the air. Since wind patterns move air eastward at higher latitudes, this heat ultimately warms Europe. The amount of heat released is quite large. A recent calculation shows that it is equal to about 35 percent of the total solar energy received by the Atlantic Ocean north of 40° latitude! This type of circulation does not occur in the Pacific or Indian Ocean, which is why Europe is significantly warmer than the high-latitude regions of the North Pacific and eastern North America at the same latitude.



6.32 Thermohaline convection loop

Warm surface waters flow into the North Atlantic, then cool and sink to the deep Atlantic Basin, creating a circulation that warms westerly winds moving onto the European continent.

GEODISCOVERIES **Web Quiz**

Take a quick quiz on the key concepts of this chapter.

A Look Ahead

This chapter has focused on weather systems and the processes by which they develop. Spawned and steered by upper-level winds, midlatitude weather systems arise from contrasts between air masses that are in contact along the polar front. Tropical weather systems draw their energy from warm tropical ocean waters and are fueled by the release of latent heat as moist oceanic air is uplifted and cooled to form clouds and rain.

With a knowledge of weather systems and how they produce precipitation, coupled with an understanding of the global circulation patterns of the atmosphere and oceans, the stage is set for global climate—which is the topic of Chapter 7. As we will see, the annual cycles of temperature and precipitation that most regions experience are quite predictable, given the changes in wind patterns, air-mass flows, and weather systems that occur with the seasons. Our description of the world's climates grows easily and naturally from the principles you have mastered thus far in your study of physical geography.

GEODISCOVERIES **Web Links**

Explore this chapter's web links for hurricane information, including the latest Weather Service data and images.

IN REVIEW WEATHER SYSTEMS

- Because global warming, produced by increasing CO_2 levels in the atmosphere, will increase the evaporation of surface water, atmospheric moisture levels will increase. This will tend to enhance the greenhouse effect. But more clouds are likely to form, and this should cool the planet. Increased moisture could also reduce temperatures by increasing the amount and duration of snow cover. Further research on the effect of global warming on climate is needed.
- A **weather system** is a recurring atmospheric circulation pattern with its associated weather. Weather systems include traveling cyclones and anticyclones, low pressure troughs, easterly waves, weak equatorial lows, and tropical cyclones.
- **Air masses** are distinguished by the latitudinal location and type of surface of their *source regions*. Air masses influencing North America include those of continental

and maritime source regions, and of arctic, polar, and tropical latitudes.

- The United States is affected by the movement of four types of air masses: continental polar (cP), maritime polar (mP), continental tropical (cT), and maritime tropical (mT).
- The boundaries between air masses are termed **fronts**. These include **cold** and **warm fronts**, where cold or warm air masses are advancing. In the **occluded front**, a cold front overtakes a warm front, pushing a pool of warm, moist air mass above the surface. Fronts also include *stationary fronts* and *dry lines*.
- The traveling anticyclone is typically a fair-weather system. At the center of the anticyclone, pressure is high and air descends.
- **Midlatitude cyclones** form at the boundary between cool, dry air masses and warm, moist air masses. In a cyclone, a vast inspiraling motion produces cold and warm fronts, and eventually an occluded front. Precipitation normally occurs with each type of front.
- *Jet stream disturbances* cause areas of convergence and divergence in upper-air flows. These create anticyclonic and cyclonic circulations at the surface that move eastward along with the disturbances.
- **Easterly waves** and *weak equatorial lows* are two types of low-latitude weather systems that bring convective showers to unstable tropical and equatorial air. In these areas of low pressure, convergence triggers abundant convective precipitation.
- **Cold-air outbreaks** occur when tongues of cold polar air invade the low latitudes.
- **Tropical cyclones** can be the most powerful of all storms. They can grow as large as 500 km (about 300 mi) with sustained winds as high 50 m/s (135 mi/hr) or more.
- Tropical cyclones develop over very warm tropical oceans where they intensify to become vast inspiraling systems of very high winds with very low central pressures. They are fueled by latent heat release in condensation, which creates warming, more uplift, and more condensation. The high winds of the tropical cyclone are partly due to the weakness of the Coriolis force at low latitudes, which requires higher winds to balance pressure gradient forces across the storm.
- Tropical cyclones form in the tropics in the summer and fall when the waters are warmest over the tropical oceans. They movie westward at first, and then often turn poleward and eastward, driven by prevailing westerlies. They are termed *hurricanes* in the Atlantic region, *typhoons* in the western Pacific, and simply *cyclones* in the Indian Ocean.
- In addition to high winds, tropical cyclones wreak destruction through heavy rainfall, causing debris flows and floods, and by **storm surges** that bring breaking waves far inland from coastal beaches.
- The TRMM satellite measures and monitors rainfall in tropical and equatorial regions. It has helped scientists model tropical and equatorial weather and climate more accurately.
- Global air and ocean circulation provides the mechanism for poleward heat transport, by which excess heat moves from the equatorial and tropical regions toward the poles. In the atmosphere, the heat is carried poleward by the Hadley cell circulation and by movements of warm and cold-air masses in jet stream disturbances. In the oceans, a global circulation moves warm surface water northward through the Atlantic Ocean. Heated in the equatorial and tropical regions, the surface water loses its heat to the air in the North Atlantic and sinks to the bottom. These heat flows help make northern and southern climates warmer than we might expect based on solar heating alone.

KEY TERMS

weather systems, p. 185
air masses, p. 185
front, p. 187
cold front, p. 187
warm front, p. 187
occluded front, p. 188
cyclonic storm, p. 191
tornado, p. 191
midlatitude cyclone, p. 192
cold-air outbreaks, p. 200
easterly wave, p. 201
tropical cyclone, p. 201
storm surge, p. 205

REVIEW QUESTIONS

1. How does water, as vapor, clouds, and precipitation, influence global climate? How might water in these forms act to enhance or retard climatic warming?
2. What is an *air mass*? What two features are used to classify air masses? Compare the characteristics and source regions for mP and cT air mass types.
3. Describe how and where midlatitude cyclones form.
4. How is the development of midlatitude cyclones linked to jet stream disturbances? What is the role of converging and diverging winds at the surface and aloft, and how are they linked?

5. What is *a cold-air outbreak*? What other names are used to describe this phenomenon?
6. Identify three weather systems that bring rain in equatorial and tropical regions. Describe each system briefly.
7. Describe the structure of a tropical cyclone.
8. Once formed, how does a tropical cyclone develop and intensify? How does the weaker Coriolis force of the low latitudes affect the wind speeds of the tropical cyclone?
9. What conditions are necessary for the development of a tropical cyclone? Give a typical track for the movement of a tropical cyclone in the northern hemisphere.
10. Why are tropical cyclones so dangerous? Explain the different types of damage they can cause. Overall, which type of damage is the most severe?
11. What is the goal of the TRMM satellite and its instruments?
12. How does the global circulation of the atmosphere and oceans provide poleward heat transport?

VISUALIZING EXERCISES

1. Identify three types of fronts and draw a cross section through each. Show the air masses involved, the contacts between them, and the direction of air-mass motion.
2. Sketch two weather maps, showing a wave cyclone in open and occluded stages. Include isobars on your sketch. Identify the center of the cyclone as a low. Lightly shade areas where precipitation is likely to occur.

ESSAY QUESTIONS

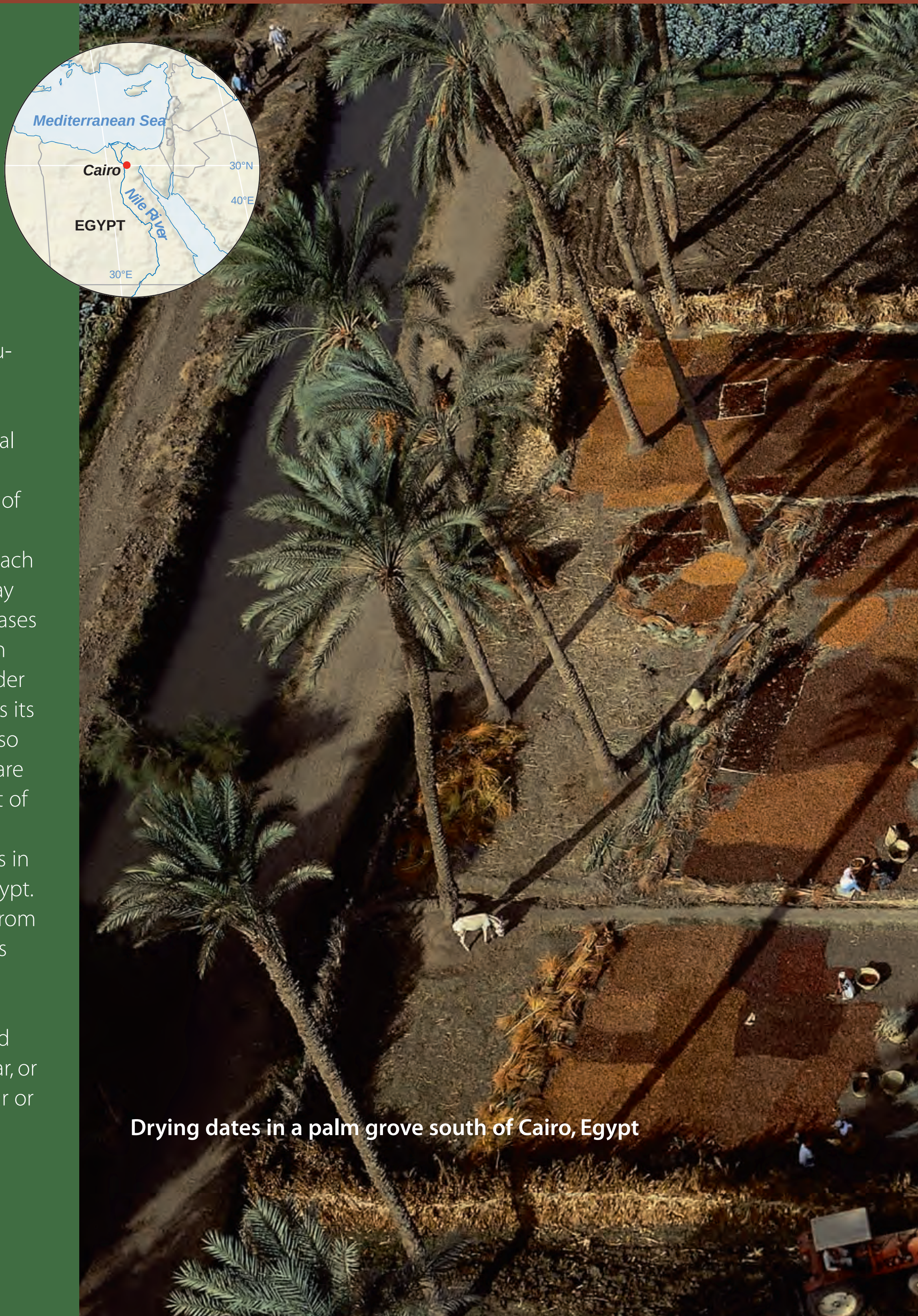
1. Compare and contrast midlatitude and tropical weather systems. Be sure to include the following terms or concepts in your discussion: air mass, convective precipitation, cyclonic precipitation, easterly wave, polar front, stable air, traveling anticyclone, tropical cyclone, unstable air, midlatitude cyclone, and weak equatorial low.
2. Prepare a description of the annual weather patterns that are experienced through the year at your location. Refer to the general temperature and precipitation pattern as well as the types of weather systems that occur in each season.

Chapter 7
Global Climates

The Earth's climates present a vast array of environments, from the icy tundra of Alaska to the tropical deserts of northern Africa and the Middle East. Over millions of years, plant and animal species have become uniquely suited to many of the Earth's climatic extremes, and over tens of thousands of years, human societies have adapted as well, learning to use the food and fiber of local plants.

The date palm is something of a botanical oddity, with its long leaves, known as palm fronds, each bearing dozens of leaflets. It may have originated in the desert oases of northern Africa, or possibly in Southwest Asia, and thrives under hot desert conditions as long as its roots can obtain water. But it also produces the sweet fruits that are a staple food and a unique part of many desert cultures.

This photo shows fresh dates in a palm grove south of Cairo, Egypt. The fresh dates range in color from red to yellow, but turn brown as they are preserved by drying in the Sun. The dried fruits can be consumed directly, or processed into date syrup, flour, palm sugar, or even fermented to form vinegar or alcoholic beverages.



Drying dates in a palm grove south of Cairo, Egypt

Global Climates

The Earth's climates span a huge range of environments, from hot, wet equatorial forests, to dry, barren deserts, to bitterly cold expanses of snow and ice. What factors generate the Earth's climates? How do the global patterns of circulation of the atmosphere and ocean affect climates? How does location—coastal or continental—affect climate and why? What is the role of elevation? of topography? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Drought in the African Sahel

One of the Earth's more distinctive climates is the wet-dry tropical climate ③ . Here, the weather is largely dry for much of the year, but there is a rainy season of a few months duration in which most of the annual rainfall occurs. Precipitation during the wet season is quite variable, ranging from little or none to torrential rainfalls that produce severe local flooding.

The wet-dry tropical climate ③ is subject to large annual differences in rainfall. Climate records show that two or three successive years of abnormally low rainfall (a drought) typically alternate with several successive years of average or higher than average rainfall. Variability is a permanent feature of this climate, and both the human inhabitants and natural ecosystems are well adjusted to it.

However, there is one region where the alternation between wet and dry years takes place on a much longer time scale. Africa's *Sahel region* (Figure 7.1), sandwiched between the continent's monsoon forests and the Sahara Desert, is a band of wet-dry tropical climate ③ with a history of wet and dry periods that are decades long. Because the wet periods are long enough for natural ecosystems and human activities to expand their productive range, the long droughts experienced in this region can be particularly devastating.

Although there has been least one severe Sahelian drought in each of the last four centuries, the drought of the late twentieth century, which began in 1968 and ran through the mid-1980s with only one brief respite, was an environmental disaster of the first magnitude. Famine killed about 100,000 people, left three-quarters of a million people dependent on food aid, and severely impacted the agriculture, livestock, and human populations of the region (Figure 7.2).

As scientists tried to explain the duration and severity of the late-twentieth-century drought, they first thought that it might have been caused by human activity through overgrazing and conversion of woodland to agriculture—a process called *desertification* or *land degradation*. These activities reduce precipitation by decreasing atmospheric moisture and by raising the surface albedo, which reduces local convective circulation and convective rainfall.

Recent studies now suggest, however, that drought in the Sahel is linked to large-scale atmospheric circulation changes that are produced by multidecadal variations in global sea-surface temperature. A pattern of sea-surface temperatures develops in the Pacific, Atlantic, and Indian oceans that weakens the African monsoon circulation, reducing or eliminating the Sahel's brief rainy season. Since the pattern can persist for a number of years, the drought produced can be quite long-lasting.

But sea-surface temperature alone is not sufficient to explain the magnitude of the late-twentieth-century Sahelian drought. It now appears that severe drought in the Sahel was produced by a combination of factors acting synergistically, including sea-surface temperature change, the retreat of natural vegetation cover in the face of drought, and changing human land use.

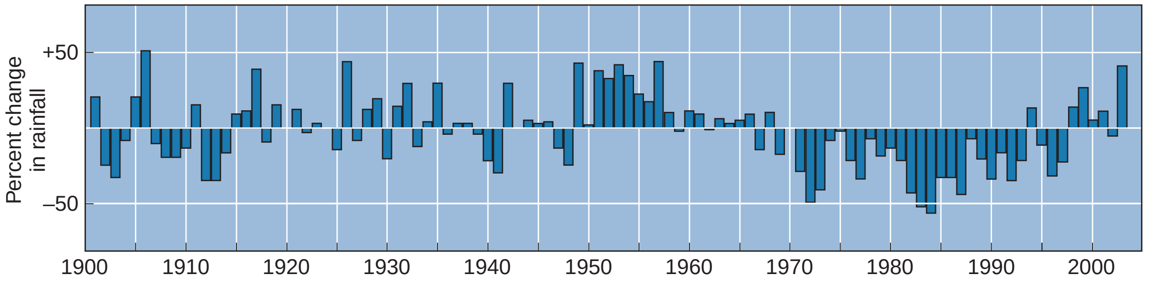
At present, rainfall in the Sahel is somewhat below historical levels, although drought is not severe (Figure 7.3). Will the devastating droughts of the 1970s and 1980s return? Some global climate models predict that global warming will lead to the persistence of sea-surface temperature patterns that trigger a Sahelian drought. Coupled with the fact that Sahelian population is doubling every 20 years, the outlook for the Sahel is not very favorable.

7.1 The African Sahel

The Sahel, or Sahelian zone, shown in color, lies south of the great Sahara Desert of North Africa.

7.2 Sahelian drought

At the height of the Sahelian drought, vast numbers of cattle had perished and even the goats were hard pressed to survive.



7.3 Rainfall in the Sahel

Rainfall fluctuations for stations in the western Sahel, 1901–2003, expressed as a percent departure from the long-term mean.

Factors Controlling Climate

Climate is the average weather of a region. The primary driving force for weather is the flow of solar energy received by the Earth and atmosphere. Because that energy flow varies on daily cycles with the planet's rotation and on annual cycles with its revolution in orbit, temperature and precipitation also vary on daily and annual cycles. However, climate includes other time cycles as well, ranging from cycles of several years' duration, such as the cycles imparted by El Niño, to cycles of hundreds of thousands of years, like the cycles of continental glaciation.

In addition to recognizing the time cycles imposed by the flow of solar energy to a given region, a few other principles are very helpful in understanding the global scope of climate. Three major factors influence the annual cycle of air temperature experienced at a location: latitude, coastal versus continental location, and elevation (Figure 7.4).

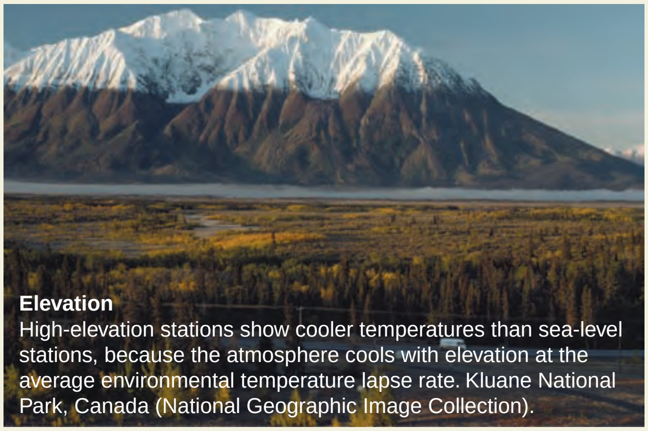
For precipitation, these same three factors are important, but precipitation is also affected by annual and monthly air temperatures, prevailing air masses, relation to mountain barriers, position of persistent high- and low-pressure centers, and prevailing wind and ocean currents.

Keeping these key ideas in mind as you read this chapter will help make the climates we discuss easier to understand and explain.

7.4 Climate controls

Factors influencing air temperature include latitude, elevation, and coastal versus continental location. For precipitation, prevailing air temperatures and air masses, mountain barriers, and prevailing wind and ocean currents are important influences.

◄ **Latitude** Insolation varies with latitude. The annual cycle of temperature at any place depends on its latitude. Near the Equator, temperatures are warmer and the annual range is low. Toward the poles, temperatures are colder and the annual range is greater. Ellesmere Island, Nunavut, Canada (National Geographic Image Collection).



Elevation
High-elevation stations show cooler temperatures than sea-level stations, because the atmosphere cools with elevation at the average environmental temperature lapse rate. Kluane National Park, Canada (National Geographic Image Collection).

Mountain barriors
Location on a mountain can greatly affect the amount of precipitation. On the windward side, the forced uplift of air over the mountains produces condensation and precipitation. On the leeward side, adiabatic warming of the air produces hot, dry conditions. Winery in Paso Robles, California

Annual and monthly air temperatures
Warm air can contain more moisture than cold air, so colder regions generally have lower precipitation than warmer regions. Also, precipitation will tend to be greater during the warmer months of the temperature cycle. Mount Des Voeux, Tavenui Island, Fiji Islands (National Geographic Image Collection).

Temperature and Precipitation Regimes

Many parts of the world show distinctive patterns of monthly temperature and precipitation, usually related to latitude and location. These patterns are referred to as *regimes* of temperature and precipitation.

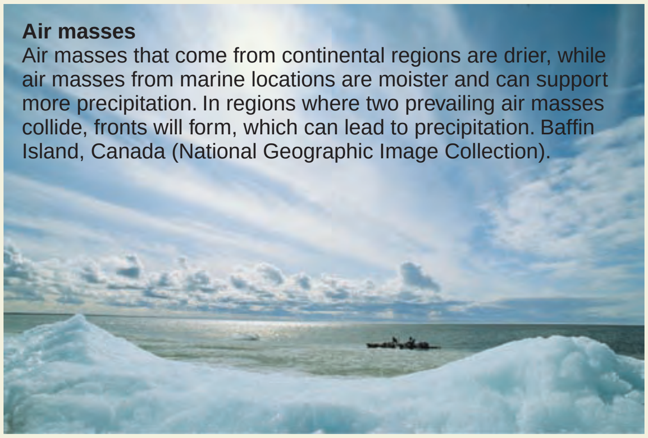
TEMPERATURE REGIMES

Figure 7.5 shows annual cycles of air temperature for different temperature regimes. The equatorial regime (Douala, Cameroon, 4° N) is uniformly very warm, with temperatures close to 27°C (81°F) year round because insolation is nearly uniform throughout the year. In contrast, temperatures in the tropical continental regime (In Salah, Algeria, 27° N) change from very hot, when the Sun is high in the sky near a solstice, to mild, when the Sun is lower at the opposite solstice.

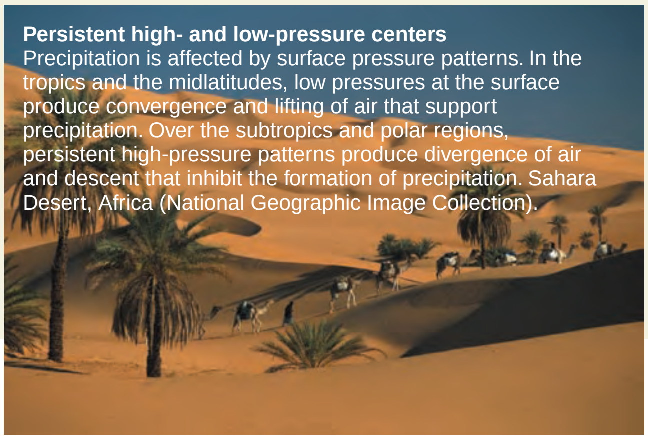
The tropical west-coast regime at Walvis Bay, Namibia (23° S)—nearly the same latitude as In Salah—has only

The contrast in temperature with season at a location depends on latitude, location, and elevation. At higher latitudes, in continental interiors, and at higher elevations, the contrast is greater.

◀ **Coastal-continental location** Ocean surface temperatures vary less with the seasons than land surface temperatures, so coastal regions show a smaller annual variation in temperature. Aerial view of Cornwall, England (National Geographic Image Collection).

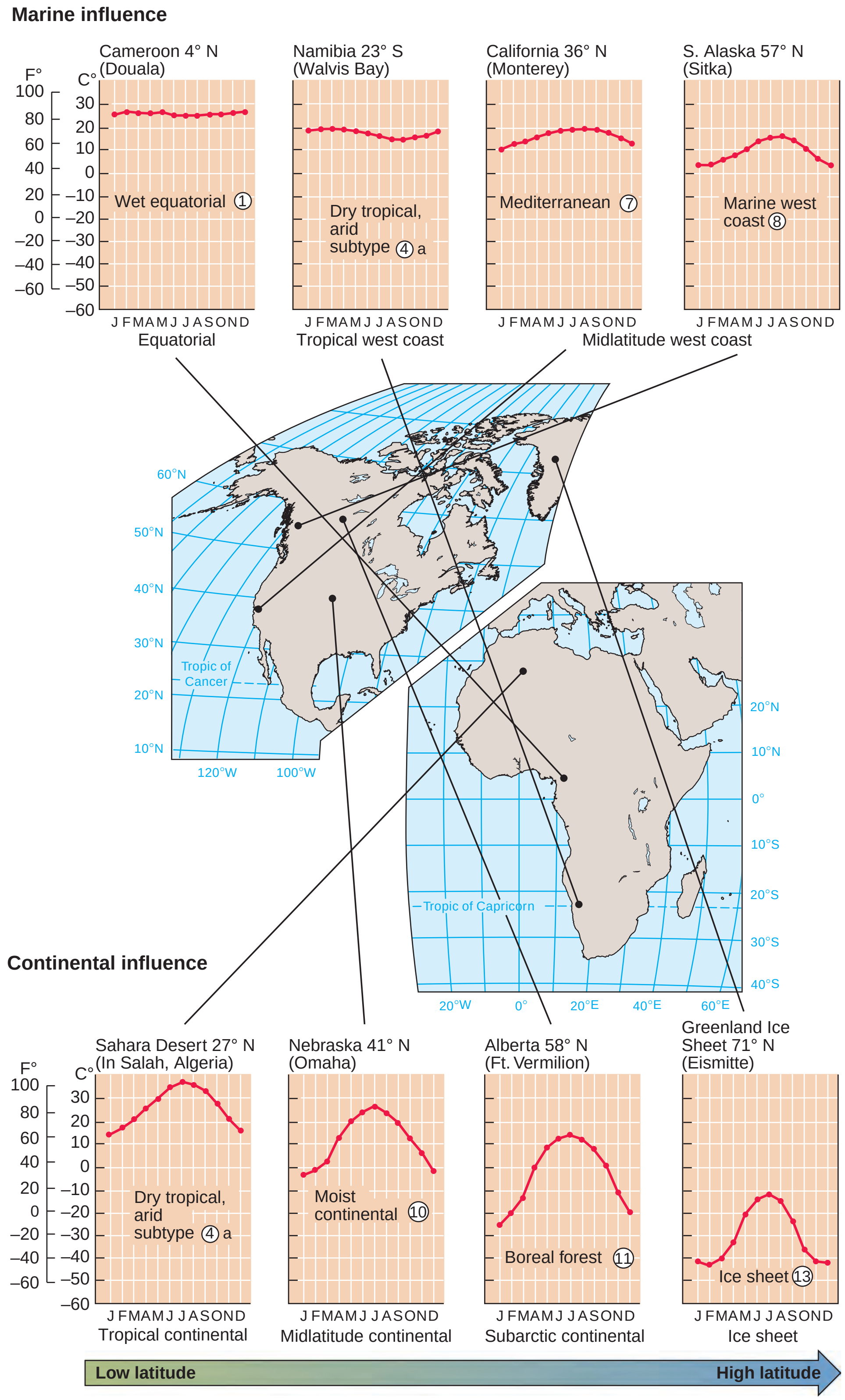


Air masses
Air masses that come from continental regions are drier, while air masses from marine locations are moister and can support more precipitation. In regions where two prevailing air masses collide, fronts will form, which can lead to precipitation. Baffin Island, Canada (National Geographic Image Collection).



Persistent high- and low-pressure centers
Precipitation is affected by surface pressure patterns. In the tropics and the midlatitudes, low pressures at the surface produce convergence and lifting of air that support precipitation. Over the subtropics and polar regions, persistent high-pressure patterns produce divergence of air and descent that inhibit the formation of precipitation. Sahara Desert, Africa (National Geographic Image Collection).

Prevailing wind and ocean currents
On the western portion of midlatitude continents, the prevailing westerly winds bring warm, moist air off the ocean and onto the continent, resulting in higher precipitation. On the eastern portion, these same winds bring dry air from the continental locations without enough moisture to produce significant precipitation. Redwood National Park, California (National Geographic Image Collection).



7.5 Temperature regimes

This figure shows typical patterns of mean monthly temperatures observed at stations around the globe. Each of these *temperature regimes* is labeled according to its latitude zone: equatorial, tropical, midlatitude, and subarctic. Some labels also describe the location of the station in terms of its position on a land mass—*continental* for a continental interior location and *west coast* or *marine* for a location close to the ocean.

a weak annual cycle and no extreme heat because of the moderating effects of its maritime location. This moderating effect persists poleward into the midlatitude west-coast regime—Monterey, California (36° N) and Sitka, Alaska (57° N). In continental interiors, however, the midlatitude continental regime of Omaha, Nebraska (41° N), and the subarctic continental regime of Fort Vermilion, Alberta (58° N), show large annual variations in mean monthly temperature of about 30°C (54°F) and 40°C (72°F), respectively. The ice sheet regime of

Greenland (Eismitte, 71° N) experiences severe cold all year.

Overall, we find that (1) annual variation in insolation, determined by latitude, provides the basic control on temperature, and (2) the effect of location—maritime or continental—moderates that variation.

Another factor affecting air temperature is elevation. High-elevation stations show cooler temperatures than sea-level stations. Temperatures are cooler because the atmosphere cools with elevation at the average environmental temperature lapse rate of 6.4°C/1000 m (3.5° F/1000 ft).

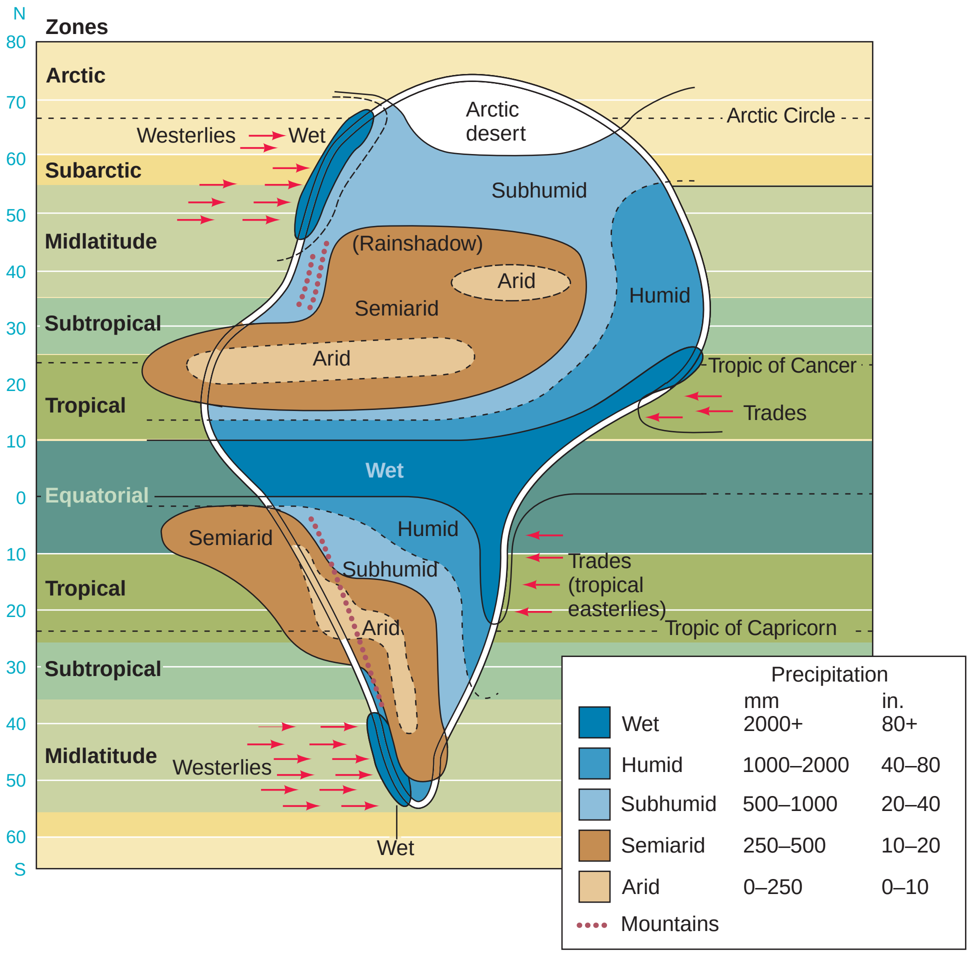
GLOBAL PRECIPITATION PATTERNS

Global precipitation patterns are largely determined by air masses and their movements, which in turn are produced by global air circulation patterns. Before taking a detailed look at global precipitation patterns, let's look at Figure 7.6, which shows the general patterns expected for a hypothetical supercontinent that has most of the features of the Earth's continents but is simplified. The map recognizes and defines five classes of annual precipitation: wet, humid, subhumid, semiarid, and arid.

Beginning with the equatorial zone, the figure shows a wet band stretching across the continent. This band is produced by convective precipitation over the equatorial lows near the intertropical convergence zone. Note that the wet band widens and is extended poleward into the tropical zone along the continent's eastern coasts. This region is kept moist by the influence of the trade winds, which move warm, moist mT air masses and tropical cyclones westward onto the continental coast. Farther poleward, humid conditions continue along the east coasts into the midlatitude zones. In these regions, subtropical high-pressure cells tend to move mT air masses from the southeast onto the continent in the summer, whereas in winter, midlatitude cyclones bring cyclonic precipitation from the west.

In the arctic zone, shown on the continent as arctic desert, precipitation remains low because air temperatures are low, and only a small amount of moisture is contained in cold air.

Another important feature of the hypothetical continent is the pattern of arid and semiarid regimes that stretches from tropical west coasts to subtropical and midlatitude continental interiors. In the tropical and



7.6 Precipitation on an idealized supercontinent

A schematic diagram of annual precipitation over an idealized continent and adjoining seas.

subtropical latitudes, the arid pattern is produced by dry, subsiding air in persistent subtropical high-pressure cells. The aridity continues eastward and poleward into semiarid continental interiors, which remain relatively dry because they are far from source regions for moist air masses. Rainshadow effects provided by coastal mountain barriers are also important in maintaining inland aridity.

Yet another obvious feature of the supercontinent is the pair of wet bands along the west coasts of the midlatitude and subarctic zones. These are produced by the eastward movement of moist mP air masses onto the continent, as driven by the prevailing westerlies.

These features of the supercontinent are echoed in the actual pattern of global precipitation, shown in Figure 7.7. This map of mean annual precipitation shows isohyets—lines drawn through all points having the same annual precipitation. Using the same logic that we used to explain the precipitation patterns of the hypothetical continent, we can recognize seven global precipitation regions as follows:

1. *Wet equatorial belt.* This zone of heavy rainfall, over 2000 mm (80 in.) annually, straddles the Equator and includes the Amazon River Basin in South America, the Congo River Basin of equatorial Africa, much of the African coast from Nigeria west to Guinea, and the East Indies. In this zone, the warm temperatures and high-moisture content of the mE air masses favor abundant convective rainfall.
2. *Trade-wind coasts.* Narrow coastal belts of high rainfall, 1500 to 2000 mm (about 60 to 80 in.), extend from near the Equator to latitudes of about 25° to 30° N and S on the eastern sides of every continent or large island. Examples include the eastern coast of Brazil, Central America, Madagascar, and northeastern Australia. The rainfall of these coasts is supplied by moist mT air masses from warm oceans that are brought over the land by the trade winds and encounter coastal hills and mountains, producing heavy orographic rainfall.

At low latitudes, annual rainfall is heavy in the wet equatorial belt and trade-wind coasts. In contrast, tropical deserts are very dry.

3. *Tropical deserts.* In contrast to the wet equatorial belt are the zones of tropical deserts lying approximately on the Tropics of Cancer and Capricorn. These are hot, barren deserts with less than 250 mm (10 in.) of rainfall annually and, in many places, with less than 50 mm (2 in.). They are located under the large, stationary subtropical cells of high pressure, in which the subsiding cT air mass is adiabatically warmed and dried.
4. *Midlatitude deserts and steppes.* Farther northward, in the interiors of Asia and North America between latitude 30° and latitude 50°, are great deserts, as well as vast expanses of semiarid grasslands known as *steppes.* Annual precipitation ranges from less than 100 mm (4 in.) in the driest areas to 500 mm (20 in.) in the moister steppes.

   Located in regions of prevailing westerly winds, these arid lands are far from sources of oceanic moisture and typically lie in rain shadows on the lee side of coastal mountains and highlands. In the southern hemisphere, the dry steppes of Patagonia, lying on the lee side of the Andean chain, are roughly the counterpart of the North American deserts and steppes.
5. *Moist subtropical regions.* On the southeastern sides of the continents of North America and Asia, in latitude 25° to 45° N, are the moist subtropical regions, with 1000 to 1500 mm (about 40 to 60 in.) of rainfall annually. Smaller areas of the same type are found in Uruguay, Argentina, and southeastern Australia. These regions are positioned on the moist western sides of the oceanic subtropical high-pressure circulations, which bring moist mT air masses from the tropical ocean onto the continent.

At higher latitudes, east and west coasts have higher precipitation, while continental interiors and arctic and polar regions are drier.

6. *Midlatitude west coasts.* Another wet location is on midlatitude west coasts of all continents and large islands lying between latitudes about 35° and 65° in the region of prevailing westerly winds. In these zones, abundant orographic precipitation occurs as a result of forced uplift of mP air masses. Where the coasts are mountainous, as in British Columbia, southern Chile, Scotland, and South Island of New Zealand, the annual precipitation is over 2000 mm (79 in.).
7. *Arctic and polar deserts.* A seventh precipitation region is formed by the arctic and polar deserts. Northward of the 60th parallel, annual precipitation is largely under 300 mm (12 in.), except for the west-coast belts. Cold cP and cA air masses cannot contain much moisture, and, consequently, they do not yield large amounts of precipitation.

PRECIPITATION REGIMES

Total annual precipitation is a useful quantity in establishing the character of a climate type, but it does not account for the seasonality of precipitation. The variation in monthly precipitation through the annual cycle is a very important factor in climate descriptions. If there is a pattern of alternating dry and wet seasons instead of a uniform distribution of precipitation throughout the year, we can expect that the natural vegetation, soils, crops, and human use of the land will all be different. It also makes a difference whether the wet season coincides with a season of higher temperatures or with a season of lower temperatures. If the warm season is also wet, growth of both native plants and crops is enhanced. If the warm season is dry, the stress on growing plants is great, and irrigation is required for most crops.

Monthly precipitation patterns can be grouped into three types: (1) uniformly distributed precipitation; (2) a precipitation maximum during the summer (or season of high Sun), in which insolation is higher; and (3) a precipitation maximum during the winter or cooler season (season of low Sun), when daily insolation is lower. Note that the uniform pattern can include a wide range of possibilities from little or no precipitation in any month to abundant precipitation in all months.

Figure 7.8 shows a set of monthly precipitation diagrams selected to illustrate the major types that occur over the globe. Two stations show the uniformly distributed pattern described above—Singapore, a wet equatorial station near the Equator (1½° N), and Tamanrasset, Algeria, a tropical desert station very near the Tropic of Cancer at 23° N. In Singapore, rainfall is abundant in all months, but some months have somewhat more rain than others. Tamanrasset has so little rain in any month that it scarcely shows on the graph.

Monthly patterns of precipitation are typically of three types—uniformly distributed, summer or high-Sun maximum, and winter or low-Sun maximum.

Chittagong, Bangladesh (22½° N), and Kaduna, Nigeria (10½° N), both show patterns of the second type—that is, a wet season at the time of high Sun (summer solstice) and a dry season at the time of low Sun (winter solstice). Chittagong is an Asian monsoon station, with a very large amount of precipitation falling during the high-Sun season. Kaduna, an African station with about half as much annual precipitation, shows a similar pattern and is also of the wet-dry tropical type. Both stations experience their wet season when the intertropical convergence zone (ITCZ) is nearby and their dry season when the ITCZ has retreated to the other hemisphere.

The summer precipitation maximum also occurs at higher latitudes on the eastern sides of continents. Shanghai, China (31° N), shows this pattern nicely in the subtropical zone. The same summer maximum persists into the midlatitudes. For example, Harbin, in eastern China (46° N), has a long, dry winter with a marked period of summer rain.

In contrast to these patterns are cycles with a winter precipitation maximum. Palermo, Sicily (38° N), is an example of this Mediterranean type of climate, named for its prevalence in the lands surrounding the Mediterranean Sea. This type experiences a very dry summer but has a moist winter. Southern and central California are also regions of this climate type.

In Mediterranean climates, summer drought is produced by subtropical high-pressure cells, which intensify and move poleward during the high-Sun season. These cells extend into the regions of Mediterranean climate, providing the hot, dry weather associated with cT air masses while blocking the passage of moister air masses from the oceans. In the low-Sun season, the subtropical high-pressure cells move equatorward and weaken, allowing frontal and cyclonic precipitation to penetrate into Mediterranean climate regions.

The dry-summer, moist-winter cycle is carried into the higher midlatitudes along narrow strips of west coasts. Shannon Airport, Ireland (53° N), has this marine west-coast type of climate, although the difference between summer and winter rainfall is not as marked.

Summers at Shannon Airport have less rainfall for two reasons. First, the blocking effects of subtropical high-pressure cells tend to extend poleward into the region, keeping moister air masses and cyclonic storms away. Second, the cyclonic storms that produce much of the winter precipitation are reduced in intensity during the high-Sun season because the temperature and moisture contrasts between polar and arctic air masses and tropical air masses are weaker in summer. The weaker contrasts are caused by increased high-latitude insolation. Without the strong temperature contrast, disturbances in the jet stream do not tend to grow as large, so neither do the underlying midlatitude cyclones.

Climate Classification

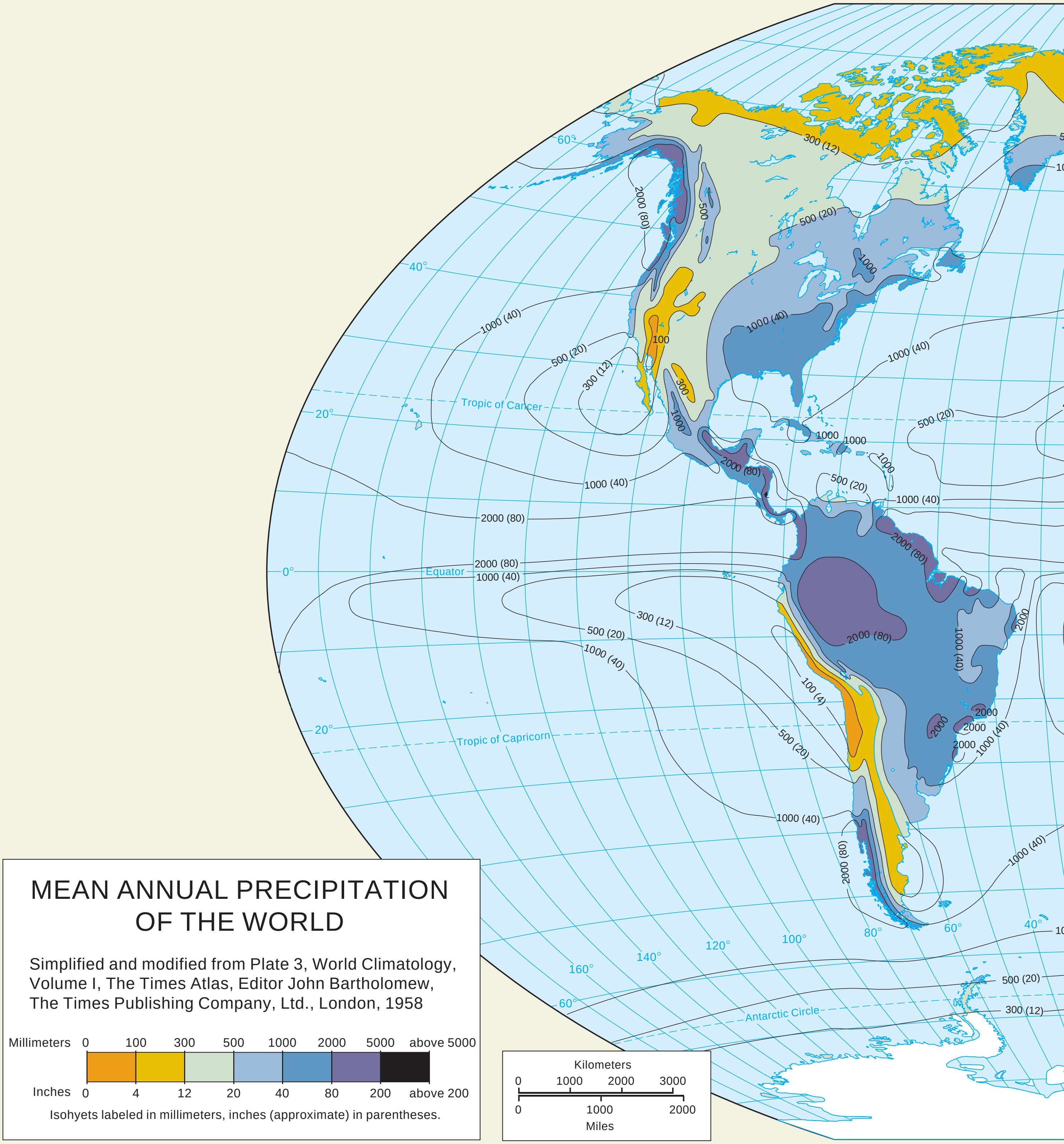
Mean monthly values of air temperature and precipitation can describe the climate of a weather station and its nearby region quite accurately. To study climates from a global viewpoint, climatologists classify these values into distinct climate types. This classification requires developing a set of rules to use in examining monthly temperature and precipitation values. By applying the rules, a climatologist can use each station's data to determine the climate to which it belongs.

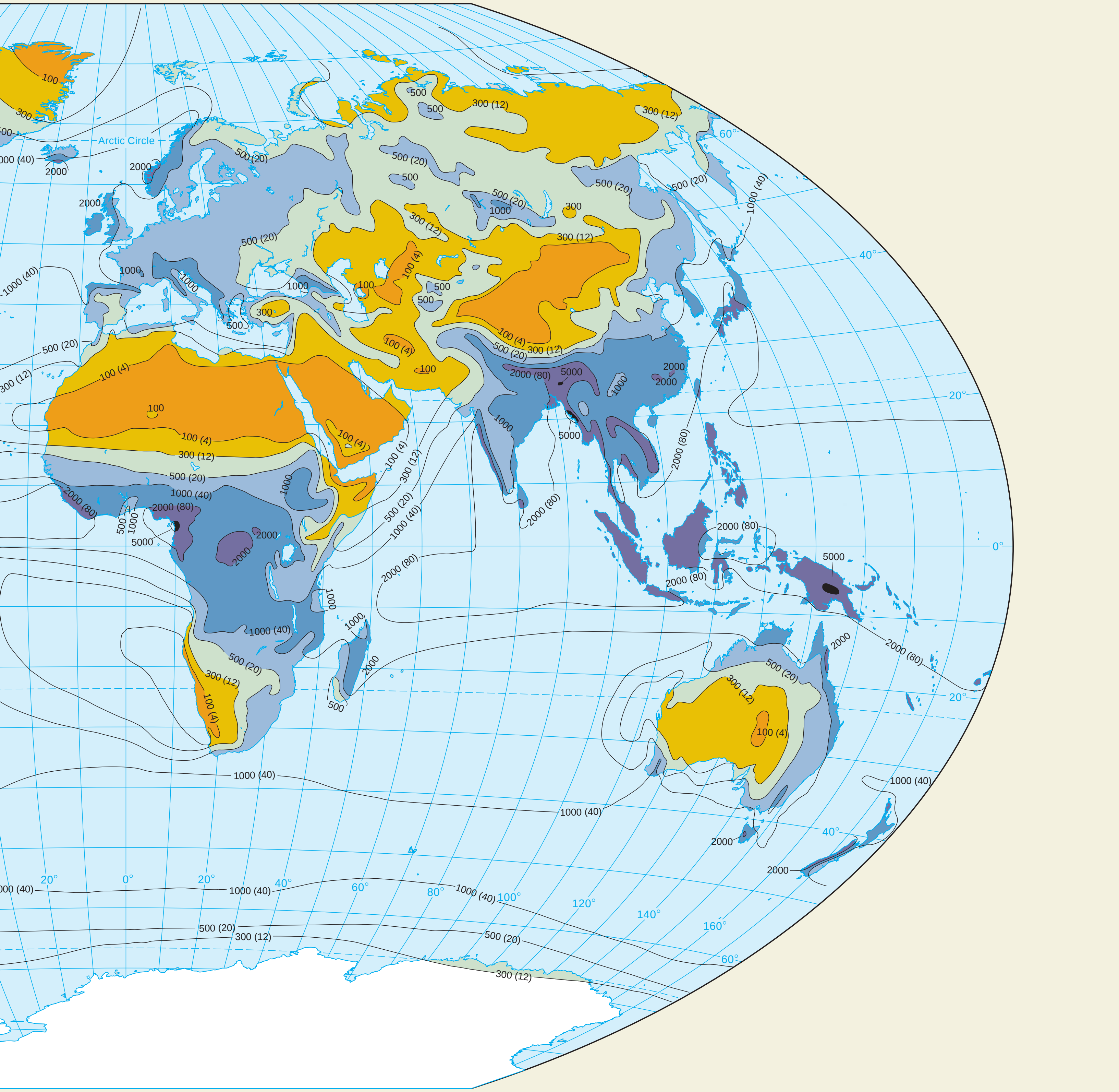
This textbook recognizes 13 distinctive climate types that are designed to be understood and explained by air-mass movements and frontal zones—that is, by the weather various regions experience throughout the year.

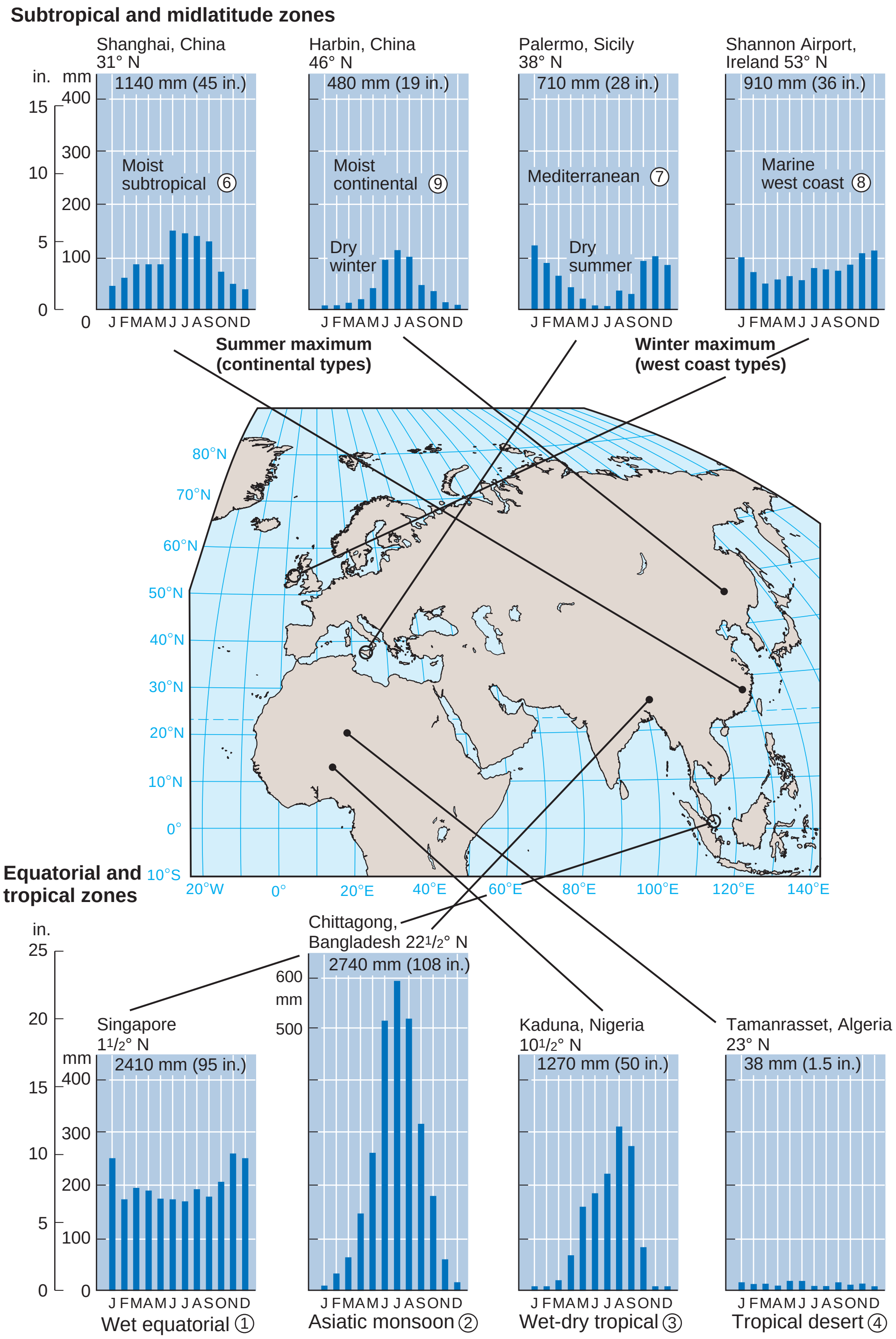
An air mass is classified according to the general latitude of its source region, which determines the temperature of the air mass and its surface type—land or ocean—within that region, which controls the moisture content. Since the air-mass characteristics control the two most important climate variables—temperature and precipitation—we can explain climates using air masses as a guide. In addition, where differing air masses are in contact, frontal zones will form. The position of these frontal zones changes with the seasons. The seasonal movements of air masses and frontal zones therefore influence annual cycles of temperature and

7.7 World precipitation

This global map of mean annual precipitation uses *isohyets*—lines drawn through all points having the same annual precipitation—labeled in mm (in.).




Arctic Circle
100
300
2000
300 (12)
500 (20)
500
1000
1000 (40)
2000 (80)
100 (4)
5000
60°
40°
20°
0°
20°
40°
60°
80°
100°
120°
140°
160°



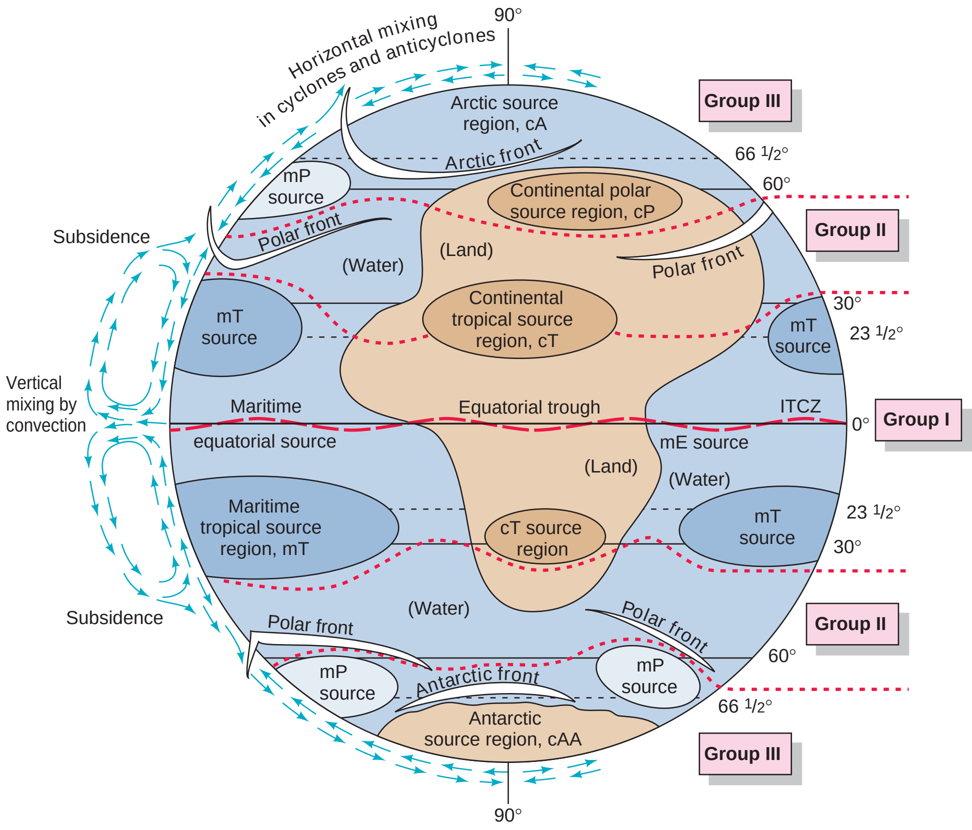
7.8 Precipitation regimes

Seasonal patterns of precipitation can have a relatively uniform monthly pattern, ranging from very wet ① to very dry ④; a precipitation maximum in summer during the high-Sun period ②, ④, ⑥, ⑨; or a precipitation maximum in the winter during the low-Sun period ⑦, ⑧.

precipitation in certain locations as well, particularly in the mid- and high latitudes.

The rules that define the climate types in this text are based on an analysis of how the amount of moisture held in the soil varies throughout the year, which is determined by air temperature and rainfall. Our discussion here will not focus on the specific climate rules but will instead focus on showing how the classification follows quite naturally from an understanding of the processes that produce variations of temperature and precipitation around the globe.

Figure 7.9 shows a schematic diagram of air-mass source regions used in conjunction with the 13 climate types described in this chapter. We have subdivided this diagram into global bands that contain three broad groups of climates: low-latitude (Group I), midlatitude (Group II), and high-latitude (Group III), described briefly as follows.



7.9 Climate groups and air-mass regions

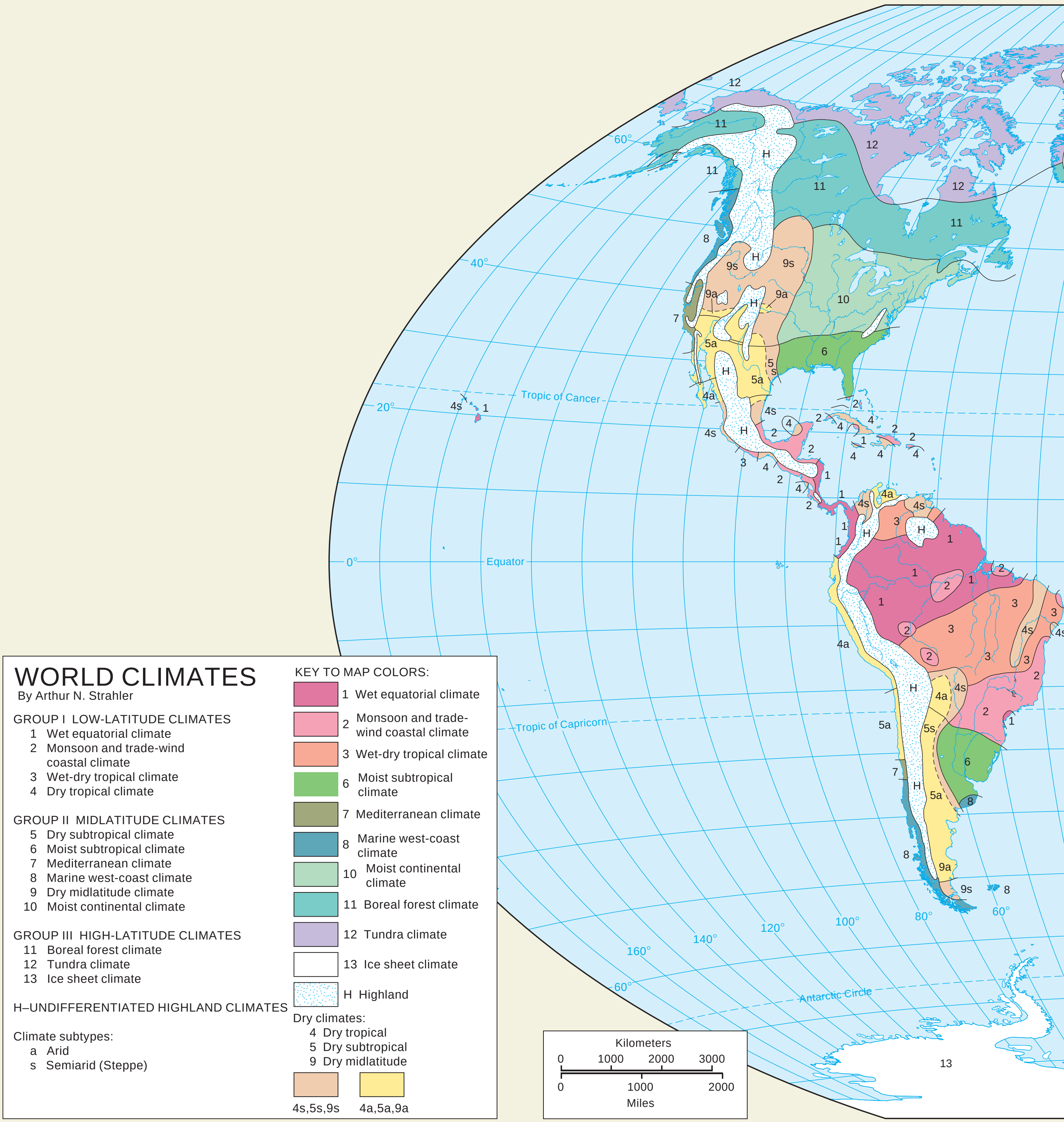
Using the map of air-mass source regions, we can identify five global bands associated with three major climate groups. Within each group is a set of distinctive climates with unique characteristics that are explained by the movements of air masses and frontal zones.

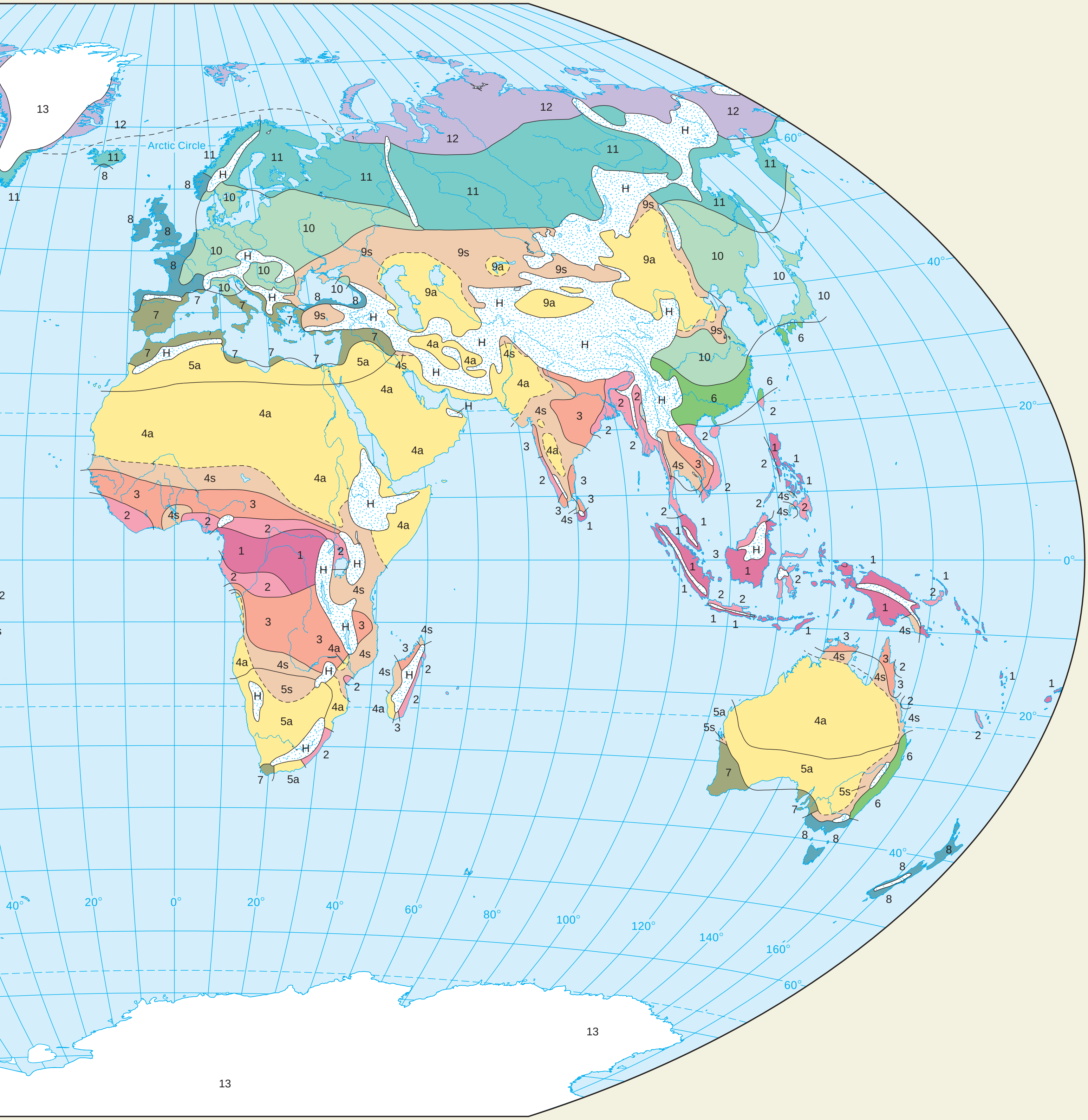
- *Group I: Low-latitude climates.* The region of low-latitude climates (Group I) is dominated by the source regions of continental tropical (cT), maritime tropical (mT), and maritime equatorial (mE) air masses. These source regions are related to the three most obvious atmospheric features that occur within their latitude band—the two subtropical high-pressure belts and the equatorial trough at the intertropical convergence zone (ITCZ). Air of polar origin occasionally invades regions of low-latitude climates. Easterly waves and tropical cyclones are important weather systems in this climate group as well.
- *Group II: Midlatitude climates.* The region of midlatitude climates (Group II) lies in the polar front zone—a zone of intense interaction between unlike air masses. In this zone, tropical air masses moving poleward and polar air masses moving equatorward are in contact. Midlatitude cyclones are normal features of the polar front, and this zone may contain as many as a dozen midlatitude cyclones around the globe at a time.
- *Group III: High-latitude climates.* The region of high-latitude climates (Group III) is dominated by polar and arctic (including antarctic) air masses. In the arctic belt of the 60th to 70th parallels, continental polar air masses meet arctic air masses along an arctic-front zone, creating a series of eastward-moving midlatitude cyclones. In the southern hemisphere, there are no source regions in the subantarctic belt for continental polar air—just a great single oceanic source region for maritime polar (mP) air masses. The pole-centered continent of Antarctica provides a single great source of the extremely cold, dry antarctic air mass (cAA). These two air masses interact along the antarctic-front zone.

Within each of these three climate groups are several climate types (or simply, climates)—four low-latitude climates (Group I), six midlatitude climates (Group II), and three high-latitude climates (Group III)—for a total of 13 climate types. Each climate has a name and a number. The name describes the general nature of the climate and also suggests its global location. The number helps to identify the climate on maps and diagrams. In the text, we will include both the climate name and number for convenience.

The world map of climates, Figure 7.10, shows the actual distribution of climate types on the continents.

7.10 Climates of the world




Arctic Circle
60°
40°
20°
0°
20°
40°
60°
40°
20°
0°
20°
40°
60°
80°
100°
120°
140°
160°

DRY AND MOIST CLIMATES

All but 2 of the 13 climate types are classified as either **dry climates** or **moist climates**. Dry climates are those in which total annual evaporation of moisture from the soil and from plant foliage exceeds annual precipitation by a wide margin. Generally speaking, the dry climates do not support permanently flowing streams. The soil is dry much of the year, and the land surface contains only a sparse plant cover—scattered grasses or shrubs—or simply lacks plant cover. Moist climates are those with sufficient rainfall to maintain the soil in a moist condition through much of the year and to sustain the year-round flow of the larger streams. Moist climates support forests of many types or prairies of dense, tall grasses.

Within the dry climates there is a wide range of aridity, from very dry deserts nearly devoid of plant life to moister regions that support a partial cover of grasses or shrubs. We will refer to two dry climate subtypes: (1) semiarid (or steppe) and (2) arid. The *semiarid* (steppe) subtype, designated by the letter *s*, is found next to moist climates. It has enough precipitation to support sparse grasses and shrubs. The *arid* subtype, indicated by the letter *a*, ranges from extremely dry climates to climates that are almost semiarid.

In dry climates, evaporation and transpiration exceed precipitation by a wide margin. In moist climates, precipitation maintains soil moisture and active streamflow for most or all of the year. Wet-dry climates alternate between wet and dry states.

In addition, 2 of our 13 climates cannot be accurately described as either dry or moist climates. These are the wet-dry tropical ③ and Mediterranean ⑦ climate types. Instead, they show a seasonal alteration between a very wet season and a very dry season. This striking contrast in seasons gives a special character to the two climates, and so we have singled them out for special recognition as wet-dry climates.

HIGHLAND CLIMATES

Mountains and high plateaus have climates that are different from those of surrounding lowlands. They tend to be cool to cold because air temperatures in the atmosphere normally decrease with altitude. They are also usually moist, getting wetter at higher locations as orographic precipitation increases.

Highland areas usually derive their annual temperature cycle and the times of their wet and dry seasons from the climate of the surrounding lowland. For example, New Delhi, the capital city of India, lies in the Ganges lowland, while Simla, a mountain refuge from the hot weather, is located at about 2200 m (about 7200 ft) in the foothills of the Himalayas (Figure 7.11). When the hot-season temperature averages over 32°C (90°F) in New Delhi, Simla is enjoying a pleasant 18°C (64°F). But note that the two temperature cycles, shown in Figure 7.12, are quite similar in shape, with January as the minimum month for both. The annual rainfall cycles are also similar in shape, but Simla receives more than double the rainfall of New Delhi.

The example of the highland climate also allows us to illustrate the use of the **climograph**—a handy pictorial device that shows the annual cycles of monthly mean air temperature and monthly mean precipitation for a location, along with some other useful information (Figure 7.12). We will make frequent use of climographs to provide examples of the 13 climate types discussed in the remainder of this chapter.

GEODISCOVERIES **Interaction of Climate, Vegetation, and Soil**

View climate, vegetation, and soils maps superimposed to see common patterns. One animation for each of five global regions.

THE KÖPPEN CLIMATE SYSTEM

An alternative climate classification is that devised by the Austrian climatologist Vladimir Köppen in 1918 and modified by Geiger and Pohl in 1953. It uses a system of letters to label climates. The classification is based on mean annual values of temperature and precipitation, the season of highest precipitation (high-Sun, low-Sun), and the precipitation of the driest month. Although it is not designed to reflect the causes of climate patterns, such as air-mass motions or coastal versus continental location, it is still in use. The system is described more fully in the Special Supplement following this chapter. We also identify the Köppen classification equivalents for the classes used below.

Low-Latitude Climates (Group I)

The low-latitude climates lie for the most part between the Tropics of Cancer and Capricorn, occupying all of the equatorial zone (10° N to 10° S), most of the tropical zone (10–15° N and S), and part of the subtropical zone. The low-latitude climate regions include the equatorial trough of the intertropical convergence zone (ITCZ), the belt of tropical easterlies (northeast and southeast trades), and large portions of the oceanic subtropical high-pressure belt. There are four low-latitude climates: wet equatorial ①, monsoon and trade-wind coastal ②, wet-dry tropical ③, and dry tropical ④. We will now look at each one in detail.

7.11 New Delhi and Simla

▼ **New Delhi** At an elevation of about 300 m (about 1000 ft), New Delhi simmers in the summer's heat (National Geographic Image Collection).

▼ **Simla** At an elevation of about 2200 m (7100 ft), Simla remains cool. Simla is a welcome refuge from the intense heat of the Gangetic Plain, where New Delhi is located, in May and June. But in July and August, Simla is much wetter.

WET EQUATORIAL CLIMATE ① (KÖPPEN: Af)

Figure 7.13 shows the world distribution of the **wet equatorial climate** ①. This climate region lies between 10° N and 10° S, and includes the Amazon lowland of South America, the Congo Basin of equatorial Africa, and the East Indies, from Sumatera to New Guinea.

The wet equatorial climate ① is dominated by warm, moist tropical and equatorial maritime air masses yielding abundant rainfall year round. The monsoon and trade-wind coastal climate ② has a strong wet season occurring when the ITCZ is nearby.

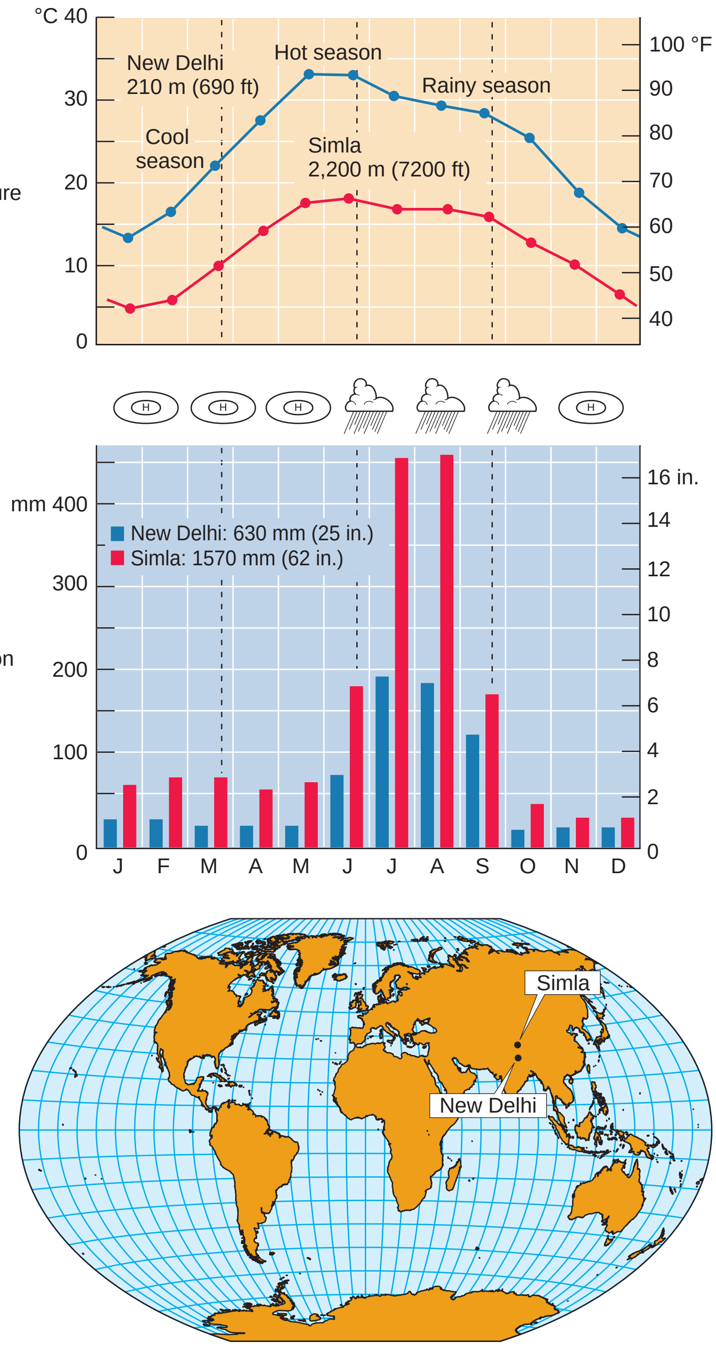
The wet equatorial climate ① is controlled by the ITCZ and is dominated by warm, moist maritime equatorial (mE) and maritime tropical (mT) air masses that yield heavy convective rainfall. There's a large amount of precipitation every month, and the annual total often exceeds 2500 mm (about 100 in.). But there is a seasonal rainfall pattern, with heavier rain when the ITCZ migrates into the region. Temperatures are uniform throughout the year, with mean monthly and mean annual temperatures close to 27°C (81°F). Typically, mean monthly air temperature will range between 26° and 29°C (79° and 84°F) for stations at low elevation in the equatorial zone (Figure 7.14).

THE MONSOON AND TRADE-WIND COASTAL CLIMATE ② (KÖPPEN: Af, Am)

Like the wet equatorial climate ①, the **monsoon and trade-wind coastal climate** ② has abundant rainfall. But here, the rainfall always shows a strong seasonal pattern. In the high-Sun season, the ITCZ is nearby, so monthly rainfall is greater. In the low-Sun season, when the ITCZ has migrated to the other hemisphere, the region is dominated by subtropical high pressure, so there is less monthly rainfall. The climate occurs between 5° and 25° N and S.

In the wet periods of the monsoon and trade-wind coastal climate ②, equatorial east coasts receive warm, moist air masses from easterly trades while tropical south and west coasts receive moist air from southwesterly monsoon winds.

As its name suggests, this climate type is produced by two different situations. On trade-wind coasts, rainfall is produced by moisture-laden maritime tropical (mT) and maritime equatorial (mE) air masses. They are moved onshore onto narrow coastal zones by trade winds or by monsoon circulation patterns. As the warm, moist air passes over coastal hills and mountains, the



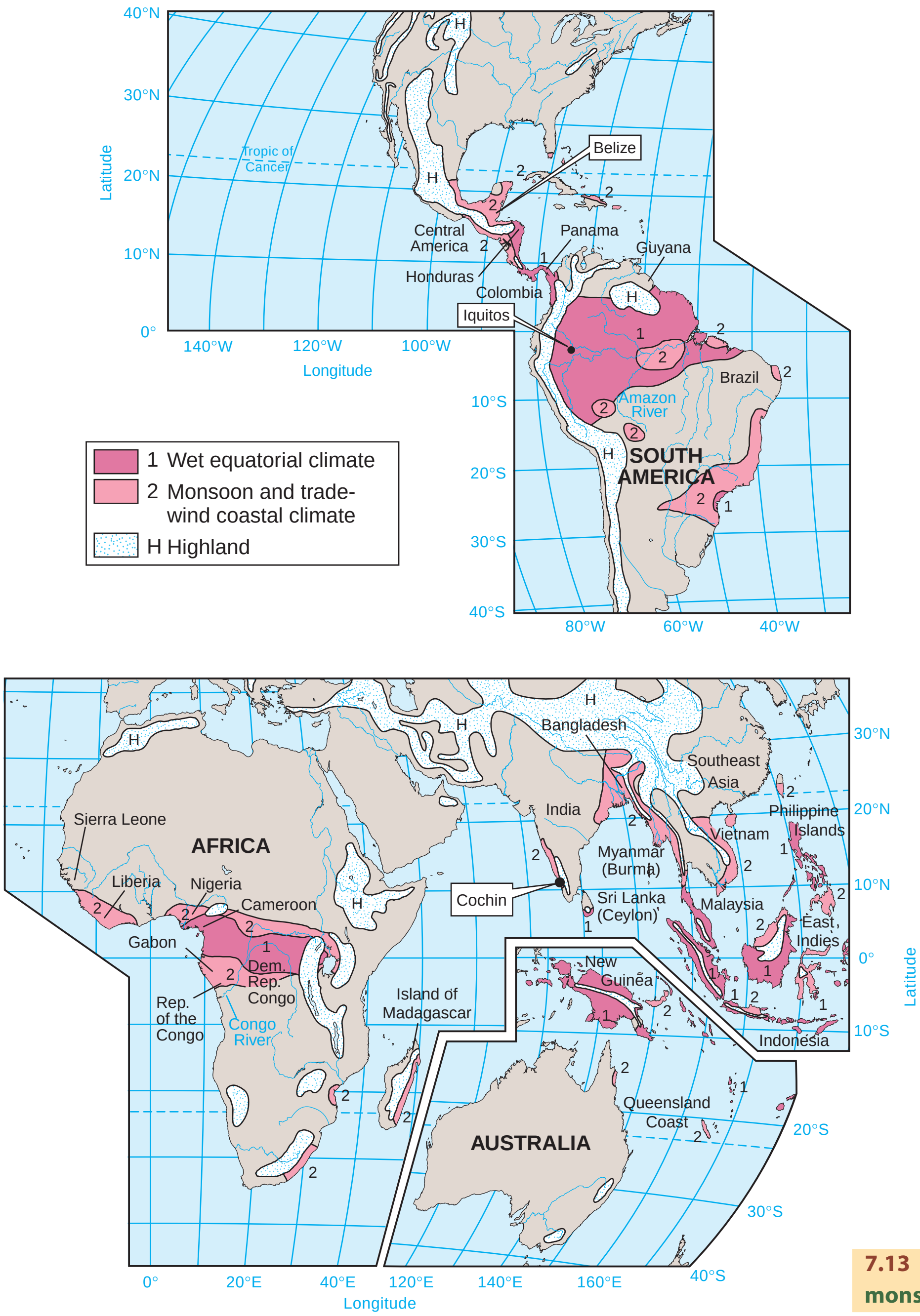
7.12 Climograph for New Delhi and Simla

The climograph is a figure that combines graphs of monthly temperature and precipitation for an observing station. This example features two stations plotted together for comparing their climates. Climographs also show total annual precipitation and annual temperature range (omitted here). Many include weather features using picture symbols.

orographic effect touches off convective shower activity. Easterly waves, which are more frequent when the ITCZ is nearby, also intensify shower activity. The east coasts of land masses experience this trade-wind effect because the trade winds blow from east to west. Trade-wind coasts are found along the east sides of Central and South America, the Caribbean Islands, Madagascar (Malagasy), Southeast Asia, the Philippines, and northeast Australia. Figure 7.15 is a climograph for the city of Belize, in the Central American country of Belize.

In the Asiatic summer monsoon, the monsoon circulation also brings mT air onshore (Figure 7.16). But the onshore monsoon winds blow from southwest to northeast, so it is the western coasts of land masses that are exposed to this moist airflow. Western India and Myanmar (formerly Burma) are examples. Moist air also penetrates well inland in Bangladesh, providing very heavy monsoon rains.

Temperatures in the monsoon and trade-wind coastal climate ② are warm throughout the year. Warmest temperatures occur in the high-Sun season, just before the ITCZ brings clouds and rain, while minimum temperatures are at the time of low Sun. Our first two climates—wet equatorial ① and monsoon and trade-wind coastal ②—create a special environment—the low-latitude rainforest (Figure 7.17). In the rainforest, temperatures are



7.13 World map of wet equatorial ① and monsoon and trade-wind coastal ② climates

uniformly warm through the year and rainfall is high. Streams flow abundantly most of the year, and the riverbanks are lined with dense forest vegetation.

THE WET-DRY TROPICAL CLIMATE ③ (KÖPPEN: Aw, Cwa)

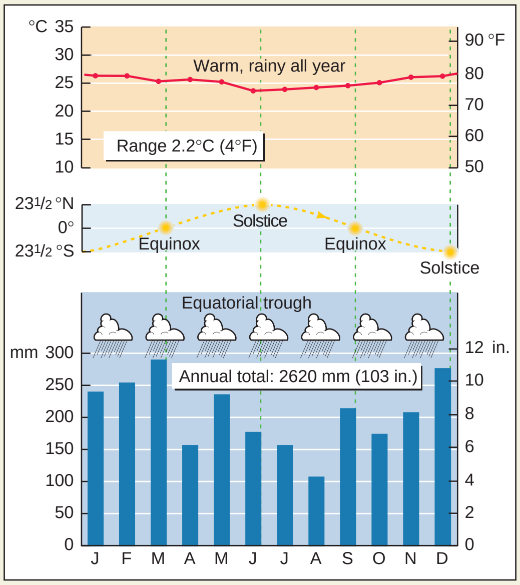
As we move farther poleward, the seasonal cycles of rainfall and temperature become stronger, and the monsoon and trade-wind coastal climate ② grades into the wet-dry tropical climate ③.

The **wet-dry tropical climate** ③ has a very dry season at low Sun and a very wet season at high Sun. During the low-Sun season, when the equatorial trough is far away, dry continental tropical (cT) air masses prevail. In the high-Sun season, when the ITCZ is nearby, the climate is dominated by moist maritime tropical (mT) and maritime equatorial (mE) air masses. Cooler temperatures in the dry season give way to a very hot period before the rains begin.

The wet-dry tropical climate ③ has a very dry season alternating with a very wet season. A typical vegetation cover in this climate is savanna woodland, a sparse cover of trees over grassland.

Figure 7.18 shows the global distribution of the

7.14 Wet equatorial climate ①

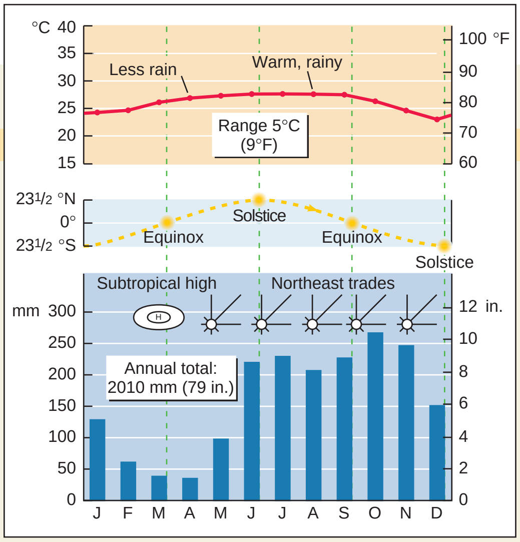


▲ **Iquitos climograph** Iquitos, in Peru (lat. 3° S), is located in the upper Amazon lowland, close to the Equator. Temperatures differ very little from month to month, and there is abundant rainfall throughout the year.

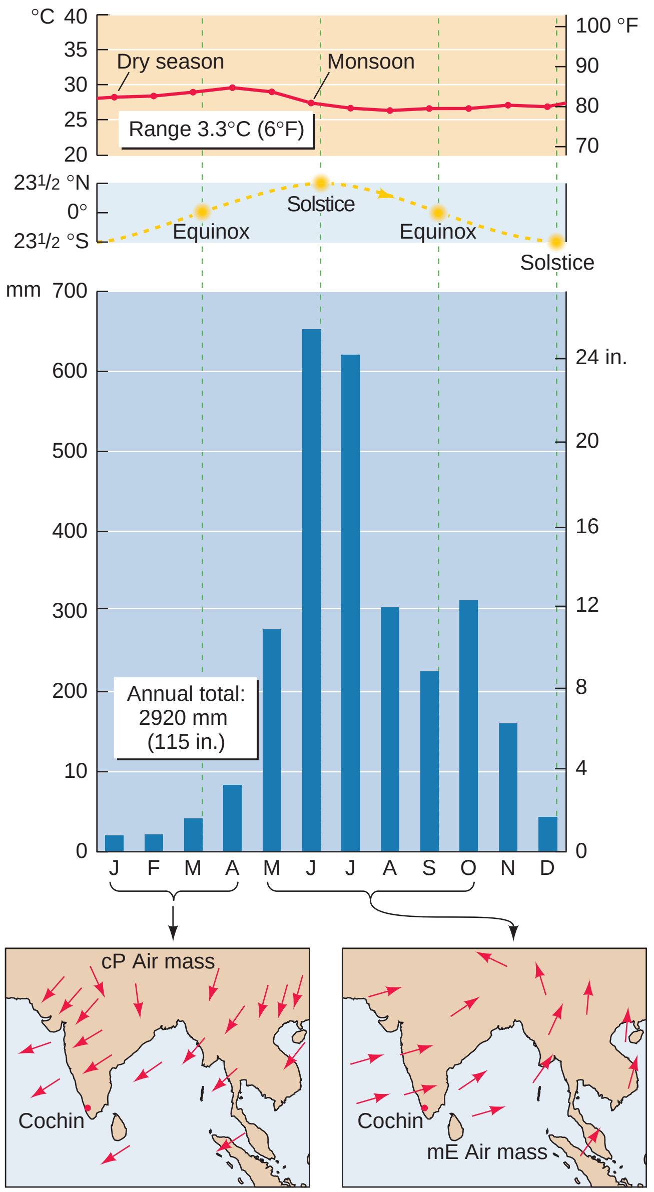
▲ **Iquitos** Frequent rainfall is a way of life on the Amazon River, near Iquitos, Peru (National Geographic Image Collection). (Iquitos is located on Figure 7.9.)

7.15 Trade-wind coastal climate ②

▲ **Belize City** Trade winds bring frequent showers to the coastal capital of Belize City, Belize (National Geographic Image Collection). (Belize is located on Figure 7.13.)



▲ **Belize climograph** This climograph for Belize, a Central American east-coast city (lat. 17° N), is exposed to the tropical easterly trade winds. Rainfall is abundant from June through November, when the ITCZ is nearby. Easterly waves are common in this season, and on occasion a tropical cyclone will bring torrential rainfall. Following the December solstice, rainfall is greatly reduced, with minimum values in March and April, when the ITCZ is farthest away.



7.16 Monsoon coastal climate ②

Cochin, on the west coast of lower peninsular India (lat. 10° N), shows an extreme peak of rainfall during the rainy monsoon, and a short dry season at time of low Sun. Air temperatures show only a very weak annual cycle, cooling a bit during the rains, so the annual range is small. (Cochin is located on Figure 7.13.)

wet-dry tropical climate ③. This climate region lies between 5° and 20° N and S in Africa and the Americas, and between 10° and 30° N in Asia. In Africa and South America, the climate occupies broad bands poleward of the wet equatorial ① and monsoon and trade-wind coastal climate ②. Because these regions are farther away from the ITCZ, less rainfall is triggered by the ITCZ during the rainy season, and in the low-Sun season subtropical high pressure dominates more strongly.

In central India and Vietnam, Laos, and Cambodia, the regions of wet-dry tropical climate ③ are somewhat protected by mountain barriers from the warm, moist mE and mT airflows provided by trade and monsoon winds. These barriers create a rain shadow effect, so that even less rainfall occurs during the rainy season and the dry season is drier still. Figure 7.19 is a climograph for Timbo, Guinea, at lat. 10° N in West Africa.

The native vegetation of the wet-dry tropical climate ③ must survive alternating seasons of very dry and very wet weather. This situation produces a *savanna environment* of sparse vegetation (Figure 7.20). In the low-Sun season, river channels that are not fed by nearby moist mountain regions are nearly or completely dry. In the high-Sun season, they fill with runoff from abundant rains. When the rains of the high-Sun season fail, there can be devastating famine.

THE DRY TROPICAL CLIMATE ④ (KÖPPEN: BWh, BSh)

The **dry tropical climate** ④ is found in the center and east sides of subtropical high-pressure cells. Here, air descends and warms adiabatically, inhibiting condensation, so rainfall is very rare and occurs only when unusual weather conditions move moist air into the region. Skies are clear most of the time, so the Sun heats the surface intensely, keeping air temperatures high. During the high-Sun period, heat is extreme. During the low-Sun period, temperatures are cooler. Given the dry air and lack of cloud cover, the daily temperature range is very large.

The driest areas of the dry tropical climate ④ are near the Tropics of Cancer and Capricorn. If you travel from the Tropics toward the Equator, rainfall increases. At first, we encounter regions that have short rainy seasons when the ITCZ is near, until finally the climate grades into the wet-dry tropical ③ type.

Figure 7.21 shows the global distribution of the dry tropical climate ④. Nearly all of the dry tropical climate ④ lies between lat. 15° and 25° N and S. The largest region is the Sahara–Saudi Arabia–Iran–Thar desert belt of North Africa and southern Asia, which includes some of the driest regions on Earth. Another large region is the desert of central Australia. The west coast of South America, including portions of Ecuador, Peru, and Chile, also exhibits the dry tropical climate ④. But temperatures there are moderated by a cool marine air layer that blankets the coast. Figure 7.22 is a climograph for a dry tropical station, Wadi Halfa, in Sudan in the heart of the North African desert.

The dry tropical climate ④ lies in the belt of persistent subtropical high pressure, so rainfall is rare. Temperatures are very hot during the high-Sun season but are significantly cooler during the low-Sun season.

The Earth's desert landscapes are actually quite varied. Although these dry deserts are largely extremely

7.17 Rainforest of the western Amazon lowland, near Manaus, Brazil

The river is a tributary of the Amazon.

arid (*a*), there are broad zones at the margins that are semiarid (*s*). These steppes have a short wet season that supports the growth of grasses on which animals (both wild and domestic) graze (Figure 7.23).

There is an important variation of the typical dry tropical climate ④ in the narrow coastal zones along the western edge of continents. These regions are strongly influenced by cold ocean currents and the upwelling of deep, cold water, just offshore. The cool water moderates coastal zone temperatures, reducing the seasonality of the temperature cycle. Figure 7.24 shows a good example of this, in Walvis Bay, in Namibia.

Midlatitude Climates (Group II)

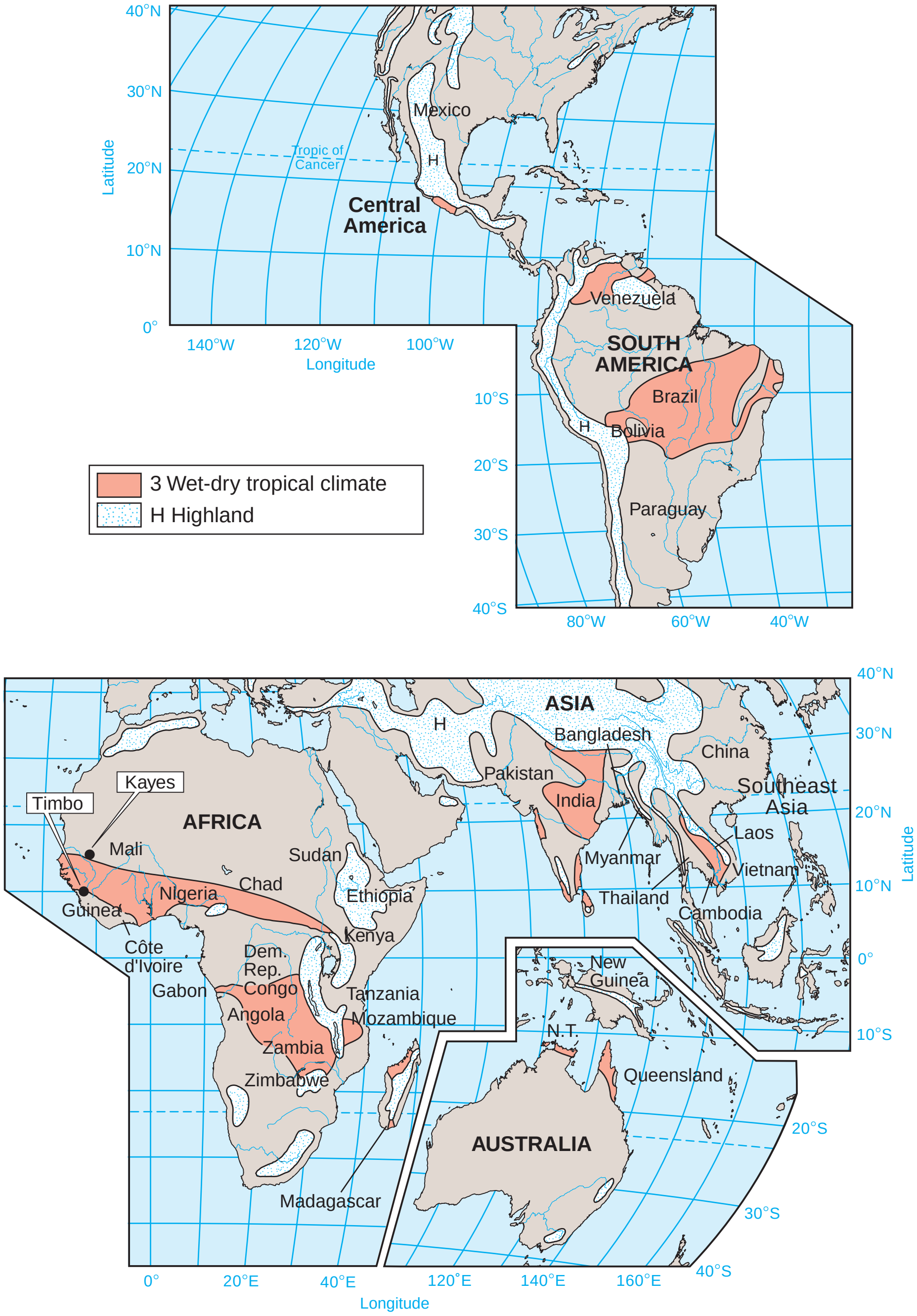
The *midlatitude climates* almost fully occupy the land areas of the midlatitude zone and a large proportion of the subtropical latitude zone. They also extend into the subarctic latitude zone, along the western fringe of Europe, reaching to the 60th parallel. Unlike the low-latitude climates, which are about equally distributed between northern and southern hemispheres, nearly all of the midlatitude climate area is in the northern hemisphere. In the southern hemisphere, the land area poleward of the 40th parallel is so small that the climates are dominated by a great southern ocean.

In the northern hemisphere, the midlatitude climates lie between two groups of very unlike air masses, which interact intensely. Tongues of maritime tropical (mT) air masses enter the midlatitude zone from the subtropical zone, where they meet and conflict with tongues of maritime polar (mP) and continental polar (cP) air masses along the polar-front zone.

The midlatitude climates include the poleward halves of the great subtropical high-pressure systems and much of the belt of prevailing westerly winds. As a result, weather systems, such as traveling cyclones and their fronts, characteristically move from west to east. This global airflow influences the distribution of climates from west to east across the North American and Eurasian continents.

There are six midlatitude climate types. They span the range from those with strong wet and dry seasons to those with uniform precipitation. Temperature cycles for these climate types are also quite varied. We will now turn to each climate type in more detail.

In midlatitude climate regions, tropical and polar air masses interact, producing traveling cyclones, traveling anticyclones, and frontal boundaries. Midlatitude climates range from very wet to very dry and usually show a strong variation in temperature and/or precipitation through the year.



7.18 World map of the wet-dry tropical climate ③

THE DRY SUBTROPICAL CLIMATE ⑤ (KÖPPEN: BWh, BWk, BSh, BSk)

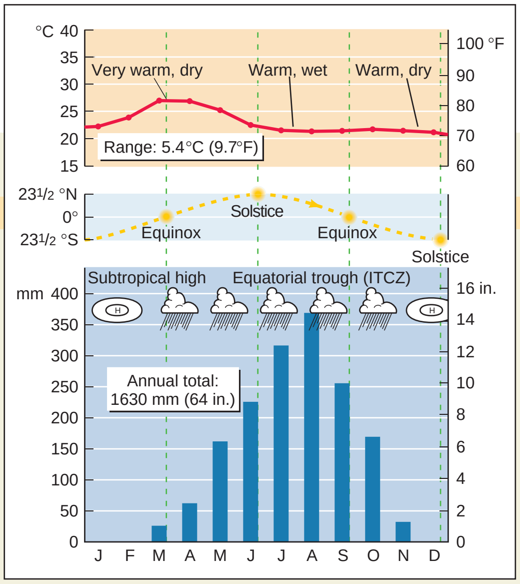
The **dry subtropical climate** ⑤ is simply a poleward extension of the dry tropical climate ④. It is caused by somewhat similar air-mass patterns, but the annual temperature range is greater for the dry subtropical climate ⑤. The lower latitude portions have a distinct cool season, and the higher latitude portions have a cold season. The cold season occurs at a time of low Sun and is caused in part by the invasion of cold continental polar (cP) air masses from higher latitudes. Midlatitude cyclones occasionally move into the subtropical zone in the low-Sun season, producing precipitation. There are both arid (*a*) and semiarid (*s*) subtypes in this climate.

The dry subtropical climate ⑤ is found in a broad band of North Africa, connecting with the Near East (Figure 7.21). Southern Africa and southern Australia also contain this climate. A band of dry subtropical climate ⑤ occupies Patagonia, in South America. In North America, the Mojave and

The dry subtropical climate ⑤ resembles the dry tropical climate ④ but has cooler temperatures during the low-Sun season, when continental polar air masses invade the region.

7.19 Wet-dry tropical climate ③

▲ **Kindia, Guinea** This busy market town, located about 150 km (about 100 mi) from Timbo, is typical of the wet-dry tropical climate ③ region of west Africa. (Timbo is located on Figure 7.18.)



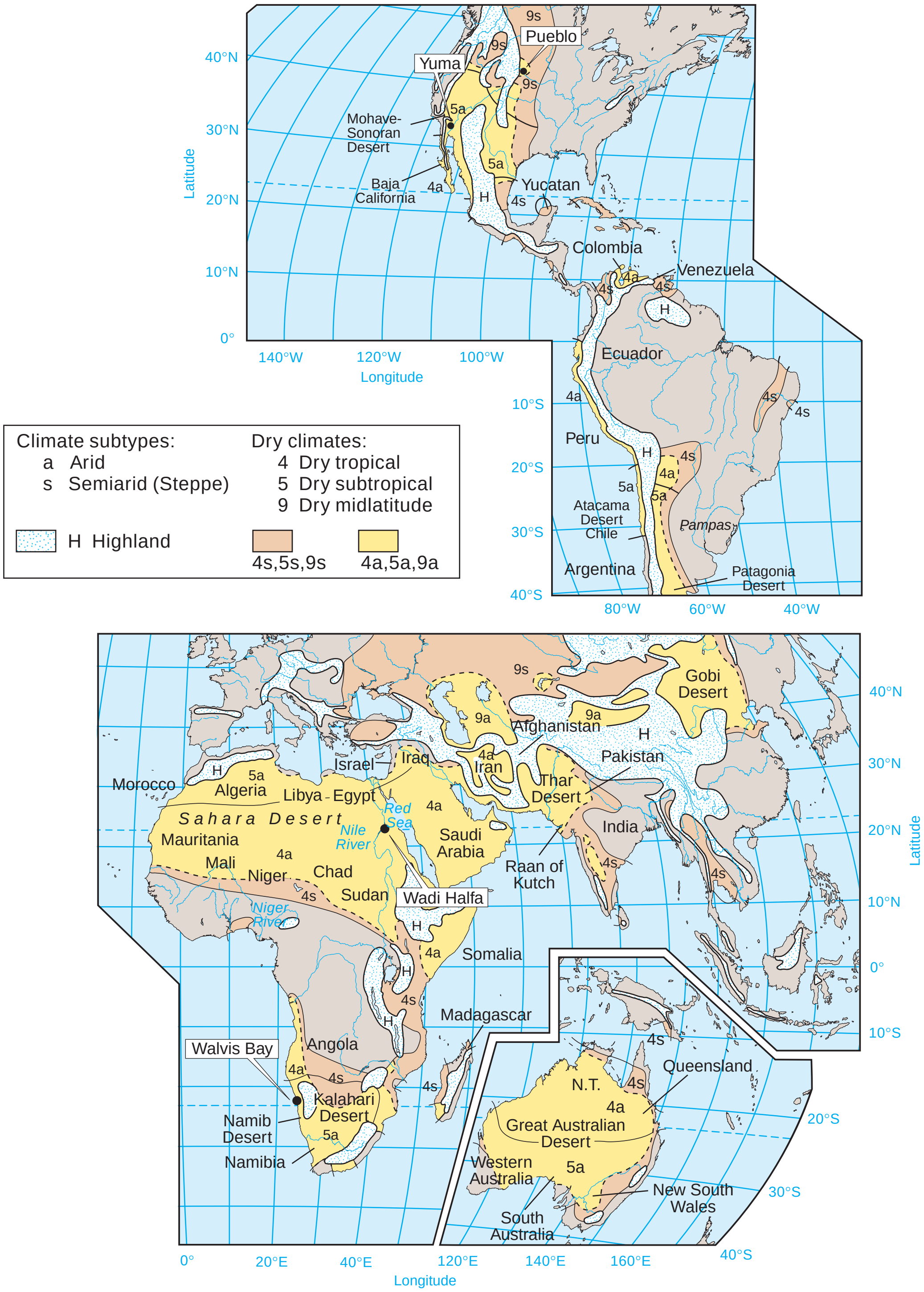
▲ **Timbo climograph** Timbo, in Guinea (lat. 10° N), in West Africa has a rainy season that begins just after the March equinox and peaks when the ITCZ has migrated to its most northerly position. Monthly rainfall decreases as the low-Sun season arrives and the ITCZ moves south. December through February are practically rainless, when subtropical high pressure dominates the climate, and stable, subsiding continental tropical (cT) air pervades the region. In February and March, insolation increases, so air temperature rises sharply. When the rains set in, the cloud cover and evaporation of rain make temperatures drop.

7.20 Savanna environments

Most plants are rain-green vegetation—staying dormant during the dry period, then bursting into leaf and bloom with the rains. There are two basic types of rain-green vegetation.

▼ **Savanna woodland** Here, coarse grasses occupy the open space between the rough-barked and thorny trees. There may also be large expanses of grassland. In the dry season, the grasses turn to straw, and many of the tree species shed their leaves to cope with the drought.

▼ **Thorntree-tall grass savanna** Thorny Acacia trees are widely spaced on this plain of tall grasses and shrubs.



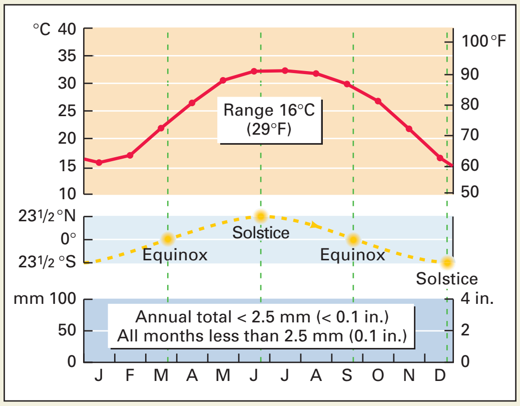
7.21 World map of the dry tropical ④, dry subtropical ⑤, and dry midlatitude ⑨ climates

The latter two climates are poleward and eastward extensions of the dry tropical climate ④ with cooler temperatures.

Sonoran deserts of the American Southwest and northwest Mexico are of this type. Figure 7.25 is a climograph for Yuma, Arizona, a city within the arid subtype of the dry subtropical climate ⑤.

The dry subtropical climate ⑤ environment is similar to that of the dry tropical climate ④. Both are very dry, and the boundary between these two climate types is gradational. But if we travel northward in the subtropical climate zone of North America, arriving at about 34° N in the interior Mojave Desert of southeastern California, we encounter environmental features that are significantly different from those of the low-latitude deserts of tropical Africa, Arabia, and northern Australia. Although the great summer heat is comparable to

7.22 Dry tropical climate ④, dry desert subtype



▲ **Wadi Halfa climograph** Wadi Halfa is on the Nile River in Sudan at lat. 22° N, almost on the Tropic of Cancer. There is a strong annual temperature cycle with a very hot period at the time of high Sun. Daytime maximum air temperatures are frequently between 43° and 48°C (about 110° to 120°F) in the warmer months. There is a comparatively cool season at the time of low Sun. There is too little rainfall to show on the climograph. Over a 39-year period, the maximum rainfall recorded in a 24-hour period at Wadi Halfa was only 7.5 mm (0.3 in.).

▲ **Wadi Halfa** This aerial view of Wadi Halfa, Sudan, situated on the Nile River, shows the town's flat-roofed residences. (Wadi Halfa is located on Figure 7.21.)

7.23 Steppes

The semiarid steppes bordering many of the world's deserts often support nomadic grazing cultures. Here Shahsavan tribespeople near Tabriz, Iran, pack their possessions in preparation for a move to summer pastures (National Geographic Image Collection).

the Sahara Desert, the low Sun brings a winter season unseen in the tropical deserts. Here, cyclonic precipitation can occur in most months, including the cool low-Sun months. Desert plants and animals have adapted to the dry environment (Figure 7.26).

THE MOIST SUBTROPICAL CLIMATE ⑥ (KÖPPEN: Cfa)

The **moist subtropical climate** ⑥ (Figure 7.27) is found on the eastern sides of continents between lat. 20° and 35° N and S. In South America, it includes parts of Uruguay, Brazil, and Argentina. In Australia, it consists of a narrow band between the eastern coastline and the eastern interior ranges. Southern China, Taiwan, and southernmost Japan are included, as is most of the Southeast of the United States, from the Carolinas to east Texas.

Circulation around subtropical high-pressure cells provides a flow of warm, moist air onto the eastern side of continents, as we have discussed. This flow of maritime tropical (mT) air dominates the moist subtropical climate ⑥. There is abundant rainfall in the summer, much of which is convective. Occasional tropical cyclones add to this summer precipitation. In Southeast Asia, this climate is characterized by a strong monsoon effect, with much more rainfall in the summer than in the winter. Summer temperatures are warm, with persistent high humidity.

The moist subtropical climate ⑥, found on the eastern sides of continents in the midlatitudes, has abundant precipitation. In summer, warm, moist, maritime tropical air masses provide convective showers, while in winter, midlatitude cyclones provide rain and occasional snow.

There is also plenty of winter precipitation, produced in midlatitude cyclones. Continental polar (cP) air masses frequently invade these climate regions in winter, bringing spells of subfreezing weather. But no winter month has a mean temperature below 0°C (32°F).

Figure 7.28 shows a climograph for Charleston, South Carolina. The native vegetation of the moist subtropical climate ⑥ is forest of several different types (Figure 7.29).

THE MEDITERRANEAN CLIMATE ⑦ (KÖPPEN: Csa, Csb)

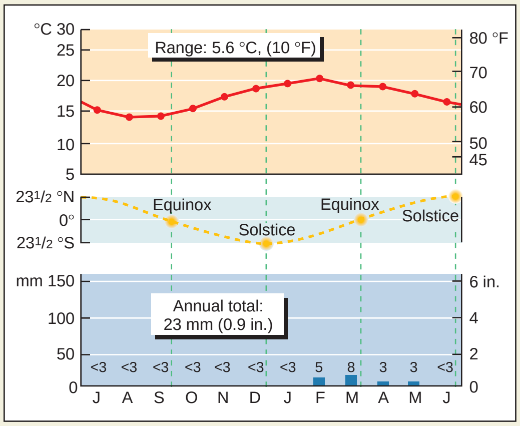
The **Mediterranean climate** ⑦ is unique because it has a wet winter and a very dry summer. This is because the climate is located along the west coasts of continents, just poleward of the dry, eastern side of the subtropical high-pressure cells. When the subtropical high-pressure cells move poleward in summer, they enter the Mediterranean climate region. Dry continental tropical (cT) air then dominates, producing the dry summer season. In winter, the moist mP air mass invades with cyclonic storms and generates ample rainfall.

The Mediterranean climate ⑦, found along midlatitude west coasts, is distinguished by its dry summer and wet winter. In summer, dry subtropical high pressure blocks rainfall, while in winter, wave cyclones produce ample precipitation.

A global map of the Mediterranean climate ⑦ is shown in Figure 7.30. It is found between lat. 30° and 45° N and S. In the southern hemisphere, it occurs

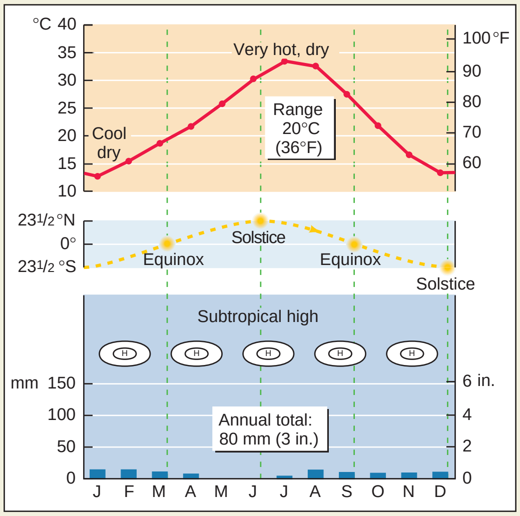
7.24 Dry tropical climate ④, western coastal desert subtype

▲ **Walvis Bay** The city of Walvis Bay is situated along the desert coast of western Africa near the Tropic of Capricorn. (Walvis Bay is located on Figure 7.21.)



▲ **Walvis Bay climograph** Walvis Bay, Namibia (lat. 23°S), is a desert station on the west coast of Africa. The monthly temperatures are remarkably cool for a location that is nearly on the Tropic of Capricorn. Because of its coastal location, the annual range of temperatures is also small—only 5°C (9°F). Coastal fog is a persistent feature of this climate.

7.25 Dry subtropical climate ⑤

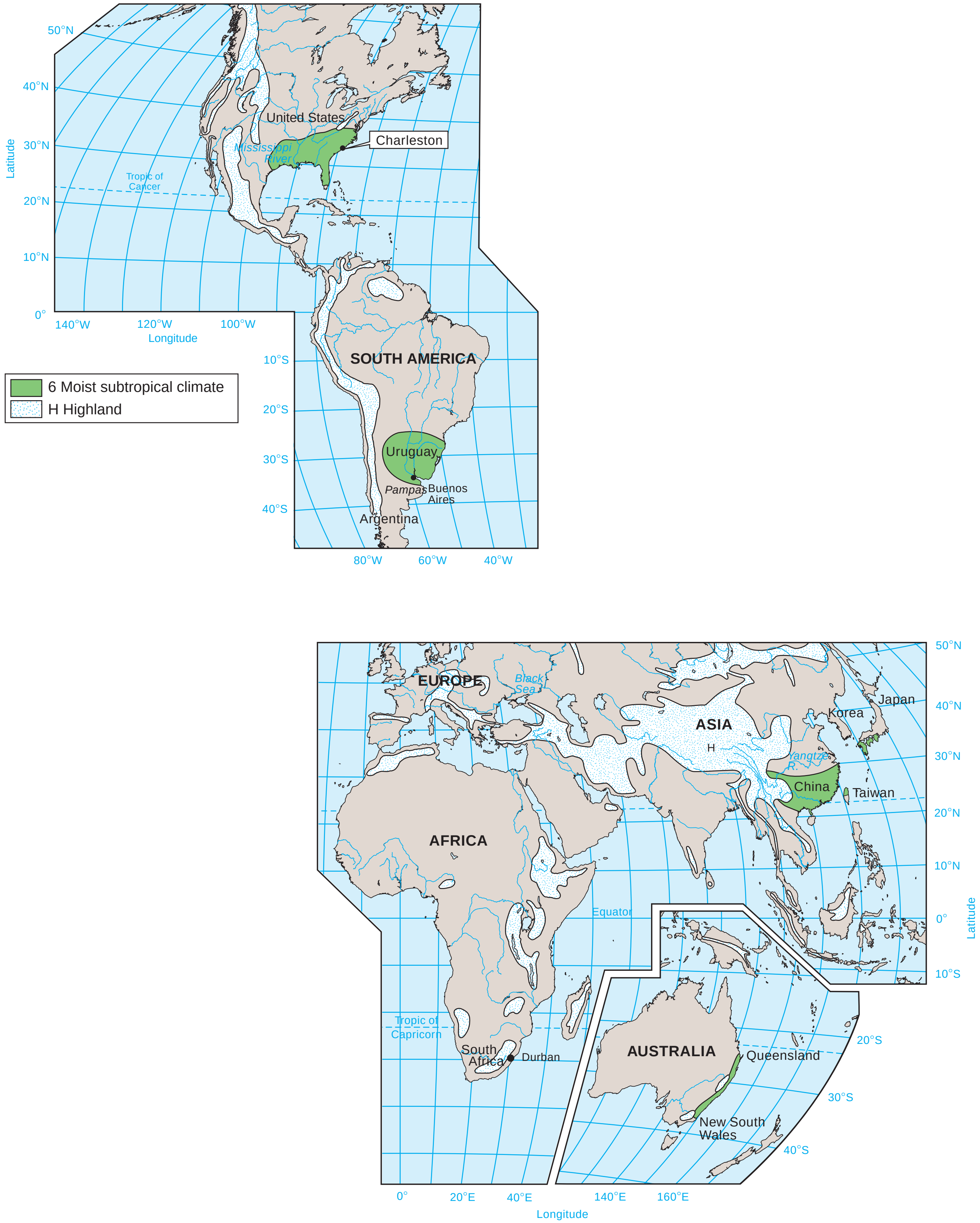


▲ **Yuma climograph** Yuma, Arizona (lat. 33° N), has a strong seasonal temperature cycle, with a dry hot summer, and freezing temperatures in December and January. The annual range is 20°C (36°F). Precipitation totals about 80 mm (3 in.) and is small in all months but has peaks in late winter and late summer. The August maximum is caused by the invasion of maritime tropical (mT) air masses, which bring thunderstorms to the region. Higher rainfalls from December through March are produced by midlatitude wave cyclones following a southerly path. Two months, May and June, are nearly rainless.

▶ **Yuma, Arizona** Spanish mission-style architecture is a highlight of this Arizona desert city. (Yuma is located on Figure 7.21.)

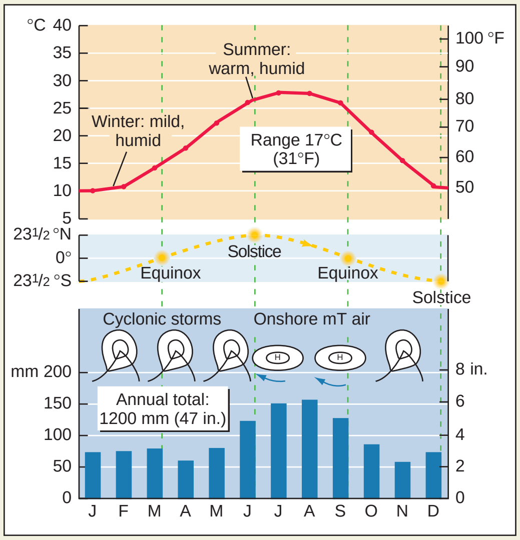
7.26 Mojave Desert

The odd-looking plants here are Joshua trees, which are abundant in the Mojave Desert. Most areas of this desert have fewer plants.



7.27 World map of the moist subtropical climate ⑥

7.28 Moist subtropical climate ⑥



▲ **Charleston climograph** Charleston, South Carolina (lat. 33° N), located on the eastern seaboard, has a mild winter and a warm summer. Total annual rainfall is abundant—1200 mm (47 in.). There is a strongly developed annual temperature cycle, with a large annual range of 17°C (31°F). Winters are mild, with the January mean temperature well above the freezing mark.

▼ **Charleston, South Carolina** These old homes on the Charleston waterfront display a local architecture well adapted to the climate of the region. The upper porches were used for outdoor living and sleeping in the hot and humid summer weather. (Charleston is located on Figure 7.27.) (National Geographic Image Collection.)

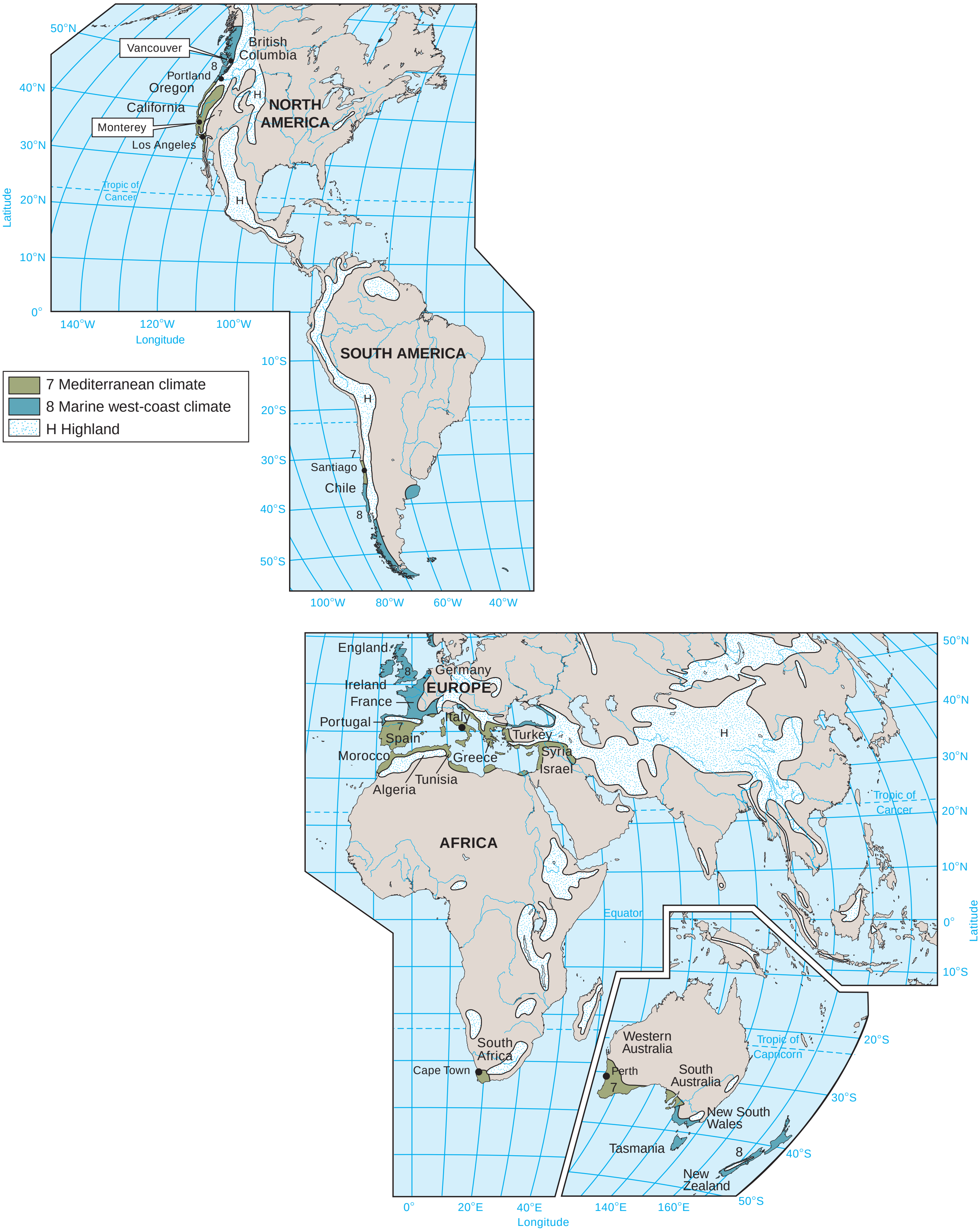
7.29 Moist subtropical forest

A mix of broadleaf deciduous trees and shrubs (oaks, hickories, poplars, for example) and occasional pines are quite typical of forests in this climate zone. Broadleaf evergreen trees and shrubs, such as the mountain laurel shown here on the left, can also occur (National Gographic Image Collection).

along the coast of Chile, in the Cape Town region of South Africa, and along the southern and western coasts of Australia. In North America, it is found in central and Southern California. In Europe, this climate type surrounds the Mediterranean Sea, giving the climate its distinctive name.

The Mediterranean climate ⑦ spans arid to humid climates, depending on location. Generally, the closer an area is to the tropics, the stronger the influence of subtropical high pressure will be, and thus the drier the climate. The temperature range is moderate, with warm to hot summers and mild winters. Coastal zones between lat. 30° and 35° N and S, such as Southern California, show a smaller annual range, with very mild winters. Figure 7.31 shows a climograph for Monterey, California.

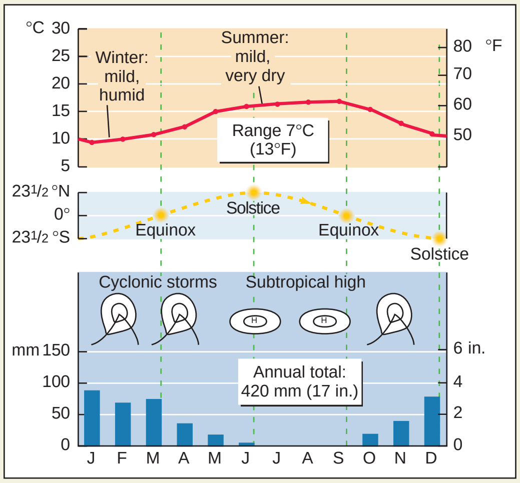
The native vegetation of the Mediterranean climate environment is adapted to survive through the long summer drought. Shrubs and trees are typically equipped with small, hard, or thick leaves that resist water loss through transpiration. These plants are called *sclerophylls*; the prefix *scler*, from the Greek for "hard," is combined with *phyllo*, which is Greek for "leaf."



7.30 World map of the Mediterranean ⑦ and marine west-coast ⑧ climates

7.31 Mediterranean climate ⑦

▲ **Monterey, California** As evident in this photo of Monterey harbor, the west coasts of the Mediterranean climate often support extensive fisheries (National Geographic Image Collection). (Monterey is located on Figure 7.30.)



▲ **Monterey climograph** Monterey, California (lat. 36° N), has a very weak annual temperature cycle because of its closeness to the Pacific Ocean. The summer is very dry. Fogs are frequent. Rainfall drops to nearly zero for four consecutive summer months but rises to substantial amounts in the rainy winter season.

THE MARINE WEST-COAST CLIMATE ⑧ (KÖPPEN: Cfb, Cfc)

The **marine west-coast climate** ⑧ occupies midlatitude west coasts. These locations receive the prevailing westerlies from a large ocean, and there are frequent cyclonic storms involving cool, moist mP air masses. Where the coast is mountainous, the orographic effect causes large amounts of precipitation annually. Precipitation is plentiful in all months, but there is often a distinct winter maximum. In summer, the rainfall is reduced because subtropical high pressure extends poleward into the region. The annual temperature range is comparatively small for midlatitudes. The marine influence keeps winter temperatures milder than at inland locations at equivalent latitudes.

> **The marine west-coast climate ⑧ features frequent cyclonic storms that provide abundant precipitation, especially when enhanced by an orographic effect. Summers are drier as subtropical high pressure moves poleward, blocking storm tracks.**

In North America, the marine west-coast climate ⑧ occupies the western coast from Oregon to northern British Columbia. In Western Europe, the British Isles, Portugal, and much of France fall under this climate. In the southern hemisphere, it includes New Zealand and the southern tip of Australia, as well as the island of Tasmania and the Chilean coast south of 35° S. The general latitude range of this climate is 35° to 60° N and S. Figure 7.32 shows a climograph for Vancouver, British Columbia.

THE DRY MIDLATITUDE CLIMATE ⑨ (KÖPPEN: BWk, BSk)

The **dry midlatitude climate** ⑨ is almost exclusively limited to the interior regions of North America and Eurasia, where it lies within the rain shadow of mountain ranges on the west or south. The ranges effectively block the eastward flow of maritime air masses, and continental polar (cP) air masses dominate the climate in winter. In summer, a dry continental air mass of local origin dominates, but occasionally maritime air masses invade, causing convectional rainfall. The annual temperature cycle is strongly developed, with a large annual range. Summers are warm to hot, but winters are cold to very cold.

> **The dry midlatitude climate ⑨ occupies continental interiors in rain shadows or far from oceanic moisture sources. Precipitation is low, and the annual temperature variation is large.**

The largest expanse of the dry midlatitude climate

⑨ is in Eurasia, stretching from the southern republics of the former Soviet Union to the Gobi Desert and northern China. True arid (*a*) deserts and extensive areas of highlands can be found in the central portions of this region. In North America, the dry western interior regions, including the Great Basin, Columbia Plateau, and the Great Plains, are of the semiarid (*s*) subtype. A small area of dry midlatitude climate ⑨ is found in southern Patagonia, near the tip of South America. The latitude range of this climate is 35° to 55° N. Figure 7.33 shows a climograph for Pueblo, Colorado. The low precipitation and cold winters of this semiarid climate produce a steppe landscape dominated by hardy perennial short grasses. A typical crop of this climate type is wheat (Figure 7.34).

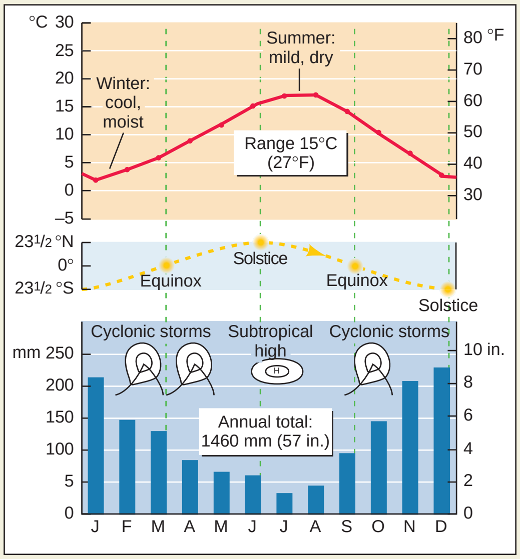
THE MOIST CONTINENTAL CLIMATE ⑩ (KÖPPEN: Dfa, Dfb, Dwa, Dwb)

The **moist continental climate** ⑩ is located in central and eastern parts of North America and Eurasia in the midlatitudes. It lies in the polar-front zone—the battleground of polar and tropical air masses. Seasonal temperature contrasts are strong, and day-to-day weather is highly variable. There is ample precipitation throughout the year, which increases in summer when maritime tropical (mT) air masses invade. Cold winters are dominated by continental polar (cP) and continental arctic (cA) air masses from subarctic source regions.

Figure 7.35 shows the global locations of the moist continental climate ⑩. It is restricted to the northern hemisphere, between lat. 30° and 55° N in North America and Asia, and in lat. 45° to 60° N in Europe. Madison, Wisconsin, in the American Midwest (Figure 7.36), provides an example. Also included is most of the eastern half of the United States from Tennessee to the north, as well as the southernmost strip of eastern Canada.

The moist continental climate ⑩ of China, Korea, and Japan has more summer rainfall and a drier winter than in North America. This is an effect of the monsoon circulation, which moves moist maritime tropical (mT) air across the eastern side of Asia in summer and dry continental polar southward through the region in winter. In Europe, the moist continental climate ⑩ lies in a higher latitude belt (45° to 60° N) and receives precipitation from mP air masses coming from the North

7.32 Marine west-coast climate ⑧

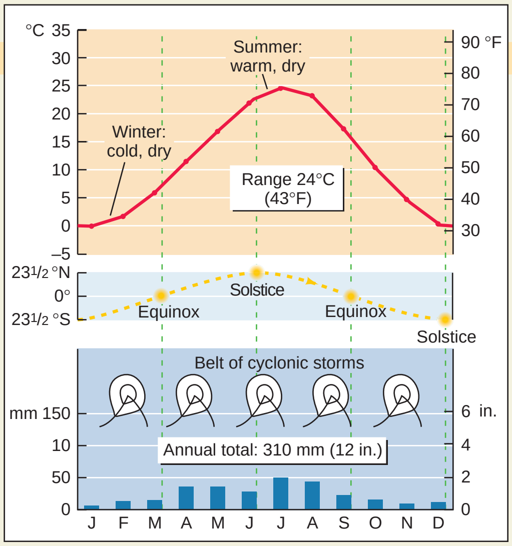


▲ **Vancouver climograph** Vancouver, British Columbia (lat. 49° N), has a large annual total precipitation, with most precipitation falling in winter. The annual temperature range is small, and winters are very mild for this latitude. Evergreen needleleaf forest is typical of this climate (National Gographic Image Collection).

▶ **Vancouver, British Columbia** Situated on the western coast of Canada, Vancouver is a major deep-water seaport. The nearby Coast Mountains are lined with conifer forests. (Vancouver is located on Figure 7.30.)

7.33 Dry midlatitude climate ⑨

▲ **Pueblo, Colorado** Located on the Arkansas River, Pueblo is the gateway to the southern Rocky Mountains. Pictured here is a pedestrian walkway along the river. (Pueblo is located on Figure 7.21.)



▲ **Pueblo climograph** Pueblo, Colorado (lat. 38° N), just east of the Rocky Mountains, has a marked summer maximum of rainfall in the summer months. Total annual precipitation is 310 mm (12 in.), and most of this is convectional summer rainfall, which occurs when moist maritime tropical (mT) air masses invade from the south and produce thunderstorms. In winter, snowfall is light. The temperature cycle has a large annual range, with warm summers and cold winters. January, the coldest winter month, has a mean temperature just below freezing.

7.34 Wheat harvest

Wheat is a major crop of the semiarid, dry midlatitude steppelands, but wheat harvests are at the mercy of rainfall variations from year to year. With good spring rains, there is an ample crop, but if spring rains fail, so does the wheat crop. Shown here is an aerial view of combines bringing in a Kansas wheat harvest (National Geographic Image Collection).

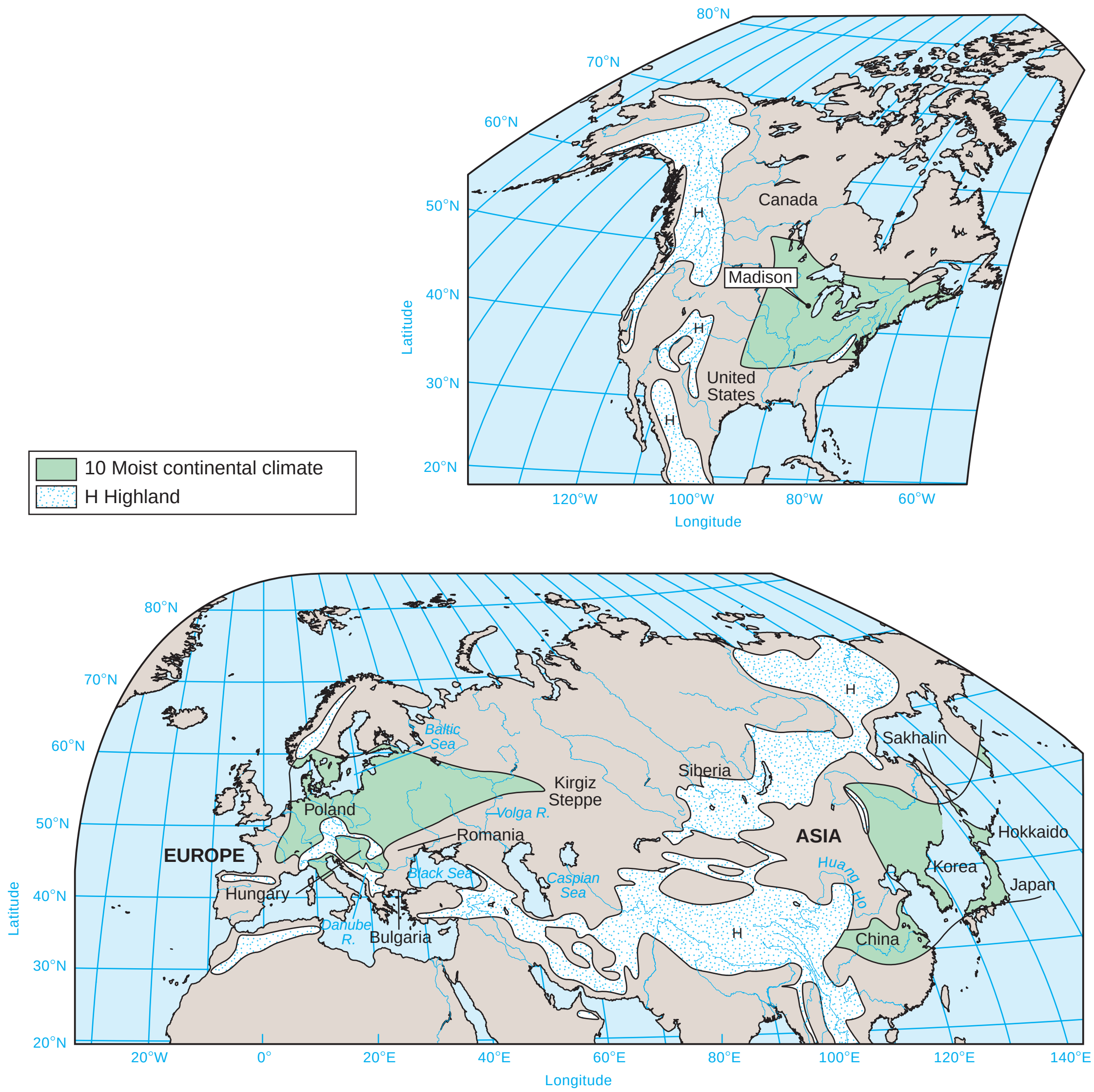
Atlantic. Most of central and eastern Europe has this climate type.

Forests are the dominant natural vegetation cover throughout most of the climate. But tall, dense grasses are the natural cover where the climate grades into drier climates, such as the dry midlatitude climate ⑨.

The moist continental climate ⑩ lies in the polar-front zone, where day-to-day weather is highly variable. Ample frontal precipitation is enhanced in summer by maritime tropical air masses. Winter temperatures fall well below freezing.

High-Latitude Climates (Group III)

By and large, the *high-latitude climates* are climates of the northern hemisphere, occupying the northern subarctic and arctic latitude zones. But they also extend southward into the midlatitude zone as far south as about the 47th parallel in eastern North America and eastern Asia. One of these, the ice sheet climate ⑬, is present in both hemispheres in the polar zones.



7.35 World map of the moist continental climate ⑩

The high-latitude climates coincide closely with the belt of prevailing westerly winds that circles each pole. In the northern hemisphere, this circulation sweeps maritime polar (mP) air masses, formed over the northern oceans, into conflict with continental polar (cP) and continental arctic (cA) air masses on the continents. Jet stream disturbances form in the westerly flow, bringing pools of warmer, moister air poleward into the region in exchange for colder, drier air that is pushed equatorward. As a result of these processes, wave cyclones are frequently produced along the arctic-front zone.

THE BOREAL FOREST CLIMATE ⑪ (KÖPPEN: Dfc, Dfd, Dwc, Dwd)

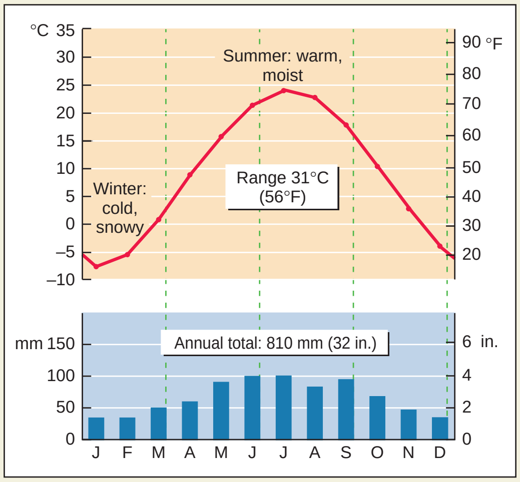
The **boreal forest climate** ⑪ is a continental climate with long, bitterly cold winters and short, cool summers. It occupies the source region for cP air masses, which are cold, dry, and stable in the winter. Very cold cA air masses very commonly invade the region. The annual range of temperature is greater than that of any other climate and is greatest in Siberia, in Russia.

Precipitation increases substantially in summer, when maritime air masses penetrate the continent with traveling cyclones, but the total annual precipitation is small. Although much of the boreal forest climate is moist, large areas in western Canada and Siberia have low annual precipitation and are therefore cold and dry.

The boreal forest climate ⑪ has long, bitterly cold winters and short, cool summers. For most of the year, cold, dry continental arctic and polar air masses dominate. In summer, occasional maritime air masses provide moisture for precipitation.

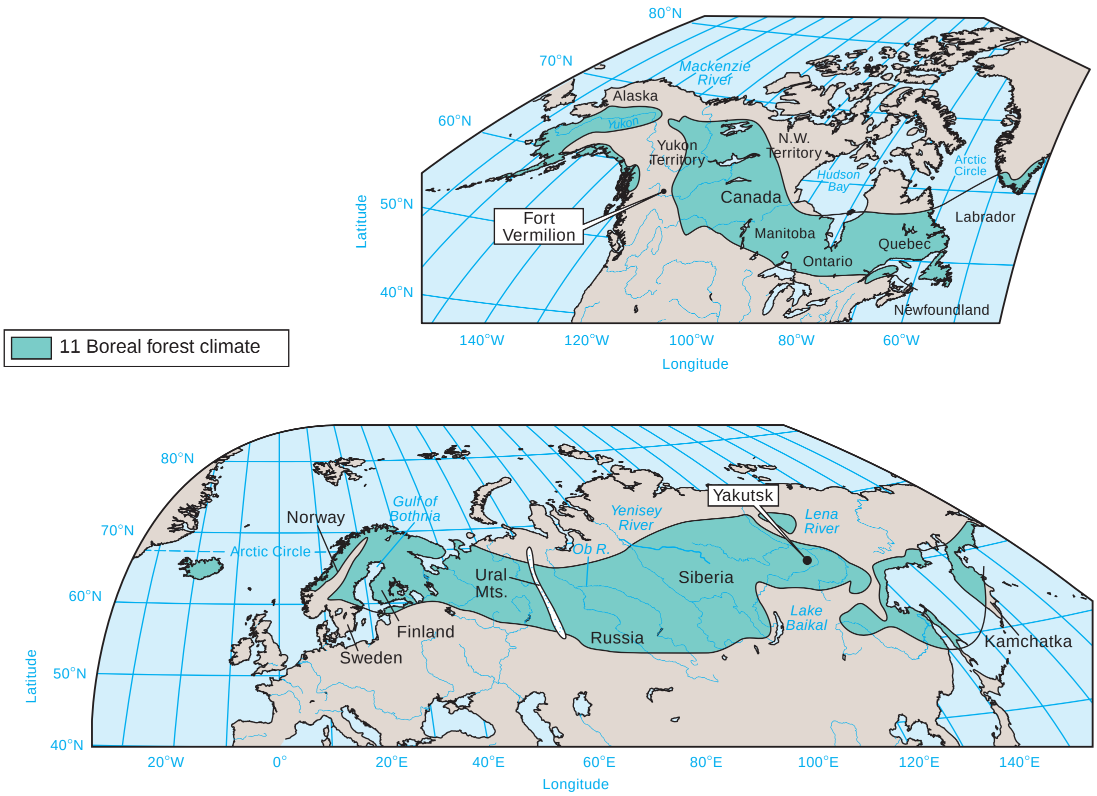
Figure 7.37 shows the global extent of the boreal forest climate ⑪, ranging from 50° to 70° N latitude.

7.36 Moist continental climate ⑩



◀ **Madison climograph** Madison, Wisconsin (lat. 43° N), has cold winters with three consecutive monthly means well below freezing—and warm summers, making the annual temperature range very large. There is ample precipitation in all months, and the annual total is large. There is a summer maximum of precipitation when the maritime tropical (mT) air mass invades, and thunderstorms form along moving cold fronts and squall lines. Much of the winter precipitation is snow, which remains on the ground for long periods.

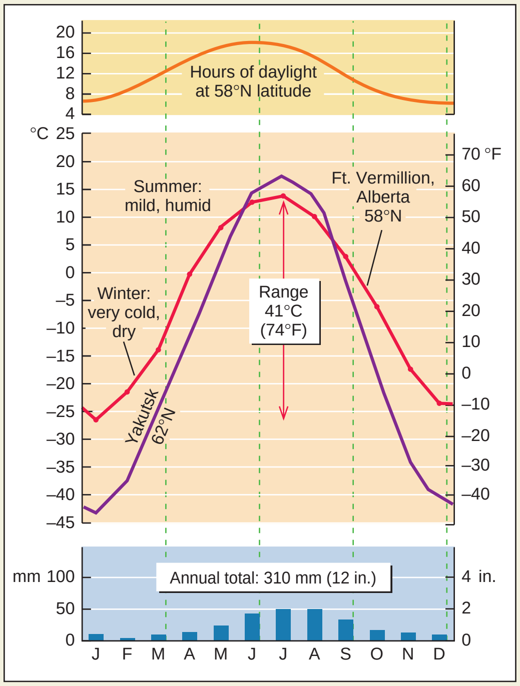
▶ **Madison, Wisconsin** The snowy winters here offer plenty of opportunity for outdoor recreation. (Madison is located on Figure 7.35.)



7.37 World map of the boreal forest climate ⑪

7.38 Boreal forest climate ⑪

▶ **Yakutsk and Fort Vermillion climographs** Extreme winter cold and a very great annual range in temperature characterize the climate of Fort Vermilion, Alberta (lat. 58° N), located on Figure 7.37. Temperatures are below freezing for seven consecutive months. The summers are short and cool. Precipitation has a marked annual cycle with a summer maximum, but the total annual precipitation is small. A snow cover remains over solidly frozen ground through the entire winter. We can also see temperature data for Yakutsk, a Siberian city at lat. 62° N. There is an enormous annual range, as well as extremely low means in winter months; January reaches about –42°C (–44°F).



◀ **Yakutsk, Siberia** These well-dressed pedestrians are making their way down a snowy street in winter. (Yakutsk is located on Figure 7.37.) (National Geographic Image Collection.)

In North America, it stretches from central and western Alaska, across the Yukon and Northwest Territories to Labrador on the Atlantic coast. In Europe and Asia, it reaches from the Scandinavian Peninsula eastward across all of Siberia to the Pacific. Figure 7.38 shows a climograph for Fort Vermilion, Alberta, plotted alongside temperature data for Yakutsk, a Siberian city.

The land surface features of much of the region of boreal forest climate were shaped beneath the great ice sheets of the Ice Age. Severe erosion by the moving ice exposed hard bedrock over vast areas and created numerous shallow rock basins that are now lakes (Figure 7.39).

The dominant upland vegetation of the boreal forest climate region is boreal forest, consisting largely of *needleleaf trees.* Although the growing season in the boreal forest climate is short, it is still possible to cultivate crops. Farming is mostly limited to lands surrounding the Baltic Sea, bordering Finland and Sweden. Crops grown in this area include barley, oats, rye, and wheat. The needleleaf forests provide paper, pulp, cellulose, and construction lumber.

7.39 Lakes in a boreal forest

Much of the boreal forest consists of low but irregular topography, formed by continental ice sheets during the Ice Age. Low depressions scraped out by the moving ice are now occupied by lakes. Alaska's Mulchatna River is in the foreground of this aerial photo.

THE TUNDRA CLIMATE ⑫ (KÖPPEN: ET)

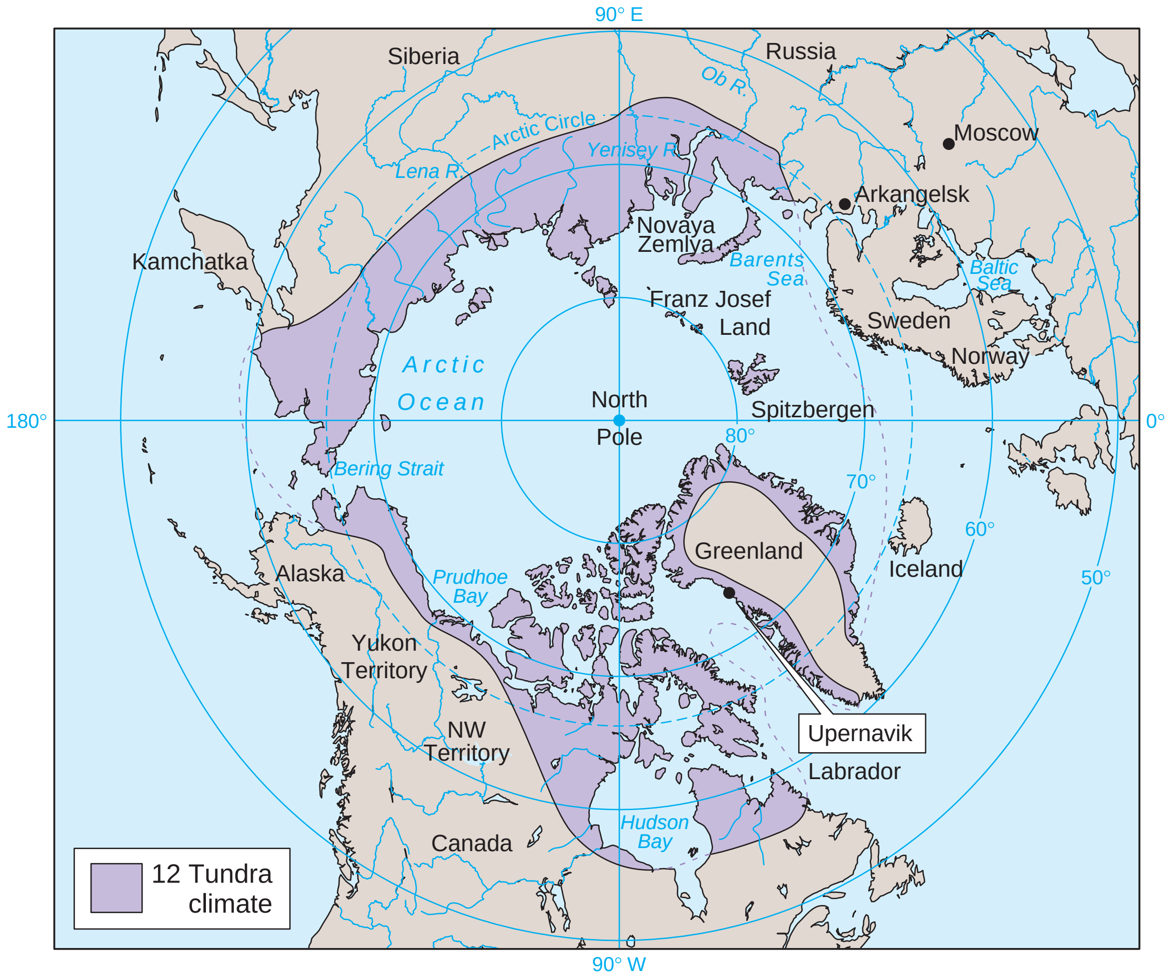
The **tundra climate** ⑫ occupies arctic coastal fringes and is dominated by polar (cP, mP) and arctic (cA) air masses. Winters are long and severe. The nearby ocean water moderates winter temperatures so they don't fall to the extreme lows found in the continental interior. There is a very short mild season, but many climatologists do not recognize this as a true summer.

The world map of the tundra climate ⑫ (Figure 7.40) shows this climate type ringing the Arctic Ocean and extending across the island region of northern Canada. It includes the Alaskan north slope, the Hudson Bay region, and the Greenland coast in North America. In Eurasia, this climate type occupies the Siberian coast, although tundra vegetation is also found on northern Iceland and along the arctic coast of Scandinavia. The Antarctic Peninsula (not shown in Figure 7.40) also belongs to this climate. The latitude range for this climate is 60° to 75° N and S, except for the northern coast of Greenland, where tundra occurs at latitudes greater than 80° N.

Figure 7.41 is a climograph for Upernavik, located on the west coast of Greenland at lat. 73° N. A short mild period, with above-freezing temperatures, is equivalent to a summer season in lower latitudes. The long winter is very cold, but the annual temperature range is not as large as that for the boreal forest climate to the south. Total annual precipitation is small. Increased precipitation beginning in July is explained by the melting of the sea-ice cover and a warming of ocean water temperatures. This increases the moisture content of the local air mass, allowing more precipitation.

The term *tundra* describes both an environmental region and a major class of vegetation. Soils of the arctic tundra are poorly developed and consist of freshly broken mineral particles and partially decomposed plant matter. Peat

The tundra climate ⑫ occupies arctic coastal fringes. Although the climate is very cold, the maritime influence keeps winter temperatures from falling to the levels of the boreal forest climate ⑪. A mild season provides a few months of thaw.



7.40 World map of the tundra climate ⑫

bogs are numerous. Soil water is solidly and permanently frozen not far below the surface, so the summer thaw brings a condition of water saturation to the soil.

Trees in the tundra are stunted because of the seasonal damage to roots by freeze and thaw of the soil layer and to branches exposed to the abrading action of wind-driven snow. In some places, a distinct tree line—roughly along the 10°C (50°F) isotherm of the warmest month—separates the forest and tundra. Geographers recognize this as the boundary between boreal forest and tundra.

Because of the cold temperatures experienced in the tundra and northern boreal forest climate zones, the ground is typically frozen to great depth. This perennially frozen ground, or *permafrost*, prevails over the tundra region. Normally, a top layer of the ground, 0.6 to 4 m (2 to 13 ft) thick, will thaw each year during the mild season.

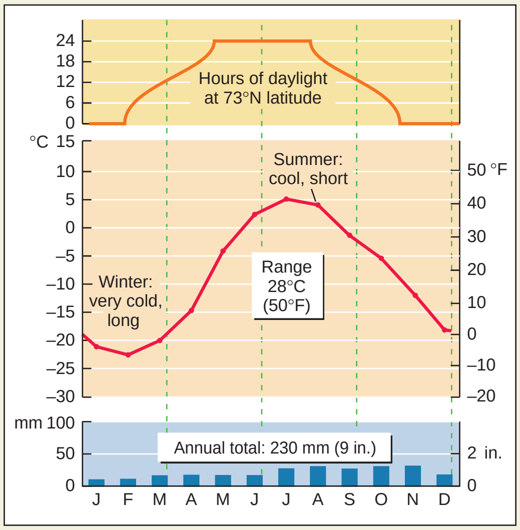
THE ICE SHEET CLIMATE ⑬ (KÖPPEN: EF)

The **ice sheet climate** ⑬ coincides with the source regions of arctic (A) and antarctic (AA) air masses, situated on the vast, high ice sheets of Greenland and Antarctica and over polar sea ice of the Arctic Ocean. Annual mean temperature is much lower than any other climate, with no monthly mean above freezing. Strong temperature inversions, caused by radiation loss from the surface, develop over the ice sheets. In Antarctica and Greenland, the high surface altitude of the ice sheets intensifies the cold. Strong cyclones with blizzard winds are frequent. Precipitation, almost all occurring as snow, is very low, but the snow accumulates because of the continuous cold. The latitude range for this climate is 65° to 90° N and S. Figure 7.42 compares temperature graphs for several representative ice sheet stations.

The ice sheet climate ⑬ has the lowest temperatures found on Earth. No month shows mean temperatures above freezing, and winter mean monthly temperatures can fall to 40°C (–40°F) and below.

GEODISCOVERIES Web Quiz
Take a quick quiz on the key concepts of this chapter.

7.41 Tundra climate ⑫



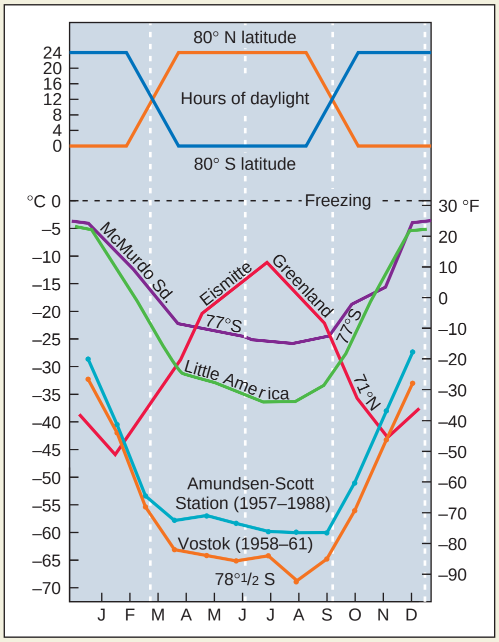
◀ **Upernavik climograph** Upernavik, located on the west coast of Greenland, (lat. 73° N), has short mild periods, with above-freezing temperatures—equivalent to a summer season in lower latitudes. The long winter is very cold, but the annual temperature range is not as large as that for the boreal forest climate to the south, such as at Fort Vermilion (Figure 7.38). Total annual precipitation is small. In July, the sea ice cover melts and the ocean water warms, raising the moisture content of the local air mass, increasing precipitation.

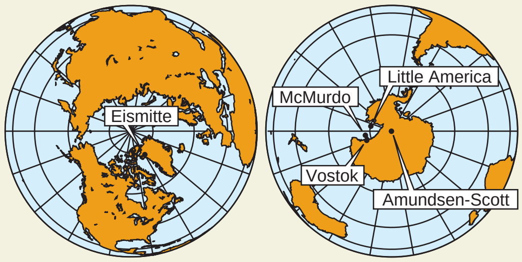
▼ **Upernavik, Greenland** A chunk of glacial ice floats past the village of Upernavik, situated on the tundra-covered slopes of a small island in Baffin Bay. (Upernavik is located on Figure 7.40.)

7.42 Ice sheet climate ⑬

▶ **Temperature graphs for five ice sheet stations** Eismitte is on the Greenland ice cap; the other stations are in Antarctica. Temperatures in the interior of Antarctica are far lower than at any other place on Earth. A low of –88.3°C (–127°F) was observed in 1958, at Vostok, about 1300 km (about 800 mi) from the South Pole at an altitude of about 3500 m (11,500 ft). At the pole (Amundsen–Scott Station), July, August, and September have averages of about –60°C (–76°F). Temperatures are considerably higher, month for month, at Little America in Antarctica because it is located close to the Ross Sea and is at a low altitude.

▼ **Antarctica** Snow and ice accumulate at higher elevations here in the Dry Valleys region of Victoria Land, Antarctica. Most of Antarctica is completely covered by ice sheets of the polar ice cap (National Geographic Image Collection).





A Look Ahead

This chapter has focused on the world's climates at the global scale. The global pattern of climates is created by global- and continental-scale atmospheric circulation processes interacting with land and sea surfaces of the Earth's continents and oceans. As we have seen repeatedly through these last seven chapters, these processes are driven by solar energy coupled with the Earth's rotation.

The climates of the Earth are remarkably diverse, ranging from the hot, humid wet equatorial climate ⑨ at the Equator to the bitterly cold and dry ice sheet climate ⑬ at the poles. The global environments associated with the Earth's climates are also highly varied, from the lush, equatorial rainforest to the stunted willows of the tundra. Climate exerts strong controls on vegetation and soils, especially at the global level. We turn to a more detailed look at biogeography, vegetation, and soils in the next three chapters.

GEODISCOVERIES Web Links

This chapter's web links lead you to lots of basic information about climates, as well as to such climate topics as the monsoon, desertification, tundra and taiga, and the dust bowl. Check it out!

IN REVIEW GLOBAL CLIMATES

- Africa's *Sahel region* has a wet-dry climate with multi-year cycles of low and high rainfall. During wet years, population and land use expand, leading to stress and famine when the dry years arrive. These cycles depend on slow changes in global sea-surface temperature patterns and are enhanced by human alteration of the land surface.
- **Climate** is the average weather of a region. It is usually characterized by average temperature and precipitation as well as their seasonality. Various climate factors control these characteristics, including a location's latitude, elevation, relation to the coast, and dominant air masses.
- *Temperature regimes* are characterized by the annual temperature and seasonal variations in temperature. These characteristics depend on latitude, which determines the annual pattern of insolation, and on location—continental or maritime—which enhances or moderates the annual insolation cycle. At higher elevations, temperatures are lower.
- Global precipitation patterns are largely determined by air masses and their movements, which in turn are produced by global air circulation patterns. Precipitation regimes are also influenced by the location of high- and low-pressure patterns associated with these global circulations. The main features of the global pattern of rainfall are:

  1. A wet equatorial belt produced by convectional precipitation around the ITCZ.
  2. Trade-wind coasts that receive moist flows of mT air from trade winds as well as tropical cyclones.
  3. Tropical deserts located under subtropical high-pressure cells.
  4. Midlatitude deserts and *steppes*, which are dry because they are far from maritime moisture sources.
  5. Moist subtropical regions that receive westward flows of moist mT air in the summer and eastward-moving wave cyclones in winter.
  6. Midlatitude west coasts, which are subjected to eastward flows of mP air and occluded wave cyclones by prevailing westerly winds.
  7. Polar and arctic deserts, where little precipitation falls because the air is too cold to hold much moisture.

- Seasonality of precipitation falls into three patterns: uniform (ranging from abundant to scarce); high-Sun (summer) maximum; and low-Sun (winter) maximum.
- There are three groups of climate types, arranged by latitude: low-latitude climates (Group I), midlatitude climates (Group II), and high-latitude climates (Group III).
- In dry climates, precipitation is largely evaporated from soil surfaces and transpired by vegetation. There are two subtypes: arid (driest) and semiarid or steppe (a little wetter). In moist climates, precipitation exceeds evaporation and transpiration. In wet-dry climates, strong wet and dry seasons alternate.
- *Highland climates* are cold and wet, and derive their characteristics from surrounding lowlands.
- The **wet equatorial climate** ① is warm to hot with abundant rainfall. This is the steamy climate of the Amazon and Congo basins. The ITCZ is always nearby, so rainfall is abundant throughout the year. The annual temperature cycle is very weak, so that the daily range greatly exceeds the annual range.
- The **monsoon and trade-wind coastal climate** ② is warm to hot, with very wet rainy seasons. When the ITCZ is in the opposite tropic, precipitation is low. With it returns monsoon circulation, and enhanced easterly waves provide increased rainfall. Temperatures are highest in the dry weather before the onset of the wet season. The climates of western India, Myanmar, Vietnam, and Bangladesh are good examples.
- The **wet-dry tropical climate** ③ is warm to hot with very distinct wet and dry seasons. It has a very dry period at the time of low Sun, and a wet season at the time of high Sun, when the ITCZ is near. Temperatures peak strongly just before the onset of the wet season. The Sahel region of Africa is a good example.
- The **dry tropical climate** ④ describes the world's hottest deserts—extremely hot in the high-Sun season, a little cooler in the low-Sun season, with little or no rainfall. Here, subtropical high pressure dominates year around. The Sahara Desert, Saudi Arabia, and the central Australian desert are examples. This climate also includes cooler deserts along subtropical west coasts.
- The **dry subtropical climate** ⑤ also includes desert climates, but is found farther poleward than the dry tropical climate ④. It is also dominated by subtropical high pressure, but has a larger annual temperature range and a distinct cool season. This type includes the hottest part of the American Southwest desert.
- The **moist subtropical climate** ⑥ is a climate of cool winters and warm, humid summers with abundant rainfall. It is dominated by maritime tropical (mT) air masses with both midlatitude and tropical cyclones. The southeastern United States and southern China are examples.
- The **Mediterranean climate** ⑦ is marked by hot, dry summers and rainy winters. Continental tropical (cT) air from subtropical high pressure dominates in summer to produce hot, dry conditions, while moist mP air invades in winter to generate ample rainfall.

Southern and central California, Spain, southern Italy, Greece, and the coastal regions of Lebanon and Israel are regions of Mediterranean climate ⑦.

- The **marine west-coast climate** ⑧ has warm summers and cool winters, with more rainfall in winter. Subtropical high pressure invades in summer, blocking precipitation. In winter, occluded cyclones provide abundant precipitation. Regions of this climate include the Pacific Northwest—coastal Oregon, Washington, and British Columbia.
- The **dry midlatitude climate** ⑨ is a dry climate of midlatitude continental interiors. A local, dry air mass dominates with occasional invasions of moist maritime air. The steppes of central Asia and the Great Plains of North America are familiar locales of this climate—warm to hot in summer, cold in winter, and with low annual precipitation.
- The **moist continental climate** ⑩ is found in the eastern United States and lower Canada—cold in winter, warm in summer, with ample precipitation through the year. Summer is wetter, with frequent invasions of maritime tropical (mT) air. In winter, continental polar (cP) and arctic (cA) air masses bring cold, dry weather. The American Northeast and upper Midwest are of this type.
- The **boreal forest climate** ⑪ is a snowy climate with short, cool summers and long, bitterly cold winters. It is the source region of continental polar (cP) air masses. Northern Canada, Siberia, and central Alaska are regions of boreal forest climate ⑪.
- The **tundra climate** ⑫ of arctic coastal fringes has a long, severe winter, although cold temperatures are somewhat moderated by the nearby Arctic Ocean. Polar and arctic air masses (cP, mP, and cA) dominate. This is the climate of the coastal arctic regions of Canada, Alaska, Siberia, and Scandinavia.
- The **ice sheet climate** ⑬ is bitterly cold and always below freezing. It is the climate of arctic (A) and antarctic (AA) air masses. It is restricted to Greenland and Antarctica.

KEY TERMS

climate, p. 220
dry climate, p. 232
moist climate, p. 232
climograph, p. 232
wet equatorial climate ①, p. 233
monsoon and trade-wind coastal climate ②, p. 233
wet-dry tropical climate ③, p. 235
dry tropical climate ④, p. 237
dry subtropical climate ⑤, p. 239
moist subtropical climate ⑥, p. 242
Mediterranean climate ⑦, p. 243
marine west-coast climate ⑧, p. 248
dry midlatitude climate ⑨, p. 248
moist continental climate ⑩, p. 249
boreal forest climate ⑪, p. 251
tundra climate ⑫, p. 254
ice sheet climate ⑬, p. 255

REVIEW QUESTIONS

1. Discuss the use of monthly records of average temperature and precipitation to characterize the climate of a region. Why are these measures useful?
2. Why are latitude and location (maritime or continental) important factors in determining the annual temperature cycle of a station?
3. List and describe the important climate control factors and how they can potentially influence temperature and precipitation in a given location.
4. Describe three temperature regimes. How are they related to latitude and location? Give examples.
5. Identify seven important features of the global map of precipitation. What factors produce them?
6. The seasonality of precipitation at a station can be described as following one of three patterns. What are they, and how do they arise? Give examples.
7. What are the three climate groups? How is each group influenced by air masses and global circulation patterns?
8. Why is the annual temperature cycle of the wet equatorial climate ① so uniform?
9. The wet-dry tropical climate ③ has two distinct seasons. What factors produce the dry season? the wet season?
10. Why is the dry tropical climate ④ dry? How do the arid (*a*) and semiarid (*s*) subtypes of this climate differ? How does the dry subtropical climate ⑤ differ from the dry tropical climate ④?
11. Both the moist subtropical ⑥ and moist continental ⑩ climates are found on eastern sides of continents in the midlatitudes. What are the major factors that determine their temperature and precipitation cycles? How do these two climates differ?
12. Both the Mediterranean ⑦ and marine west-coast ⑧ climates are found on the west coasts of continents. Why do they experience more precipitation in winter than in summer? How do the two climates differ?

13. The boreal forest ⑪ and tundra ⑫ climates are both climates of the northern regions, but the tundra is found fringing the Arctic Ocean, and the boreal forest is located farther inland. Compare these two climates from the viewpoint of coastal-continental effects.

14. What is the coldest climate on Earth? How is the annual temperature cycle of this climate related to the cycle of insolation?

VISUALIZING EXERCISES

1. Sketch the temperature and rainfall cycles for a typical station in the monsoon and trade-wind coastal climate ②. What factors contribute to the seasonality of the two cycles?
2. Sketch climographs for the Mediterranean climate ⑦ and the dry midlatitude climate ⑨. What are the essential differences between them? Explain why they occur.
3. Suppose South America were turned over. That is, imagine that the continent was cut out and flipped over end-for-end so that the southern tip was at about 10° N latitude and the northern end (Venezuela) was positioned at about 55° S. The Andean chain would still be on the west side, but the shape of the land mass would now be quite different. Sketch this continent and draw possible climate boundaries, using your knowledge of global air circulation patterns, frontal zones, and air mass movements.

ESSAY QUESTIONS

1. The intertropical convergence zone (ITCZ) moves north and south with the seasons. Describe how this movement affects the four low-latitude climates.
2. Discuss the role of the polar front and the air masses that come in conflict in the polar-front zone in the temperature and precipitation cycles of the midlatitude and high-latitude climates.
3. What climate is your home in? Compare it to the climate of another location with which you are familiar. In your comparison, stress the factors that determine the thermal and precipitation regimes, including the global circulation patterns, air masses, and frontal zones that influence each climate. Construct a possible climograph for each.

Special Supplement—The Köppen Climate System

Air temperature and precipitation data have formed the basis for several climate classifications. One of the most important of these is the Köppen climate system, devised in 1918 by Dr. Vladimir Köppen of the University of Graz in Austria. For several decades, this system, with various later revisions, was the most widely used climate classification among geographers. Köppen was both a climatologist and plant geographer, so that his main interest lay in finding climate boundaries that coincided approximately with boundaries between major vegetation types.

Under the Köppen system, each climate is defined according to assigned values of temperature and precipitation, computed in terms of annual or monthly values. Any given station can be assigned to its particular climate group and subgroup solely on the basis of the records of temperature and precipitation at that place.

Note that mean annual temperature refers to the average of 12 monthly temperatures for the year. Mean annual precipitation refers to the average of the entire year's precipitation as observed over many years.

The Köppen system features a shorthand code of letters designating major climate groups, subgroups within the major groups, and further subdivisions to distinguish particular seasonal characteristics of temperature and precipitation. Five major climate groups are designated by capital letters as follows:

A ***Tropical rainy climates***
The average temperature of every month is above 18°C (64.4°F). These climates have no winter season. Annual rainfall is large and exceeds annual evaporation.

B ***Dry climates***
Evaporation exceeds precipitation on the average throughout the year. There is no water surplus; hence, no permanent streams originate in B climate zones.

C ***Mild, humid (mesothermal) climates***
The coldest month has an average temperature of under 18°C (64.4°F), but above –3°C (26.6°F); at least one month has an average temperature above 10°C (50°F). The C climates thus have both a summer and a winter.

D ***Snowy-forest (microthermal) climates***
The coldest month has an average temperature of under –3°C (26.6°F). The average temperature of the warmest month is above 10°C (50°F). (Forest is not generally found where the warmest month is colder than 10°C (50°F).)

E ***Polar climates***
The average temperature of the warmest month is below 10°C (50°F). These climates have no true summer.

Note that four of these five groups (*A*, *C*, *D*, and *E*) are defined by temperature averages, whereas one (*B*) is defined by precipitation-to-evaporation ratios. Groups *A*, *C*, and *D* have sufficient heat and precipitation for the growth of forest and woodland vegetation. Figure S7.1 shows the boundaries of the five major climate groups, and Figure S7.2 is a world map of Köppen climates.

Subgroups within the five major groups are designated by a second letter according to the following code.

S ***Semiarid (steppe)***
W ***Arid (desert)***

(The capital letters S and W are applied only to the dry B climates.)

f Moist, adequate precipitation in all months, no dry season. This modifier is applied to A, C, and D groups.
w Dry season in the winter of the respective hemisphere (low-Sun season).
s Dry season in the summer of the respective hemisphere (high-Sun season).
m Rainforest climate, despite short, dry season in monsoon type of precipitation cycle. Applies only to A climates.

From combinations of the two letter groups, 12 distinct climates emerge:

A ***Tropical rainforest climate***
The rainfall of the driest month is 6 cm (2.4 in.) or more.

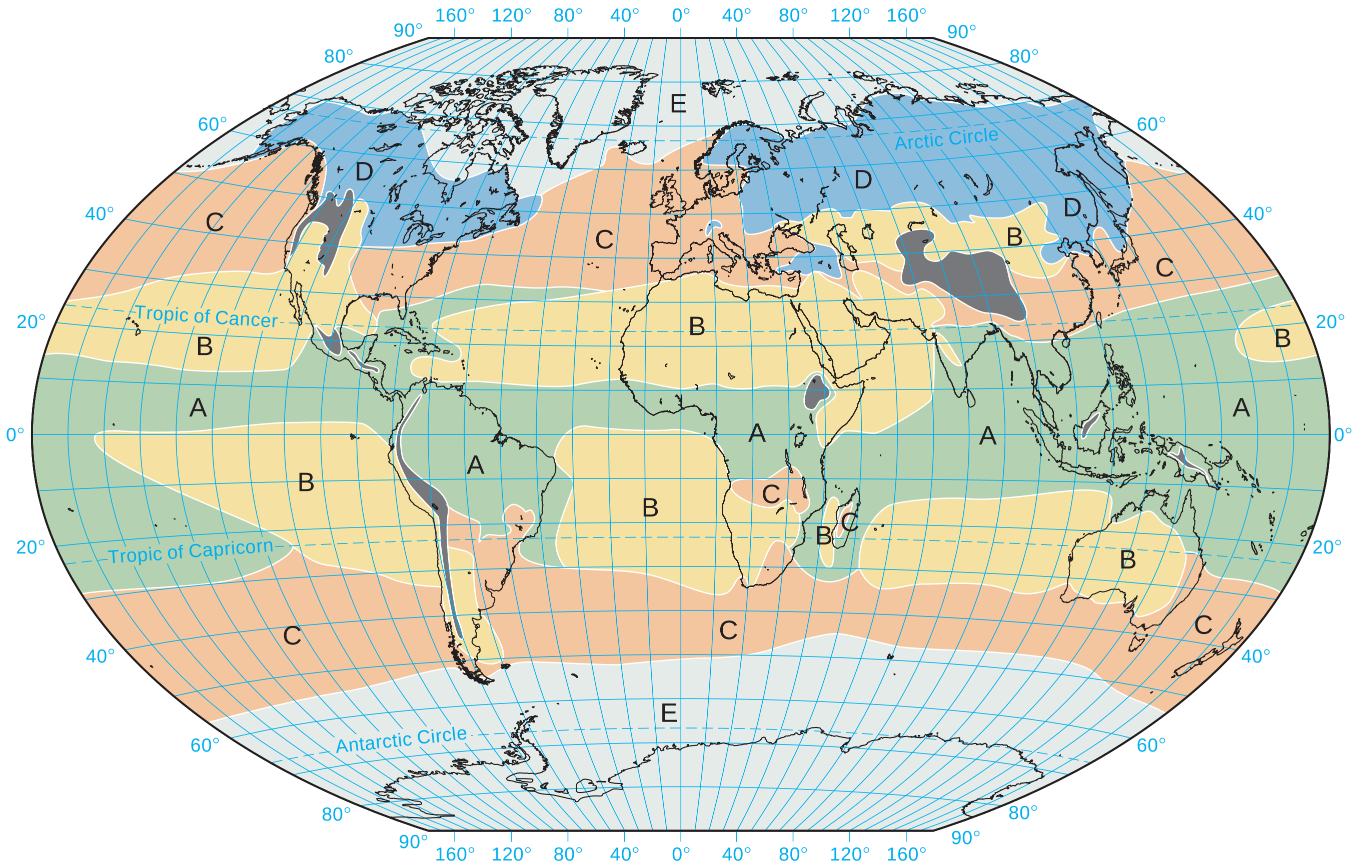
Am ***Monsoon variety of* Af**
The rainfall of the driest month is less than 6 cm (2.4 in.). The dry season is strongly developed.

Aw ***Tropical savanna climate***
At least one month has rainfall less than 6 cm (2.4 in.). The dry season is strongly developed.

Figure S7.3 shows the boundaries between Af, Am, and Aw climates as determined by both annual rainfall and rainfall of the driest month.

BS ***Steppe climate***
A semiarid climate characterized by grasslands, it occupies an intermediate position between the desert climate (BW) and the more humid climates of the A, C, and D groups. Boundaries are determined by formulas given in Figure S7.4.

BW ***Desert climate***
Desert has an arid climate with annual precipitation of usually less than 40 cm (15.7 in.). The boundary with the adjacent steppe climate (BS) is determined by formulas given in Figure S7.4.



S7.1 Generalized Köppen climate map

Highly generalized world map of major climate regions according to the Köppen classification. Highland areas are in black. (Based on Goode Base Map.)

C ***Mild humid climate with no dry season***
Precipitation of the driest month averages more than 3 cm (1.2 in.).

Cw ***Mild humid climate with a dry winter***
The wettest month of summer has at least 10 times the precipitation of the driest month of winter. (Alternative definition: 70 percent or more of the mean annual precipitation falls in the warmer six months.)

Cs ***Mild humid climate with a dry summer***
Precipitation of the driest month of summer is less than 3 cm (1.2 in.). Precipitation is at least three times as much as the driest month of summer. (Alternative definition: 70 percent or more of the mean annual precipitation falls in the six months of winter.)

Df ***Snowy-forest climate with a moist winter***
No dry season.

Dw ***Snowy-forest climate with a dry winter***

ET ***Tundra climate***
The mean temperature of the warmest month is above 0°C (32°F) but below 10°C (50°F).

EF ***Perpetual frost climate***
In this ice sheet climate, the mean monthly temperatures of all months are below 0°C (32°F).

To denote further variations in climate, Köppen added a third letter to the code group. The meanings are as follows:

a With hot summer; warmest month is over 22°C (71.6°F); C and D climates.
b With warm summer; warmest month is below 22°C (71.6°F); C and D climates.
c With cool, short summer; less than four months are over 10°C (50°F); C and D climates.
d With very cold winter; coldest month is below –38°C (–36.4°F); D climates only.
h Dry-hot; mean annual temperature is over 18°C (64.4°F); B climates only.
k Dry-cold; mean annual temperature is under 18°C (64.4°F); B climates only.

As an example of a complete Köppen climate code, BWk refers to a cool desert climate, and Dfc refers to a cold, snowy-forest climate with a cool, short summer.

S7.2 Köppen climates of the world

World map of climates according to the Köppen–Geiger–Pohl system.

KÖPPEN-GEIGER SYSTEM OF CLIMATE CLASSIFICATION

After R. Geiger and W. Pohl (1953)

Key to letter code designating climate regions:

FIRST LETTER

A C D Sufficient heat and precipitation for growth of high-trunked trees.
A Tropical climates. All monthly mean temperatures over 18°C (64.4°F).
B Dry climates. Boundaries determined by formula using mean annual temperature and mean annual precipitation (see graphs).
C Warm temperature climates. Mean temperature of coldest month: 18°C (64.4°F) down to –3°C (26.6°F).
D Snow climates. Warmest month mean over 10°C (50°F). Coldest month mean under –3°C (26.6°F).
E Ice climates. Warmest month mean under 10°C (50°F).

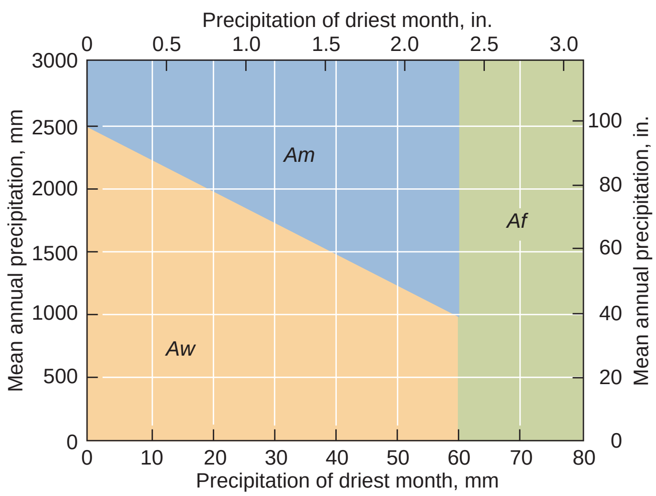
SECOND LETTER

S Steppe climate. } Boundaries determined by formulas (See graphs).
W Desert climate. }
f Sufficient precipitation in all months.
m Rainforest despite a dry season (i.e., monsoon cycle).
s Dry season in summer of the respective hemisphere.
w Dry season in winter of the respective hemisphere.

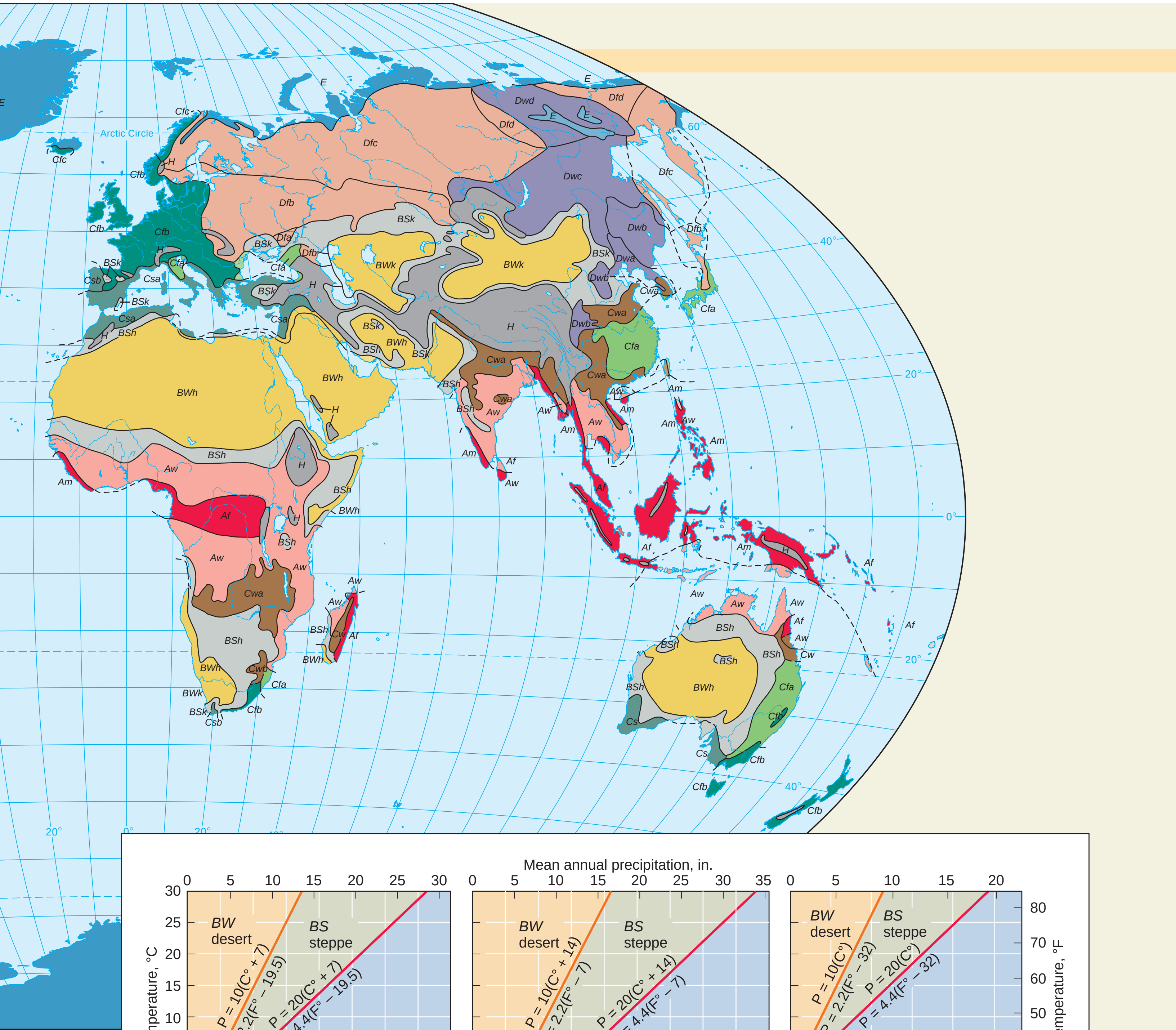
THIRD LETTER

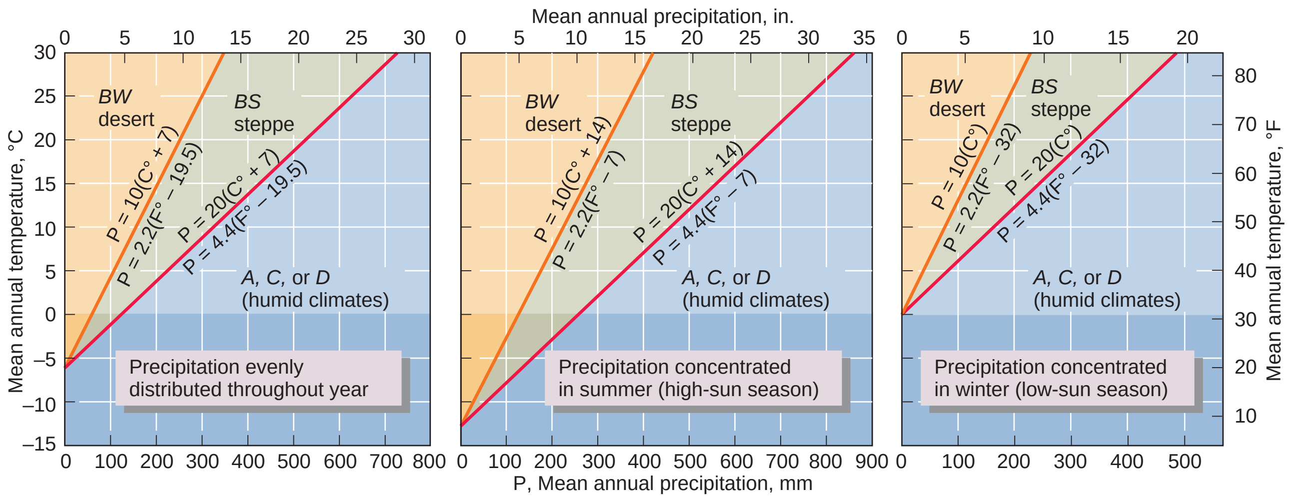
a Warmest month mean over 22°C (71.6°F).
b Warmest month mean under 22°C (71.6°F). At least 4 months have means over 10°C (50°F).
c Fewer than 4 months with means over 10°C (50°F).
d Same as c, but coldest month mean under –38°C (–36.4°F).
h Dry and hot. Mean annual temperature over 18°C (64.4°F).
k Dry and cold. Mean annual temperature under 18°C (64.4°F).

H Highland climates.



S7.3 Boundaries of the A climates





S7.4 Boundaries of the B climates

Upper figures: metric system. Lower figures: English system.

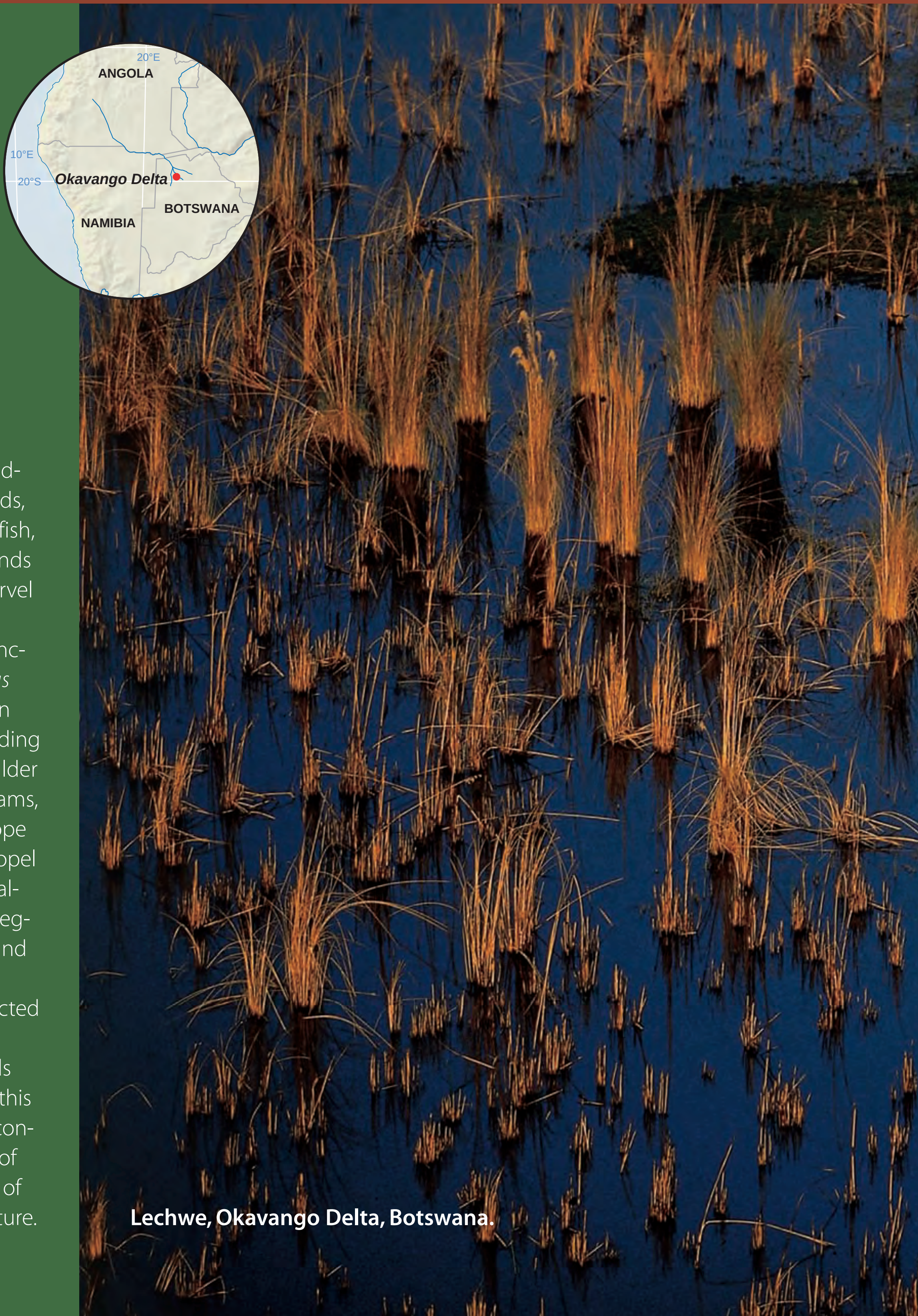
Chapter 8
Biogeographic Processes

In the center of southern Africa lies a vast labyrinth of swamps that marks the terminus of the Okavango River. Once connected to the Indian Ocean through the Limpopo River of Mozambique, the Okavango now drains the hills and ranges of southern Angola into the huge interior lowland of Botswana.

A vast watery oasis on the northern edge of the Kalahari Desert, the Okavango Delta is home to hordes of teeming wildlife, including 400 species of birds, 95 reptiles and amphibians, 70 fish, and 40 large mammals. Thousands of tourists visit each year to marvel at the delta's abundant wildlife.

One of the delta's more distinctive species is the lechwe (*Kobus leche*), an antelope found only in the swamps of the region. Standing about 1 meter high at the shoulder and weighing about 100 kilograms, this small, golden-brown antelope has long hind legs that help propel it rapidly through the delta's shallow waters. Hidden in islets of vegetation, the lechwe finds food and protection from predators.

The Okavango Delta is protected from development under the Ramsar Convention on Wetlands of International Importance, so this unique wilderness habitat will continue to enrich our knowledge of the biogeography and ecology of southern Africa well into the future.



Lechwe, Okavango Delta, Botswana.

Biogeographic Processes

This chapter is about the processes that determine where and when organisms are found on the Earth's varied land surface. How do organisms use the Sun to power their life activities? What environmental factors limit the distribution of organisms? How do organisms interact with one another? How do plant and animal communities change with time if left undisturbed? Where do species come from? How do they change and evolve? How do they find their way from place to place across the globe? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Human Impact on the Carbon Cycle

Carbon is an element that is abundant at the Earth's surface and is also essential for life. Carbon cycles continuously among the land surface, atmosphere, and ocean in many complex pathways. However, these flows are now strongly influenced by human activity. The most important human impact on the carbon cycle is the burning of fossil fuels, which releases carbon dioxide (CO_2) into the atmosphere and enhances global warming. Another important human impact lies in changing the Earth's land covers—for example, in clearing forests or abandoning agricultural areas—which can release or take up atmospheric CO_2. Let's look at these impacts in more detail.

Figure 8.1 shows a simple diagram of the global atmospheric carbon budget for the period 2000–2005. The magnitudes of the annual flows are shown in gigatons (Gt) of carbon per year (1 gigaton = 10^9 metric tons = 10^{12} kg = 1.1×10^9 English tons = 1.1 English gigatons). These flows are estimates, and a second value after the first indicates its uncertainty.

Fossil fuel burning contributes about 7.2 ± 0.3 Gt of carbon per year, nearly all in the form of carbon dioxide. About 2.2 ± 0.5 Gt of carbon per year is taken up by the oceans, reducing the atmospheric content by that amount. In addition, yearly uptake of carbon dioxide by land ecosystems is estimated at about 0.9 ± 0.6 Gt of carbon. Taken together, these two flows out of the atmosphere leave about 4.1 ± 0.1 Gt of additional carbon remaining in the atmosphere each year.

Two processes are responsible for the uptake of carbon by the oceans. First, carbon dioxide dissolves in sea water, which removes carbon from the atmosphere. Second, phytoplankton—microscopic plants living in the ocean—take up carbon dioxide in photosynthesis. When they die, they produce organic matter that sinks to the ocean floor, removing it from short-term circulation. The removal of carbon dioxide is moderated somewhat by another process in which the formation of calcium carbonate by diatoms and other marine organisms releases CO_2. Taken together, these oceanic processes remove about 30 percent of the carbon released to the atmosphere each year by fossil fuel burning.

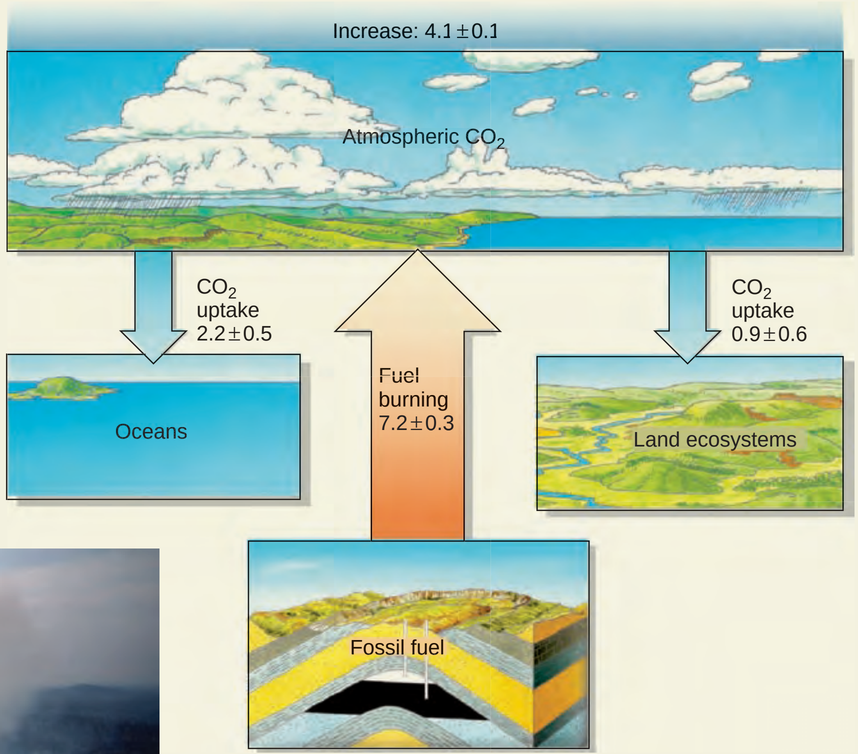
Land ecosystems cycle carbon by photosynthesis, respiration, decomposition, and combustion. Photosynthesis and respiration are basic physiological processes of plants that absorb CO_2 from the atmosphere and release it, respectively. Decomposition is the process in which bacteria and fungi digest dead organic matter, and is actually a form of respiration. Combustion refers to uncontrolled combustion, as when an ecosystem burns in a forest fire.

These processes, taken as a whole, remove about 0.9 Gt of carbon per year from the atmosphere—about 12 percent of the contribution of fossil fuel burning. This uptake of atmospheric CO_2 by land ecosystems means that plant biomass—the amount of carbon-bearing material contained in living and dead plant matter—is increasing at that rate. However, forests are presently diminishing in area as they are logged or converted to farmland or grazing land. This conversion is primarily occurring in tropical and equatorial regions, and it is estimated to release about 1.6 Gt of carbon per year (1990s estimate) to the atmosphere. If this large amount is being released, then the remaining area of land ecosystems must be taking up at least that much carbon, and more—totaling about 2.5 Gt per year—to provide a net uptake of 0.9 Gt/yr.

Independent evidence seems to confirm this conclusion. In Europe, for example, forest statistics show an increase of growing stock—the volume of living trees—of at least 25 percent since 1970. In North America, forest areas are increasing in many regions as agricultural production has abandoned marginal areas to natural forest regrowth. New England is a good example of this trend.

8.1 Human impact on the carbon cycle

▶ **The global carbon cycle** Values are in gigatons of carbon per year.



▲ **Forest clearing** Clearing of forests and shrublands for agriculture and grazing lands releases carbon through burning or enhanced decay of new biomass. Here, fires burn in the Amazon River Basin as cattle ranchers convert forest to grassland.

▲ **Carbon in soils** Soil organic matter releases carbon dioxide when digested by microorganisms. When soil temperature increases in response to global warming, digestion and CO_2 release will increase. Shown here is a peat bog near Zakopane, Poland. Grass covers the peat in the foreground. Slabs of peat, cut from the bog's surface, are drying and will later be burned as fuel.

◀ **Forest growth** Growth of forests, planted or natural, builds terrestrial biomass and removes carbon from the atmosphere.

A century ago, only a small portion of New England was forested. Now only a small portion is cleared.

Some of the increase in global biomass may also be due to warmer temperatures and increased atmospheric CO_2 concentrations, which enhance photosynthesis to make plants more productive. Another stimulating factor is nitrogen fertilization of soils by the washout of nitrogen pollutant gases in the atmosphere.

While the dynamics of forests are important in the global carbon cycle, soils may be even more important. Recent inventories estimate that about four times as much carbon resides in soils than in above-ground plant biomass. The largest reservoir of soil carbon is in the boreal forest. In fact, there is about as much carbon in boreal forest soils as in all above-ground vegetation.

This soil carbon has accumulated over thousands of years under cold conditions that have retarded its decay. However, there is now great concern that global warming, which is acting more strongly at high latitudes, will increase the rate of decay of this vast carbon pool, releasing CO_2 as microorganisms digest the organic matter. Boreal forests, which are presently taking up CO_2, may soon start releasing it, causing even more warming. Figure 8.1 shows some terrestrial sources and sinks of carbon, including soil organic matter.

Fossil fuel burning contributes more than 7 Gt of carbon to the atmosphere per year. Oceanic processes remove about 2 Gt and land ecosystems about 1 Gt, leaving about 4 Gt of carbon accumulation per year.

Reducing the rate of carbon dioxide buildup in the atmosphere is a matter of great international concern. As we noted in Chapter 3, the world's nations have been struggling to implement a plan to control these emissions. While much good progress has been made, more work is needed. An effective global commitment to reduction of CO_2 releases and control of global warming still awaits us.

Energy and Matter Flow in Ecosystems

This chapter is the first of two chapters that look at biogeography. **Biogeography** focuses on the distribution of plants and animals—the *biota*—over the Earth. It identifies and describes the processes that influence plant and animal distribution patterns. *Ecological biogeography* looks at how the distribution patterns of organisms are affected by the environment. *Historical biogeography* focuses on how spatial distribution patterns of organisms arise over time and space.

Before we turn to those processes, we must begin by looking at some ideas from the domain of **ecology**, which is the science of the interactions among life-forms and their environment. These ideas concern how organisms live and interact as ecosystems and how energy and matter are cycled by ecosystems. The term **ecosystem** refers to a group of organisms and their environment (Figure 8.2). Ecosystems take up matter and energy as plants and animals grow, reproduce, and maintain life. That matter and energy can be recycled within the ecosystem or exported out of the ecosystem. Ecosystems balance the various processes and activities within them. Many of these balances are robust and self-regulating, but some are quite sensitive and can be easily upset or destroyed.

The clearing of forests or shrublands for agriculture or grazing releases carbon to the atmosphere, while vegetation regrowth and expansion into abandoned lands takes up carbon.

THE FOOD WEB

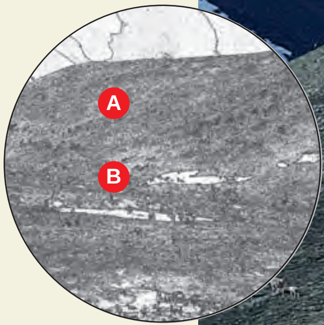
Energy is transferred through an ecosystem in steps, making up a *food chain* or a **food web**. At the bottom of the chain are the *primary producers*, which absorb sunlight and use the light energy to convert carbon dioxide and water into *carbohydrates* (long chains of sugar molecules) and eventually into other biochemical molecules, by *photosynthesis* (Figure 8.3). The primary producers support the *consumers*—organisms that ingest other organisms as their food source. Finally, *decomposers* feed on decaying organic matter, from all levels of the web. Decomposers are largely microscopic organisms (microorganisms) and bacteria.

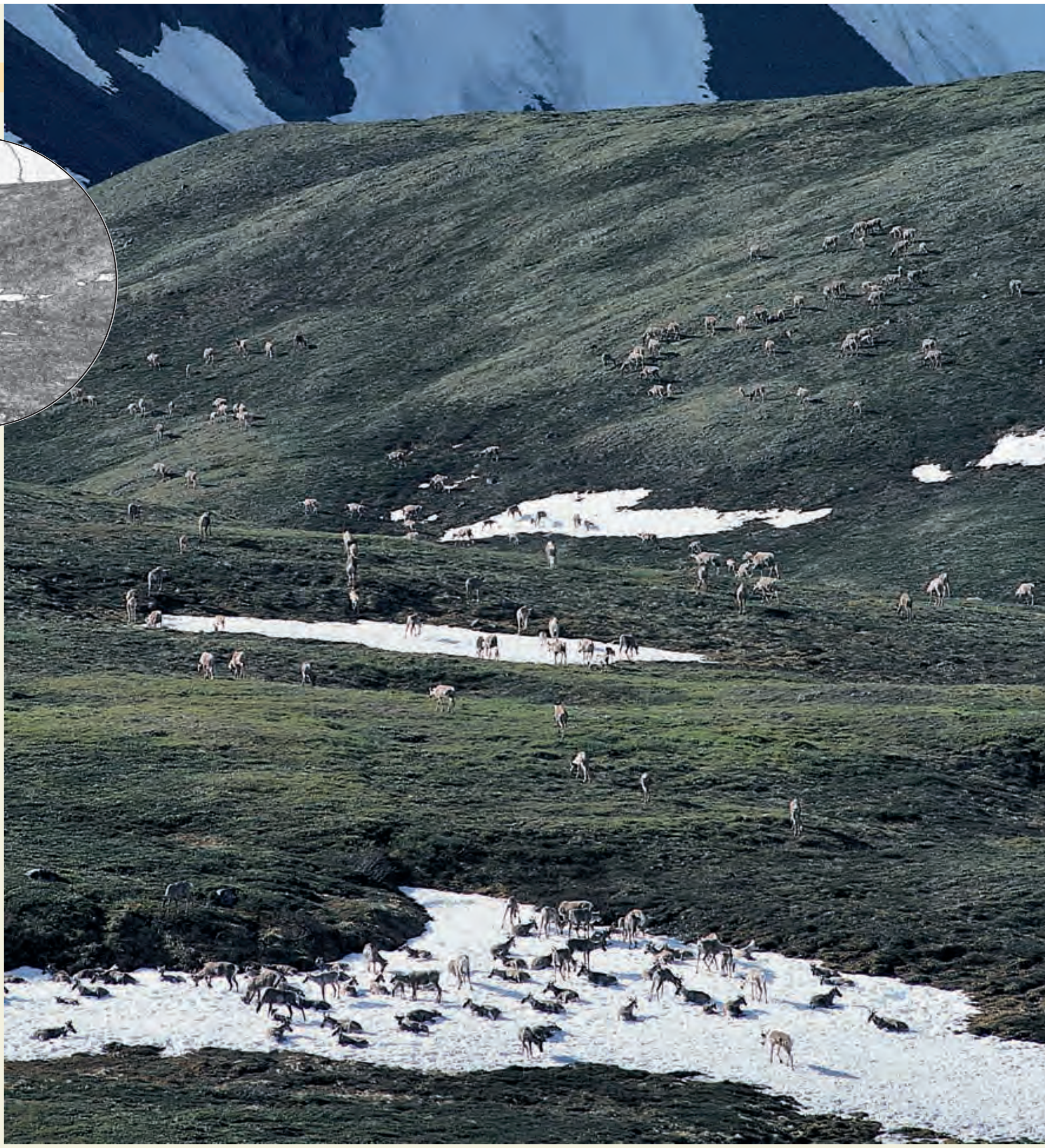
The food web is really an energy flow system, tracing the path of solar energy through the ecosystem. Solar energy is absorbed by the primary producers and stored in the chemical products of photosynthesis. As these organisms are eaten and digested by consumers, chemical energy is released. This chemical energy is used to power new biochemical reactions, which again produce stored chemical energy in the consumers' bodies.

The food web describes how food energy flows from organism to organism within an ecosystem. Primary producers support primary, secondary, and higher-level consumers. Decomposers feed on dead plant and animal matter from all levels.

Energy is lost at each level in the food web through *respiration*. You can think of this lost energy as fuel burned to keep the organism operating. Energy expended in respiration is ultimately lost as waste heat and cannot be stored for use by other organisms higher up in the food chain. This means that, generally, both the numbers of organisms and their total amount of

8.2 Ecosystem gallery





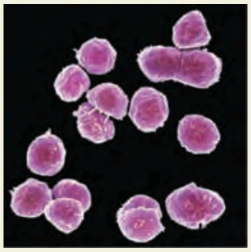
▶ **Caribou in the foothills of the Brooks Range** The caribou, a large grazing mammal, is one of the more important primary consumers of the tundra ecosystem.

EYE ON THE LANDSCAPE What else would the geographer see? Notice the "blobs" of soil on this slope (A), distinguished by color and shape. These are solifluction lobes (Chapter 13), produced in the short arctic summer when the snow melts and the surface layer of soil thaws. The saturated soil creeps downhill in lobes until it dries out sufficiently and its motion stops. Also note the snow patches (B). In some years, these will persist through the summer.

▼ **Freshwater marsh** The marsh or swamp ecosystem supports a wide variety of life-forms, both plant and animal. Here, a group of white ibises forages for food in the shallow waters of Okefenokee Swamp, Georgia (National Geographic Image Collection).

▼ **Savanna** The savanna ecosystem, with its abundance of grazing mammals and predators, has a rich and complex food web. Here a line of African elephants travels single-file across the savanna plains of the Savuti region, Botswana (National Geographic Image Collection).

8.3 The food web of a salt marsh



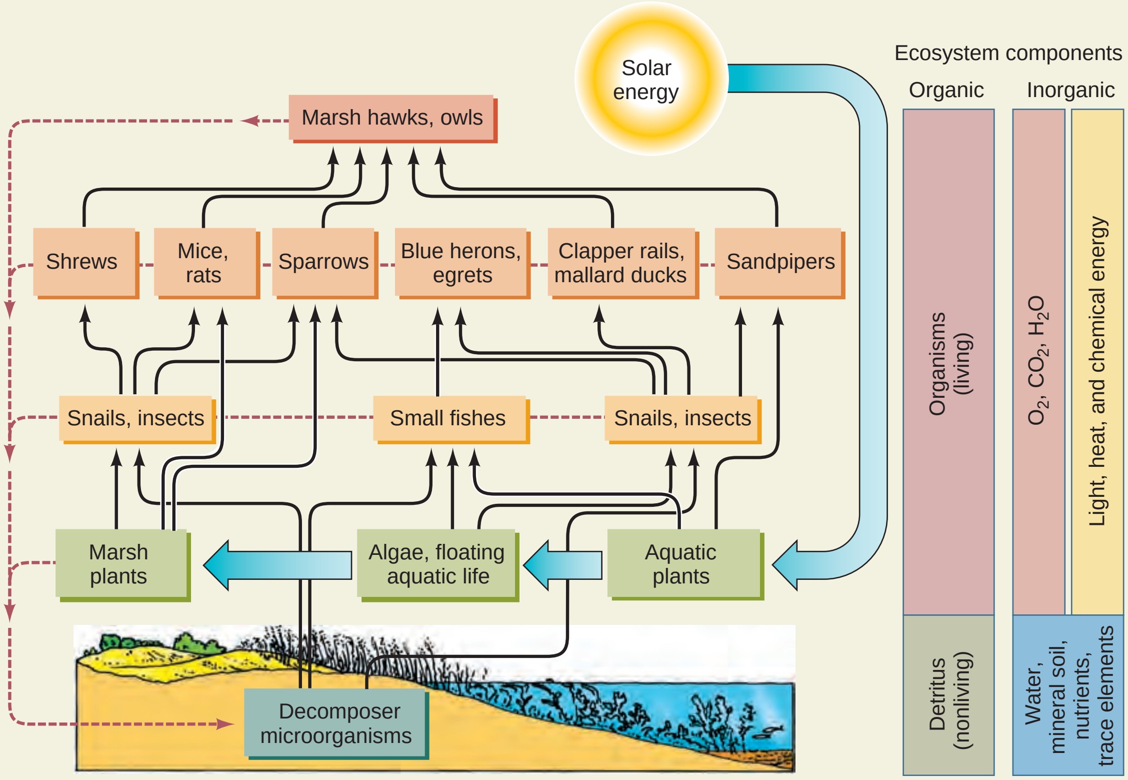
Decomposers Microscopic organisms and bacteria feed on detritus, or decaying organic matter, from all levels of the web.

Primary producers The plants and algae in the food web are the primary producers. They use light energy to convert carbon dioxide and water into carbohydrates. These organisms, engaged in photosynthesis, form the base of the food web.

Primary consumers The lowest level of consumers are the primary consumers (the snails, insects and fishes).

Secondary consumers At the next level are the secondary consumers (the mammals, birds, and larger fishes), which feed on the primary consumers.

Higher level consumers Still higher levels of feeding occur in the salt-marsh ecosystem as marsh hawks and owls consume the smaller animals below them in the food web. In most ecosystems there are about four levels of consumers.



▲ A salt marsh is a good example of an ecosystem. It contains a variety of organisms—algae and aquatic plants, microorganisms, insects, snails, and crayfish, fishes, birds, shrews, mice, and rats. There are also inorganic components—water, air, clay particles and organic sediment, inorganic nutrients, trace elements, and light energy.

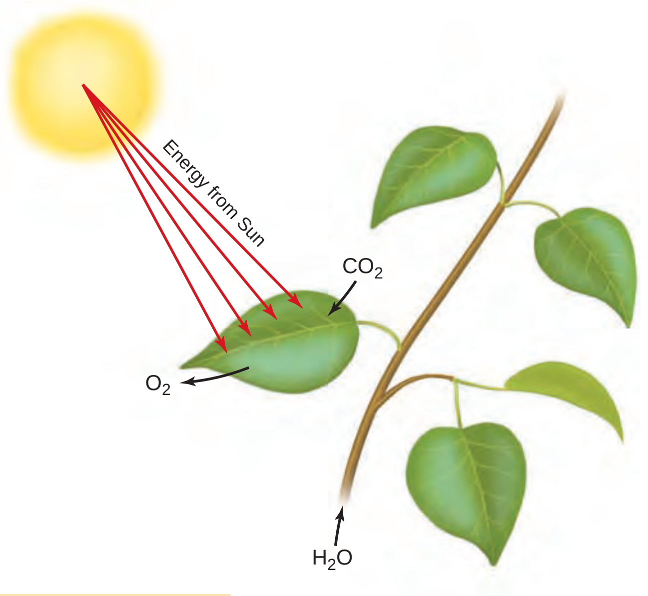
living tissue must decrease greatly up the food chain. In general, only 10 to 50 percent of the energy stored in organic matter at one level can be passed up the chain to the next level. Normally, there are about four levels of consumers.

The number of individuals of any species present in an ecosystem depends on the resources available to support them. If these resources provide a steady supply of energy, the population size will normally stay steady. But resources can vary with time, for example, in an annual cycle. In those cases, the population size of a species depending on these resources may fluctuate in a corresponding cycle.

PHOTOSYNTHESIS AND RESPIRATION

Simply put, photosynthesis is the production of carbohydrate (Figure 8.4). Carbohydrate is a general term for a class of organic compounds that are made from the elements carbon, hydrogen, and oxygen. Carbohydrate molecules are composed of short chains of carbon bonded to one another. Hydrogen (H) atoms and hydroxyl (OH) molecules are also attached to the carbon atoms. We can symbolize a single carbon atom with its attached hydrogen atom and hydroxyl molecule as –CHOH–. The leading and trailing dashes indicate that the unit is just one portion of a longer chain of connected carbon atoms.

Photosynthesis is the process in which plants combine water, carbon dioxide, and solar energy to form carbohydrate. Respiration is the reverse process, in which carbohydrate is oxidized in living tissues to yield the energy that sustains life.



8.4 Photosynthesis

Leaves take in CO_2 from the air and H_2O from their roots, using solar energy absorbed by chlorophyll to combine them, forming carbohydrate. In the process, O_2 is released. Photosynthesis takes place in chloroplasts—tiny grains in plant cells that have layers of chlorophyll, enzymes, and other molecules in close contact.

Photosynthesis of carbohydrate requires a series of complex biochemical reactions using water (H_2O) and carbon dioxide (CO_2) as well as light energy. This process requires *chlorophyll*, a complex organic molecule that absorbs light energy for use by the plant cell. A simplified chemical reaction for photosynthesis can be written as:

$$H_2O + CO_2 + \text{light energy} \rightarrow \text{–CHOH–} + O_2$$

Oxygen gas molecules (O_2) are a by-product of photosynthesis. Because gaseous carbon as CO_2 is "fixed" to a solid form in carbohydrate, we also call photosynthesis a *carbon fixation* process.

Respiration is the opposite of photosynthesis. In this process, carbohydrate is broken down and combines with oxygen to yield carbon dioxide and water. The overall reaction is:

$$\text{–CHOH–} + O_2 \rightarrow CO_2 + H_2O + \text{chemical energy}$$

As with photosynthesis, the actual reactions involved are not this simple. The chemical energy released is stored in several types of energy-carrying molecules in living cells and used later to synthesize all the biological molecules used to sustain life.

We have to take respiration into account when talking about the amount of new carbohydrate placed in storage. *Gross photosynthesis* is the total amount of carbohydrate produced by photosynthesis. *Net photosynthesis* is the amount of synthesized carbohydrate remaining after respiration has broken down sufficient carbohydrate to power the plant:

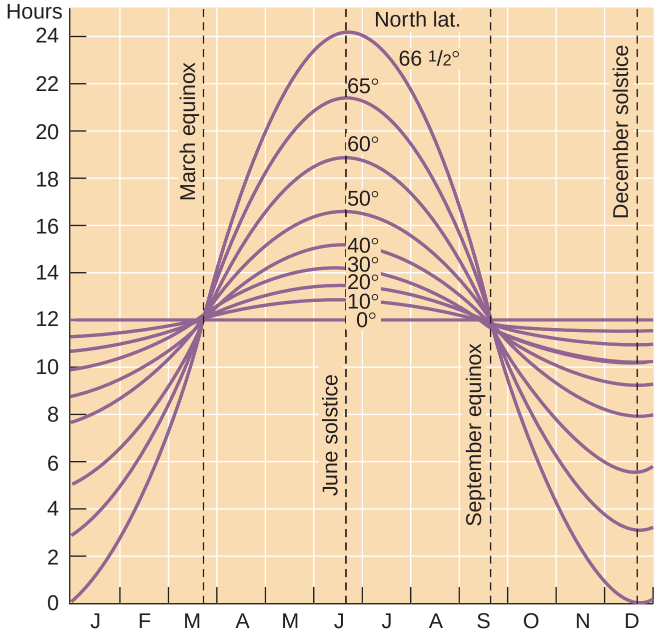
$$\text{Net photosynthesis} = \text{Gross photosynthesis} - \text{Respiration}$$

The rate of net photosynthesis depends on the intensity of light energy available, up to a limit. Most green plants only need about 10 to 30 percent of full summer sunlight for maximum net photosynthesis. Once the intensity of light is high enough for maximum net photosynthesis, the duration of daylight becomes an important factor in determining the rate at which the products of photosynthesis build up in plant tissues (Figure 8.5). The rate of photosynthesis also increases as air temperature increases, up to a limit (Figure 8.6).

Day length, air and soil temperature, and water availability are the most important climatic factors that control net primary productivity.

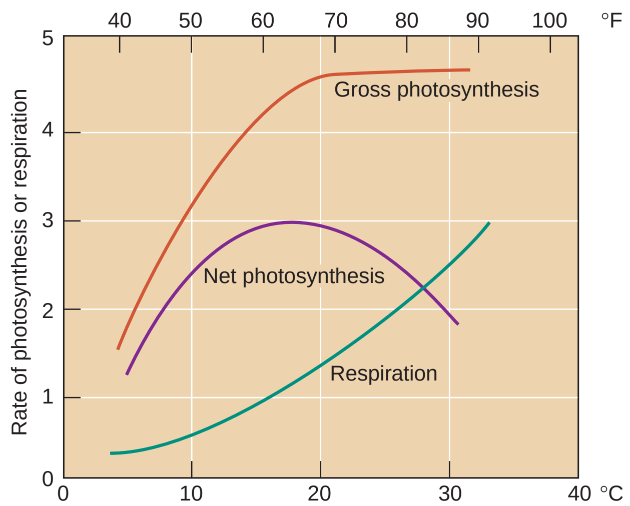
NET PRIMARY PRODUCTION

Plant ecologists measure the accumulated net production by photosynthesis in terms of **biomass**, which is



8.5 Day-length variation

The graph shows the duration of the daylight period at various latitudes in the northern hemisphere throughout the year. The angle of the Sun's rays also changes with latitude and the seasons. The vertical scale gives the number of hours the Sun is above the horizon, with changing seasons. At low latitudes, days are not far from the average 12-hour length throughout the year. At high latitudes, days are short in winter but long in summer. In subarctic latitudes, photosynthesis can go on in summer during most of the 24-hour day, compensating for the short growing season.



8.6 Temperature and energy flow

The figure shows the results of a laboratory experiment in which sphagnum moss was grown under constant illumination but increasing temperature. Gross photosynthesis increased rapidly to a maximum at about 20°C (68°F), then leveled off. But net photosynthesis—the difference between gross photosynthesis and respiration—peaked at about 18°C (64°F), then fell off rapidly because respiration continued to increase with temperature.

the dry weight of organic matter. This quantity could, of course, be stated for a single plant or animal, but a more useful measurement is the biomass per unit of surface area within the ecosystem—that is, grams of biomass per square meter or (metric) tons of biomass per hectare (1 hectare = 10^4 m^2). Of all ecosystems, forests have the greatest biomass because of the large amount of wood that the trees accumulate through time. The biomass of grasslands and croplands is much smaller in comparison. The biomass of freshwater bodies and the oceans is about one-hundredth that of the grasslands and croplands.

> **Net primary production measures the rate of accumulation of carbohydrate by primary producers. Equatorial rainforests and freshwater swamps and marshes are among the most productive ecosystems, while deserts are least productive.**

The amount of biomass per unit area tells us about the amount of photosynthetic activity, but it can be misleading. In some ecosystems, biomass is broken down very quickly by consumers and decomposers. So if we want to know how productive the ecosystem is, it's better to work out the annual yield of useful energy produced by the ecosystem, or the *net primary production*. Net primary production represents a source of renewable energy derived from the Sun that can be exploited to fill human energy needs. The use of biomass as an energy source involves releasing solar energy that has been fixed in plant tissues through photosynthesis. It can take place in a number of ways—by burning wood for fires, for example.

Figure 8.7 shows the net primary production of various ecosystems in units of grams of dry organic matter produced annually from one square meter of surface. The highest values are in two quite unlike environments: forests and wetlands (swamps, marshes, and estuaries). Agricultural land compares favorably with grassland, but the range is very large in agricultural land, reflecting many factors such as availability of soil water, soil fertility, and use of fertilizers and machinery.

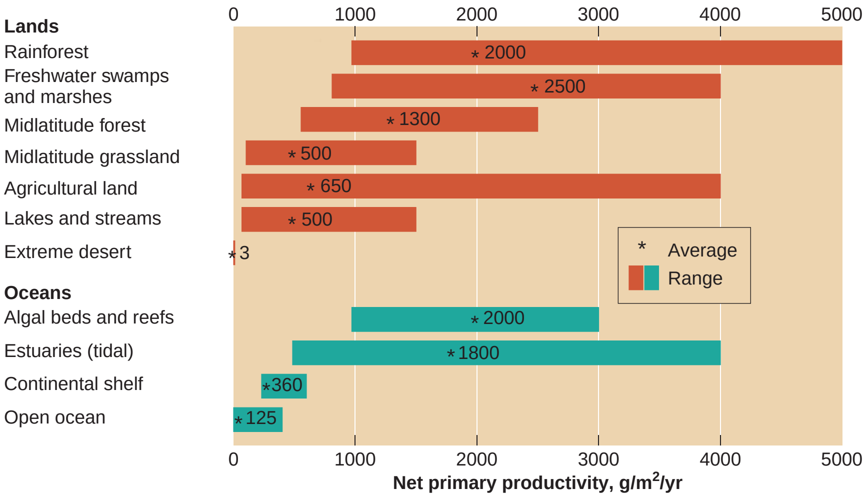
Open oceans aren't generally very productive. Continental shelf areas are better, supporting much of the world's fishing industry (Figure 8.8). Upwelling zones are also highly productive.

GEODISCOVERIES **Remote Sensing and Biosphere Interactivity**

Explore satellite images from local to global scales to examine land and ocean productivity. Identify ocean algae blooms.

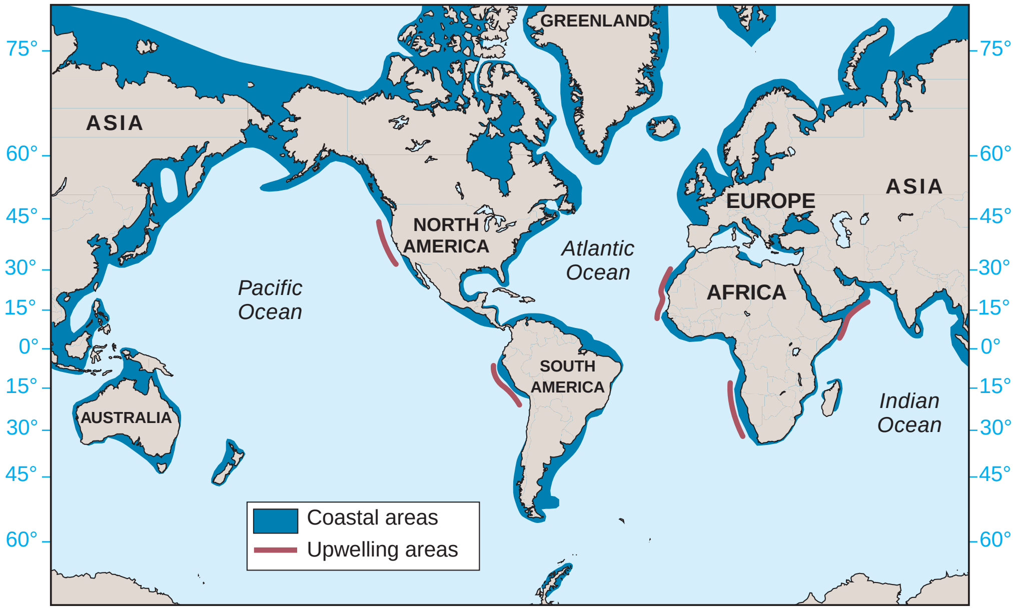
THE CARBON CYCLE

We've seen how energy from the Sun flows through ecosystems, passing from one part of the food chain to the next. Ultimately, that energy is radiated to space and lost



8.7 Net primary production of ecosystems

Freshwater swamps and marshes are most productive on land, and algal beds and reefs are most productive in the ocean.



8.8 Distribution of world fisheries

Coastal areas and upwelling areas together supply over 99 percent of world production.

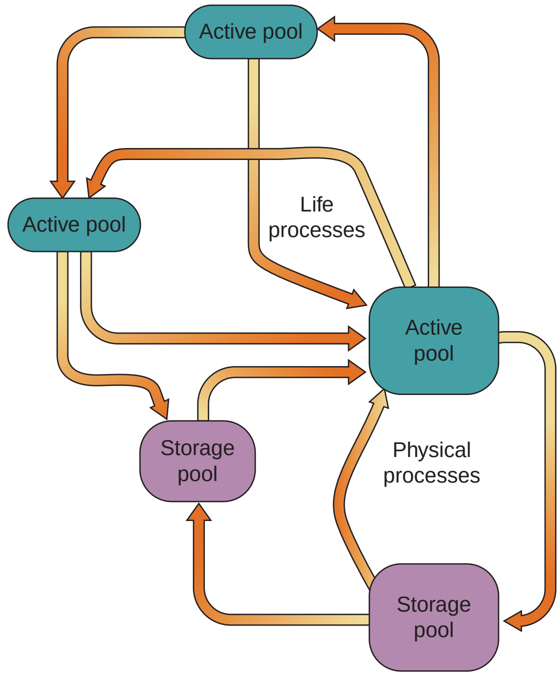
from the biosphere. Matter also moves through ecosystems, but because gravity keeps surface material earthbound, matter can't be lost in the global ecosystem. As molecules are formed and re-formed by chemical and biochemical reactions within an ecosystem, the atoms that compose them are not changed or lost. In this way, matter is conserved, and atoms and molecules are used and reused, or cycled, within ecosystems.

Atoms and molecules move through ecosystems under the influence of both physical and biological processes. We call the pathways that a particular type of matter takes through the Earth's ecosystem a **biogeochemical cycle** (sometimes referred to as a *material cycle* or *nutrient cycle*).

The major features of a biogeochemical cycle are diagrammed in Figure 8.9. Any area or location of concentration of a material is a **pool**. There are two types of pools: *active pools*, where materials are in forms and places easily accessible to life processes, and *storage pools*, where materials are more or less inaccessible to life.

A system of pathways of material flows connects the various active and storage pools within the cycle. Pathways can involve the movement of material in all three states of matter—gas, liquid, and solid. For example, carbon moves freely in the

The carbon cycle is a biogeochemical cycle in which carbon flows among storage pools in the atmosphere, ocean, and on the land. Human activity has affected the carbon cycle, causing carbon dioxide concentrations in the atmospheric storage pool to increase.



8.9 General features of a biogeochemical cycle

atmosphere as carbon dioxide gas and freely in water as dissolved CO_2 and as carbonate ion ($CO_3^{=}$). It also takes the form of a solid in deposits of limestone and dolomite (calcium and magnesium carbonate).

Ecologists have studied and documented biogeochemical cycles for many elements, including carbon, oxygen, nitrogen, sulfur, and phosphorus. Of these, the **carbon cycle** is probably the most important. That's because all life is composed of carbon compounds of one form or another and human activities are modifying the carbon cycle in significant ways.

Figure 8.10 looks at this process in more detail. Atmospheric carbon dioxide makes up less than 2 percent of all the carbon. The atmospheric pool is supplied by plant and animal respiration in the oceans and on the lands, by outgassing volcanoes, and by fossil fuel combustion in industry and power generation. The atmosphere loses carbon to oceanic and terrestrial photosynthesis.

As noted earlier in this chapter, humans are affecting the carbon cycle by burning fossil fuels. CO_2 is being released to the atmosphere at a rate far beyond that of any natural process, causing global warming. Another important human impact lies in changing the Earth's land covers—for example, in clearing forests or abandoning agricultural areas, or in letting agricultural areas grow back to forests or rangelands.

THE NITROGEN CYCLE

The *nitrogen cycle* is another important biogeochemical cycle. Nitrogen makes up 78 percent of the atmosphere by volume, so the atmosphere is a vast storage pool in this cycle. Figure 8.11 diagrams the nitrogen cycle.

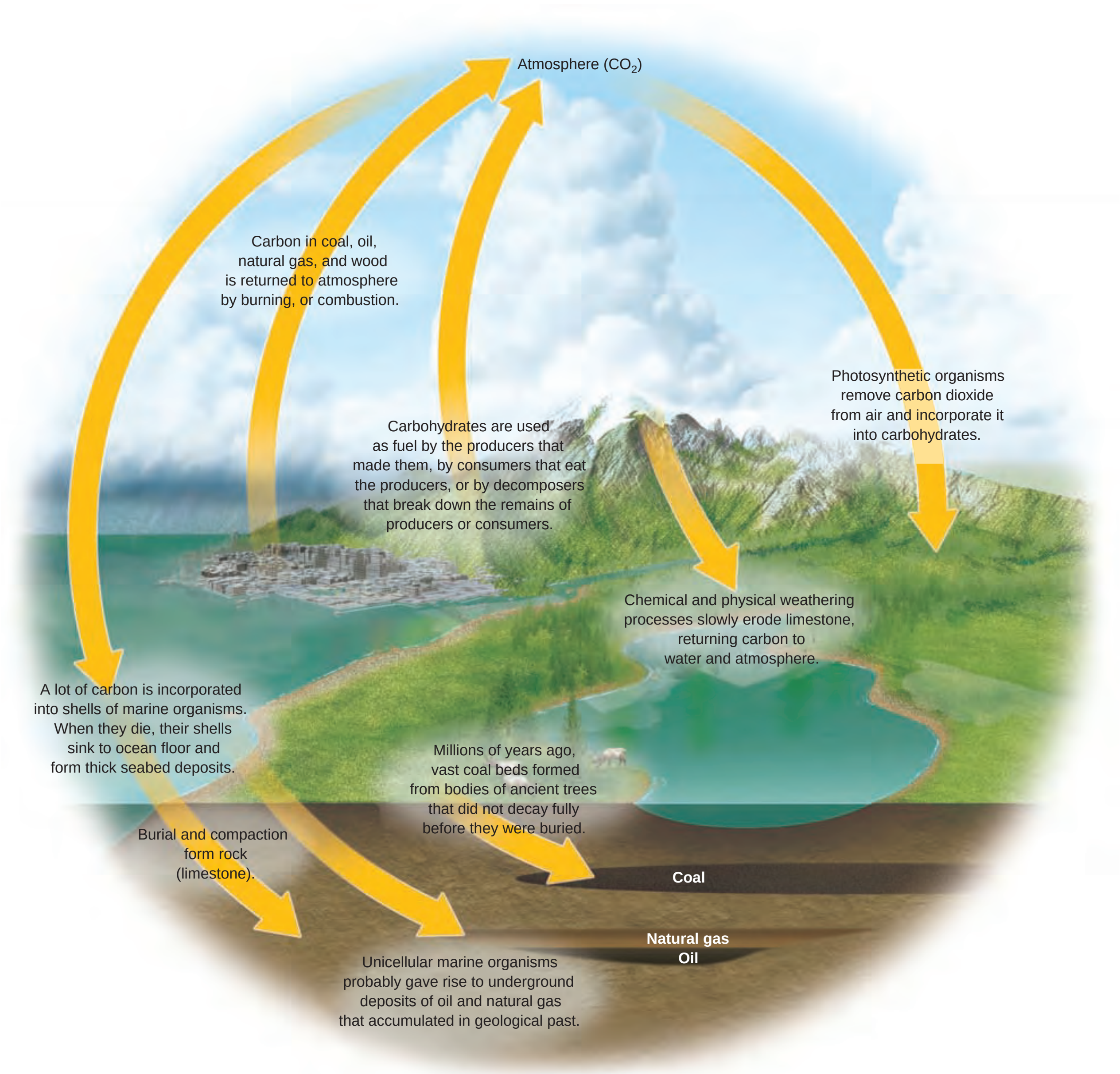
Nitrogen as N_2 in the atmosphere can't be assimilated directly by plants or animals. But certain microorganisms, including some soil bacteria and blue-green algae, can change N_2 into useful forms in a process called *nitrogen fixation*. Legumes—such as clover, alfalfa, soybeans, peas, beans, and peanuts—are also able to fix nitrogen, with help from bacteria. They have a symbiotic relationship with bacteria of the genus *Rhizobium*, which is associated with some 190 species of trees and shrubs. The bacteria infect these plants' root cells and supply nitrogen to the plant through nitrogen fixation, while the plants supply nutrients and organic compounds needed by the bacteria. Crops of legumes are often planted in seasonal rotation with other food crops to ensure an adequate nitrogen supply in the soil. Other soil bacteria convert nitrogen from usable forms back to N_2, in a process called *denitrification* that returns the nitrogen to the atmosphere. Other processes shown in the figure are ammonification, nitrification, and assimilation.

At the present time, nitrogen fixation far exceeds denitrification, thanks to human activity. We fix nitrogen in the manufacture of nitrogen fertilizers; by oxidizing nitrogen in the combustion of fossil fuels; and through the widespread cultivation of legumes. At present rates, nitrogen fixation from human activity nearly equals all natural biological fixation, and usable nitrogen is accumulating in the Earth's ecosystems.

Much of this newly fixed nitrogen is carried from the soil into rivers and lakes and ultimately to the ocean, causing water pollution. The nitrogen stimulates the growth of algae and phytoplankton, which in turn reduce quantities of dissolved oxygen through respiration. Oxygen then drops to levels that are too low for many desirable forms of aquatic life. These problems will be accentuated in years to come because industrial fixation of nitrogen in fertilizer manufacture is doubling about every six years at present. The global impact of such large amounts of nitrogen reaching rivers, lakes, and oceans on the Earth's global ecosystem remains uncertain.

Ecological Biogeography

We've seen how energy and matter move through ecosystems. But if we want to fully understand ecosystems, we'll also need to look at *ecological biogeography*, which examines the distribution patterns of plants and animals from the viewpoint of their physiological needs. That is, we must examine how the individual organisms of an ecosystem interact with their environment. From fungi digesting organic matter on a forest floor to ospreys fishing in a coastal estuary, each organism has a range of environmental conditions that limits its survival as



8.10 The carbon cycle

Carbon moves through the cycle as a gas, as a liquid, and as a solid. In the gaseous portion of the cycle, carbon moves largely as carbon dioxide (CO_2), which is a free gas in the atmosphere and a dissolved gas in fresh and saltwater. In the sedimentary portion of its cycle, we find carbon in carbohydrate molecules in organic matter, as hydrocarbon compounds in rock (petroleum, coal), and as mineral carbonate compounds such as calcium carbonate ($CaCO_3$).

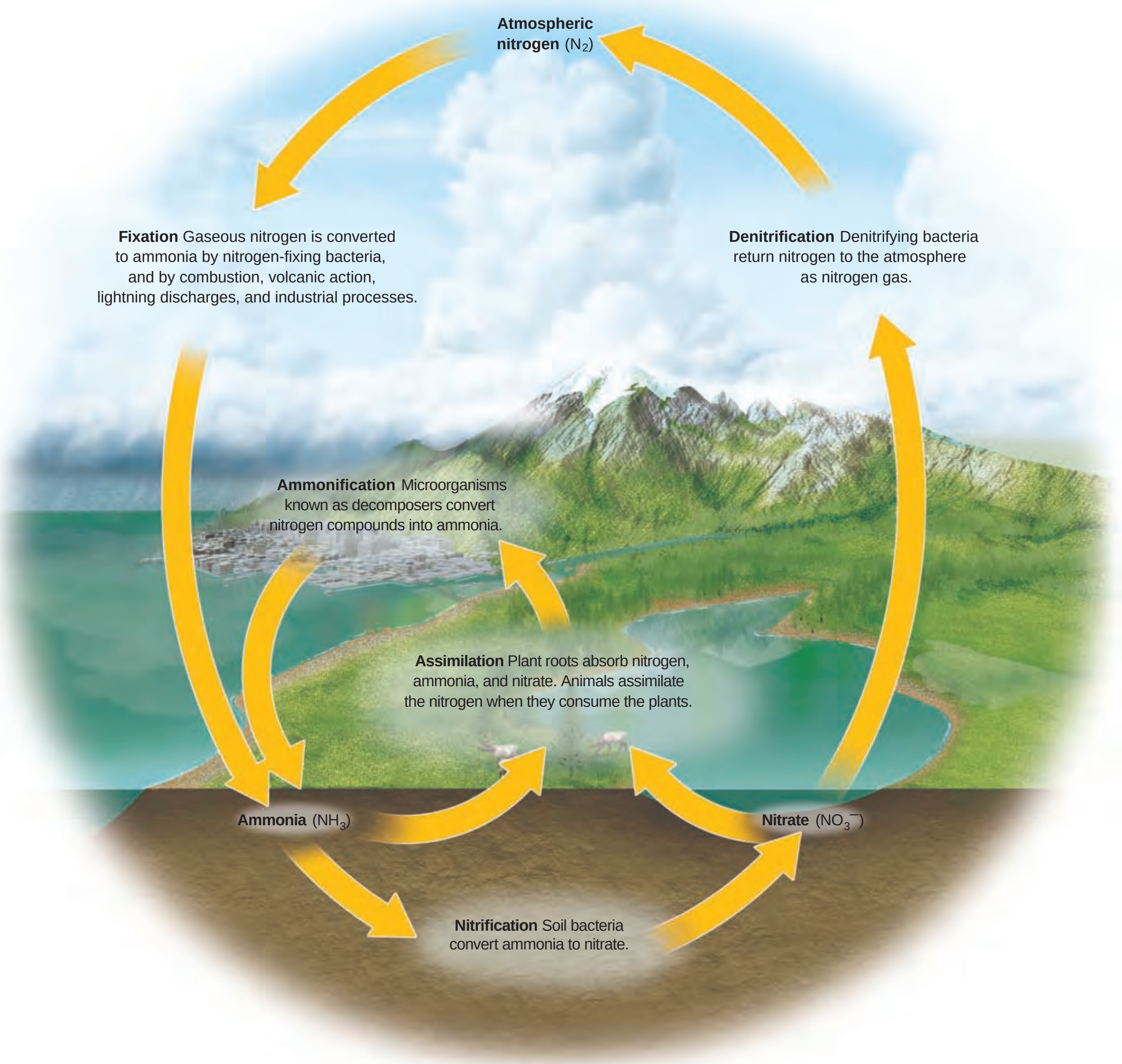
well as a set of characteristic adaptations that it exploits to obtain the energy it needs to live.

Let's start by looking at the relationship between organisms and their physical environment. Figure 8.12 shows how living conditions can change across the Canadian boreal forest such that different regions support different ecosystems. In this way, we can distinguish six distinct **habitats** across the Canadian boreal forest: upland, bog, bottomland, ridge, cliff, and active sand dune.

The habitat of a species describes the physical environment that harbors its activities. The ecological niche describes how it obtains its energy and how it influences other species and its own environment.

We use the term *ecological niche* to describe the functional role played by an organism as well as the physical space it inhabits. If the habitat is the individual's "address," then the niche is its "profession," including how and where it obtains its energy and how it influences other species and the environment around it.

When describing the ecological niche, we talk about the organism's tolerances and responses to changes in



8.11 The nitrogen cycle

The five processes of the nitrogen cycle are nitrogen fixation, nitrification, assimilation, ammonification, and denitrification.

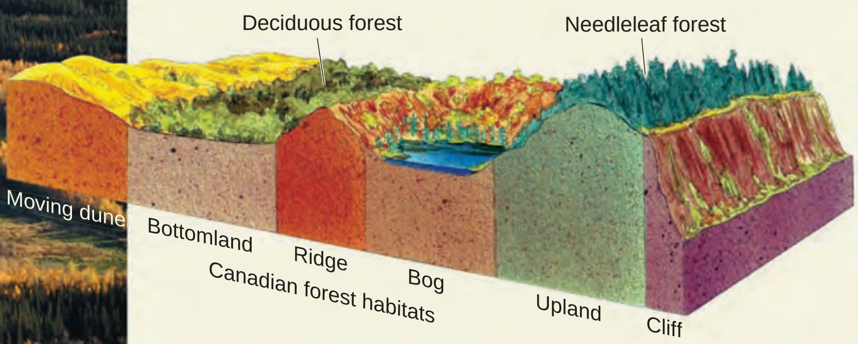
moisture, temperature, soil chemistry, illumination, and other factors. Although many different species may occupy the same habitat, only a few of these species will ever share the same ecological niche, for, as we'll see shortly, evolution will tend to separate those that do.

As we move from habitat to habitat, we find that each is the home of a group of organisms that occupy different but interrelated ecological niches. We can define a *community* as an assemblage of organisms that live in a particular habitat and interact with one another. Although every organism must adjust to variations in the environment on its own, we find that similar habitats often contain similar communities. Biogeographers and ecologists recognize specific types of communities, called *associations*, in which typical organisms are likely to be found together. These associations are usually defined by species, as in the beech-birch-maple forest that is found from the Great Lakes region to New England in suitable habitats.

WATER NEED

Let's now turn to the environmental factors that help determine where organisms, as individuals and

8.12 Habitats of the Canadian boreal forest



▲ Habitats of the Canadian boreal forest are quite varied and include moving dune, bottomland, ridge, bog, upland, and cliff.

◀ This aerial view of the Mackenzie River shows some of the boreal forest habitats shown above. Deciduous forest, about to shed its leaves in the fall, occupies moist bottomland habitats, while spruce and fir occupy the uplands. Swamps and bogs show low grasses and sedges, which are still green (National Geographic Image Collection).

species, are found. The first of these is the availability of water.

Plants and animals have adapted to cope with the abundance or scarcity of water in a variety of ways (Figure 8.13). Plants that are adapted to drought conditions are called **xerophytes**. ("Xerophyte" comes from the Greek roots xero-, meaning "dry," and phyton, meaning "plant.")

Xerophytes are plants that are adapted to a dry and sometimes hot environment. Examples are phreatophytes, which have deep roots, and succulents, which store water internally in spongy tissues.

Some xerophytes have a thick layer of wax or waxlike material on leaves and stems, helping them to seal water inside. Others adapt to a desert environment by greatly reducing their leaf area or by bearing no leaves at all. Needlelike leaves, or spines in place of leaves, also conserve water.

Plants in water-scarce environments are also better at obtaining and storing water. For example, their roots may extend deeply to reach soil moisture far from the surface until they reach ground water. Plants drawing from ground water are called *phreatophytes*. Other desert plants produce a widespread, but shallow, root system, so they can absorb water from short desert downpours that saturate only the uppermost soil layer. Leaves and stems of desert plants known as *succulents* are often thickened by a spongy tissue that stores water. The common prickly pear cactus is an example (Figure 8.13).

Many small desert plants have a very short life cycle—germinating from seed, leafing out, bearing flowers, and producing seed in the few weeks immediately following a heavy rain shower. They survive the dry period as dormant seeds that require no moisture.

Certain climates, such as the wet-dry tropical climate ③, have a yearly cycle with one season in which water is unavailable to plants because of lack of precipitation. In these climates, some species of trees, termed *tropophytes*, are deciduous, shedding their leaves at the onset of the dry season and growing new ones with the arrival of the wet season. The Mediterranean climate ⑦ also has a strong seasonal wet-dry alternation, with dry summers and wet winters. Plants in this climate often have hard, thick, leathery, evergreen leaves and are referred to as *sclerophylls* (Figure 8.13).

8.13 Organisms adapted to water scarcity

▼ The prickly pear cactus (*Opuntia*), a desert succulent, retains water in its thick, fleshy stems (cactus pads) for use during long periods without rainfall. San Pedro Valley, Arizona (National Geographic Image Collection).

▲ This California live oak holds most of its tough, waxy leaves through the dry season. Such hard-leaved evergreen trees and woody shrubs are called sclerophylls.

▶ The namaqua chameleon lives in the Kalahari Desert of southern Africa. It changes its skin color to regulate its body temperature, turning black in the morning to absorb solar rays and light gray during the day to reflect them.

Xeric animals have evolved methods that are somewhat similar to those used by the plants. Many of the invertebrates stay dormant during the dry period. When rain falls, they emerge to take advantage of the new and short-lived vegetation that often results. Many species of birds only nest when the rains occur, the time of most abundant food for their offspring. The tiny brine shrimp of the Great Basin may wait many years in dormancy until normally dry lakebeds fill with water, an event that occurs perhaps three or four times a century. The shrimp then emerge and complete their life cycles before the lake evaporates. Other animals have evolved more unique adaptations, such as changing their body color to absorb or reflect solar energy, depending on their internal temperature (Figure 8.13).

Mammals are by nature poorly adapted to desert environments, but many survive through a variety of mechanisms that enable them to avoid water loss. Just as plants reduce transpiration to conserve water, many desert mammals do not sweat through skin glands. Instead they rely on other methods of cooling, such as avoiding the Sun and becoming active only at night. In this respect, they are joined by most of the rest of the desert fauna, which spend their days in cool burrows in the soil and their nights foraging for food.

TEMPERATURE

Temperature affects physiological processes occurring in plant and animal tissues. In general, colder climates have fewer plant and animal species.

The temperature of the air and soil directly influences the rates of physiological processes in plant and animal tissues. In general, each plant species has an optimum temperature associated with each of its functions, such as photosynthesis, flowering, fruiting, or seed germination. There are limiting lower and upper temperatures for these individual functions as well and for the total survival of the plant itself.

Temperature can also act indirectly on plants and animals. Higher air temperatures reduce the relative humidity of the air, enhancing transpiration from plant leaves as well as increasing direct evaporation of soil water.

In general, the colder the climate, the fewer the species capable of surviving. We only find a few plants and animals in the severely cold arctic and alpine environments of high latitudes and high altitudes. In plants, ice crystals can grow inside cells in freezing weather, disrupting cellular structures. Cold-tolerant plant species are able to expel excess water from cells to spaces between cells, where freezing does no damage.

Most animals can't regulate their temperature internally. These animals, including reptiles, invertebrates, fish, and amphibians, are *cold-blooded animals*—their body temperature passively follows the environment. With a few exceptions (notably fish and some social insects), these animals are active only during the warmer parts of the year. They survive the cold weather of the midlatitude zone winter by becoming dormant.

Some vertebrates enter a state called *hibernation*, in which their metabolic processes virtually stop and their body temperatures closely parallel those of the surroundings (Figure 8.14). Most hibernators seek out burrows, nests, or other environments where winter temperatures do not reach extremes or fluctuate rapidly. Soil burrows are particularly suited to hibernation because below the uppermost layers, soil temperatures don't vary a great deal.

Warm-blooded animals, like us, maintain tissues at a constant temperature by internal metabolism. This group includes the birds and mammals. Fur, hair, and feathers insulate the animals by trapping dead air spaces next to the skin surface. A thick layer of fat will also provide excellent insulation (Figure 8.14). Other adaptations are for cooling—for example, sweating or panting uses the high latent heat of vaporization of water to remove heat. The seal's flippers and bird's feet expose blood-circulating tissues to the cooler surroundings, promoting heat loss (Figure 8.14).

OTHER CLIMATIC FACTORS

Light also helps determine local plant distribution patterns. Some plants are adapted to bright sunlight, whereas others require shade (Figure 8.15). The amount of light available to a plant will depend in large part on the plant's position. Tree crowns in the upper layer of a forest receive maximum light but correspondingly reduce the amount available to lower layers. In extreme

8.14 Temperature adaptations

▼ These little brown bats are hibernating together in a cluster. Their body temperature falls, and their heartbeat slows. They can survive for almost half the year in this state.

▲ A heavy coat and a thick layer of body fat insulate this Alaskan brown bear, allowing the mammal to maintain a constant body temperature.

▶ Feet and flippers can assist in cooling by exposing the circulating blood supply to cooler surroundings. Here a seal relaxes in a shallow ocean pool in the Galápagos Islands (National Geographic Image Collection).

8.15 Sun-loving and shade-loving plants

California poppies and desert dandelions thrive in bright sun (left). In contrast, cow parsnip prefers the deep shade in Mount Hood National Forest, Oregon (right) (National Geographic Image Collection).

cases, forest trees so effectively cut off light that the forest floor is almost free of shrubs and smaller plants.

In certain deciduous forests of midlatitudes, the period of early spring, before the trees are in leaf, is one of high light intensity at ground level, permitting the smaller plants to go through a rapid growth cycle. In summer these plants largely disappear as the tree leaf canopy is completed. Other low plants in the same habitat require shade and do not appear until the leaf canopy is well developed.

The light available for plant growth varies by latitude and season. As we saw earlier, the number of daylight hours in summer increases rapidly with higher latitude and reaches its maximum poleward of the Arctic and Antarctic Circles, where the Sun may be above the horizon for 24 hours. The rate of plant growth in the short frost-free summer is greatly accelerated by the prolonged daylight.

In addition to temperature and moisture, ecological factors of light intensity, length of the daylight period, length of the growing season, and wind duration and intensity act to influence plant and animal distribution patterns.

In midlatitudes, where many species are deciduous, the annual rhythm of increasing and decreasing periods of daylight determines the timing of budding, flowering, fruiting, and leaf shedding. Even on overcast days there is usually enough light for most plants to carry out photosynthesis at their maximum rates.

Light also influences animal behavior. The day–night cycle controls the activity patterns of many animals. Birds, for example, are generally active during the day, whereas small foraging mammals, such as weasels, skunks, and chipmunks, are more active at night. In midlatitudes, as autumn days grow shorter and shorter, squirrels and other rodents hoard food for the coming winter season. Later, increasing hours of daylight in the spring trigger such activities as mating and reproduction.

Wind is also an important environmental factor in the structure of vegetation in highly exposed positions. Wind causes excessive drying, desiccating the exposed side of the plant and killing its leaves and shoots. Trees of high-mountain summits are often distorted in shape, with trunks and branches bent to near-horizontal, facing away from the prevailing wind direction.

Taken separately or together, moisture, temperature, light, and wind can limit the distribution of plant and animal species. Biogeographers recognize that there is a critical level of climatic stress beyond which a species cannot survive. This means that we can mark out a *bioclimatic frontier*—a geographic boundary showing the limits of the potential distribution of a species.

GEOMORPHIC FACTORS

Geomorphic, or landform, factors such as slope steepness, slope aspect (the orientation of a sloping ground surface with respect to geographic north), and relief (the difference in elevation of divides and adjacent valley bottoms) help differentiate habitats for ecosystems.

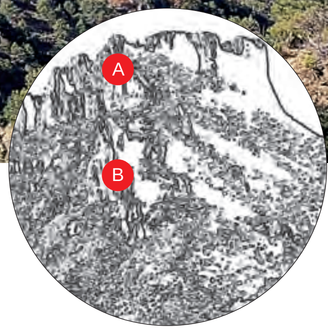
Slope steepness affects the rate at which precipitation drains from a surface, which indirectly influences plants and animals. On steep slopes, surface runoff is rapid, but on gentle slopes, more precipitation penetrates into the soil, providing a moister habitat. Steep slopes often have thin soil because they are more easily eroded, while soil on gentler slopes is thicker. Slope aspect controls plants' exposure to sunlight and prevailing winds. Slopes facing the Sun have a warmer, drier environment than slopes that face away from the Sun. In midlatitudes, these slope-aspect contrasts may be strong enough to produce quite different biotic communities on north-facing and south-facing slopes (Figure 8.16).

> **Geomorphic (landform) factors influencing plant and animal distributions include slope angle, slope aspect, and relief. Edaphic (soil) factors include soil particle size and the amount and nature of organic matter in the soil.**

On divides, peaks, and ridge crests, rapid drainage dries the soil, which is also more exposed to sunlight and drying winds. By contrast, the valley floors are wetter because water converges there. In humid climates, the ground water table in valley floors may lie close to or at the ground surface, producing marshes, swamps, ponds, and bogs.

EDAPHIC FACTORS

Soils can vary widely from one small area to the next, influencing the local distribution of plants and animals. *Edaphic factors* are connected to the soil. For example, sandy soils store less water than soils with abundant silt and clay, so they are often home to xerophytes. If there's a high amount of organic matter in the soil, then the soil will be rich in nutrients and will harbor more plant species. The relationship can work in the opposite direction, too—biota can change soil conditions, as when a prairie grassland builds a rich, fertile soil beneath it.



8.16 Slope orientation and habitat

In this scene from the Chisos Mountains of Big Bend National Park, dry south-facing slopes on the left support a community of low, xerophytic shrubs, while moister north-facing slopes on the right support an open forest cover of piñon pine and juniper.

EYE ON THE LANDSCAPE **What else would the geographer see?** The vertical faces of these cliffs (A) and pinnacles (B) are most likely joint planes—planes of fractures in the rock resulting from cooling or from release of the pressure of overlying rock removed by erosion. Joints are discussed in Chapter 13.

DISTURBANCE

Disturbance includes fire, flood, volcanic eruption, storm waves, high winds, and other infrequent catastrophic events that damage or destroy ecosystems and modify habitats. Although disturbance can greatly alter the nature of an ecosystem, it is often part of a natural cycle of regeneration that gives short-lived or specialized species the opportunity to grow and reproduce.

For example, fire will strike most forests sooner or later (Figure 8.17). In many cases, the fire is beneficial. It cleans out the understory and consumes dead and decaying organic matter while leaving most of the overstory trees untouched. Fire helps expose mineral soil on the forest floor and fertilizes it with new ash, providing a productive environment for dormant seeds. In addition, shrubs and forbs no longer shade the soil from sunlight. Among tree species, pines are typically well adapted to germinating under such conditions. In fact, the jack pine of eastern North America and the lodgepole pine of the intermountain West have cones that remain tightly closed until the heat of a fire opens them, allowing the seeds to be released.

Disturbance by factors such as fire, flooding, or high winds is a natural process to which many ecosystems are adapted. In semiarid regions, fires act to maintain grasslands and open forests.

Fires also preserve grasslands. Grasses are fire-resistant because they have extensive root systems below ground and germinal buds located at or just below the surface. But woody plants that might otherwise invade grassland areas are not so resistant and are usually killed by grass fires.

In many regions, active fire suppression has reduced the frequency of burning to well below natural levels. That may sound like a good thing, but in forests, this causes dead wood to build up on the forest floor. So, when a fire does start, it's destructive—burning hotter and more rapidly and consuming the crowns of many overstory trees.

Flooding is another important disturbance. It displaces animal communities and also deprives plant roots of oxygen. Where flooding brings a swift current, mechanical damage rips limbs from trees and scours out roots. High winds are another significant factor that can topple individual trees as well as whole forest stands (Figure 8.18).

INTERACTIONS AMONG SPECIES

Species don't react with just their physical surroundings. They also interact with each other. That interaction may benefit at least one of the species, be negative to one or both species, or have no effect on either species.

Competition is a negative interaction. It happens whenever two species need a common resource that is in short supply (Figure 8.19). Both populations suffer from lowered growth rates than they would have had if only one species were present. Sometimes one species will win the competition and crowd out its competitor. At other times, the two species may remain in competition indefinitely.

Competition is an unstable situation. If a genetic strain within one of the populations emerges that can use a substitute resource, its survival rate will be higher than that of the remaining strain, which still competes. The original strain may become extinct. In this way, evolutionary mechanisms tend to reduce competition among species.

8.17 Forest fire

Fire sweeps through a forest of pines. In some types of forests, frequent fires are beneficial to maintaining community habitats.

8.18 Tree throw

When strong winds blow down a healthy tree, the root mat lifts off the ground, leaving a pit. The lifted soil eventually falls back next to the pit to make a mound, which is a favored spot for the germination of young trees.

8.20 Predation

This South American giant anteater lives on termites.

Predation and *parasitism* are other negative interactions between species. Predation occurs when one species feeds on another (Figure 8.20). There are obvious benefits for the predator species, which obtains energy for survival, but, of course, the interaction has a negative outcome for the prey species. Parasitism occurs when one species gains nutrition from another, typically when the parasite organism invades or attaches to the body of the host in some way.

Although we tend to think that predation and parasitism are always negative—benefiting one species at the expense of the other—in some cases it works out well for the prey or host populations, too, in the long run. A classic example is the rise and fall of the deer herd on the Kaibab Plateau north of the Grand Canyon in Arizona (Figure 8.21). Predation and parasitism will also remove the weaker individuals, improving the attacked species' genetic composition.

Negative interactions among species include competition, predation, parasitism, herbivory, and allelopathy. Positive interactions include commensalism, protocooperation, and mutualism, which are three forms of symbiosis.

Another type of negative interaction between species is *herbivory*. When animals graze, they can reduce the viability of the plant species population. Although some plants can maintain themselves well in the face of grazing pressure, others are quite sensitive to overgrazing. *Allelopathy*, also a negative interaction, occurs when one plant species produces chemical toxins that inhibit other species.

We mentioned the symbiotic relationship between legumes and the nitrogen-fixing *Rhizobium* bacteria—which benefits both species—when we looked at the nitrogen cycle, earlier in the chapter. **Symbiosis** includes three types of positive interactions: commensalism, protocooperation, and mutualism. In *commensalism*, one of the species is benefited and the other is unaffected. Sometimes the relationship benefits both parties but isn't essential for their survival. This type of relationship is called *protocooperation*. If the relationship reaches a point where one or both species cannot survive alone, it's called *mutualism*. The relationship between the nitrogen-fixing bacterium *Rhizobium* and legumes is a classic example of mutualism because *Rhizobium* needs the plant for its own survival.

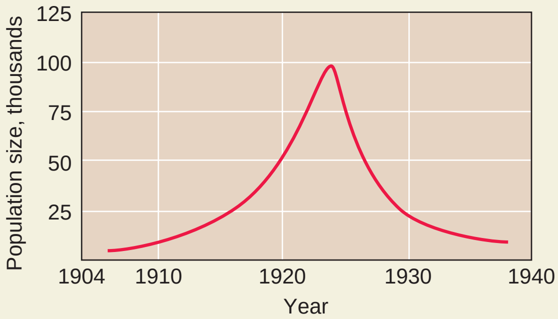
8.19 Competition

A pride of lions and a herd of elephants peaceably share a water hole in Chobe National Park, Botswana. Other animals must wait their turns (National Geographic Image Collection).

8.21 Rise and fall of the Kaibab deer herd

▼ This buck is a member of today's Kaibab deer herd, which is a population of mule deer. They are named for their large ears, which resemble a mule's, and are common throughout western North America.

▼ This graph plots the population size of the deer herd in the Kaibab National Forest, Arizona. The herd grew from about 4000 to nearly 100,000 between 1907 and 1924 when the government began controlling predatory wolves, coyotes, and mountain lions and protecting game. But confined in an area of 283,000 hectares (700,000 acres), the huge deer population proved too much for the land, and overgrazing led to a population crash. In one year, half the animals starved to death; by the late 1930s, the population had declined to a stable level near 10,000. Predation had maintained the deer population at levels that were in harmony with the supportive ability of the environment.



GEODISCOVERIES **Remote Sensing and Biosphere Interactivity**

See disturbance at work by analyzing satellite images of fires and deforestation from Los Alamos to Madagascar.

Ecological Succession

> **In ecological succession, an ecosystem proceeds through seral stages to reach a climax. Primary succession occurs on new soil, while secondary succession occurs where disturbance has removed or altered existing communities.**

Plant and animal communities change through time. Walk through the country and you'll see patches of vegetation in many stages of development—from open, cultivated fields through grassy shrublands to forests. Clear lakes gradually fill with sediment and become bogs. We call these changes—in which biotic communities succeed one another on the way to a stable end point—**ecological succession**.

In general, succession forms the most complex community of organisms possible, given its physical conditions of the area. The series of communities that follow one another is called a *sere*. Each of the temporary communities is referred to as a *seral stage*. The stable community, which is the end point of succession, is the *climax*. If succession begins on a newly constructed deposit of mineral sediment, it is called *primary succession*. If, on the other hand, succession occurs on a previously vegetated area that has been recently disturbed, perhaps by fire, flood, windstorm, or human activity, it is referred to as *secondary succession*.

Primary succession could happen on a sand dune, a sand beach, the surface of a new lava flow or freshly fallen layer of volcanic ash, or the deposits of silt on the inside of a river bend that is gradually shifting, for example. Such sites are often little more than deposits of coarse mineral fragments. In other cases—floodplain silt deposits, for example—the surface layer is made of redeposited soil, with substantial amounts of organic matter and nutrients.

Succession begins with the *pioneer stage*. It includes a few plant and animal pioneers that are unusually well adapted to otherwise inhospitable conditions that may be caused by rapid water drainage, dry soil, excessive sunlight exposure, wind, or extreme ground and lower air temperatures. As pioneer plants grow, their roots penetrate the soil. When the plants decay, their roots add organic matter directly to the soil, while their fallen leaves and stems add an organic layer to the ground surface. Large numbers of bacteria and invertebrates begin to live in the soil. Grazing mammals feed on the small plants and birds forage the newly vegetated area for seeds and grubs.

The pioneers soon transform conditions, making them favorable for other species that invade the area and displace the pioneers. The new arrivals may be larger plants with foliage that covers the ground more extensively. If this happens, the climate near the ground will have less extreme air and soil temperatures, higher humidity, and less intense insolation. These changes allow still other species to invade and thrive. When the succession has finally run its course, a climax community of plant and animal species in a more or less stable composition will have been established.

Sand dune colonization is a good example of primary succession (Figure 8.22). Animal species also change as succession proceeds. This is especially noticeable in the insects and invertebrates, which go from sand spiders and grasshoppers on the open dunes to sowbugs and earthworms in the dune forest.

Secondary succession can occur after a disturbance alters an existing community. *Old-field succession*, taking place on abandoned farmland, is a good example of secondary succession (Figure 8.24).

GEODISCOVERIES **Succession**
View this animation to see the sequence of successional changes that occur when a beaver dam turns a low valley in the boreal forest into a bog.

SUCCESSION, CHANGE, AND EQUILIBRIUM

So far, we've been describing successional changes caused by the actions of the plants and animals themselves. One set of inhabitants paves the way for the next. As long as nearby populations of species provide colonizers, the changes lead automatically from bare soil or fallow field to climax forest. This type is called *autogenic* (self-producing) *succession*.

But in many cases, autogenic succession does not run its full course. Environmental disturbances, such as wind, fire, flood, or clearing for agriculture interrupt succession temporarily or even permanently. For example, winds and waves can disturb autogenic succession on seaside dunes, or a mature forest may be destroyed by fire. In addition, inhospitable habitat conditions such as site exposure, unusual bedrock, or impeded drainage can hold back or divert the course of succession so successfully that the climax is never reached.

We can view the pattern of plant and animal communities on the landscape as a balance between succession, in which the community modifies its own habitat and composition, and environmental disturbance, such as wind, flood, fire, or logging.

Introducing a new species can also greatly alter existing ecosystems and successional pathways. The parasitic chestnut blight fungus was introduced from Asia to New York City in 1904. From there, it spread across the eastern states, decimating populations of the American chestnut tree within a period of about 40 years. This tree species, which may have accounted for as many as one-fourth of the mature trees in eastern forests, is now found only as small blighted stems sprouting from old root systems.

8.22 Dune succession

▼ In the earliest stages of succession on coastal dunes, beach grass colonizes the barren habitat. It propagates by underground stems that creep beneath the surface of the sand and send up shoots and leaves. Cape Cod, Massachusetts.

▼ Once the dunes are stabilized, low tough shrubs take over, paving the way for drought-resistant tree species, such as pines and hollies. This coastal dune forest is on Dauphin Island, Alabama.

FOCUS ON REMOTE SENSING

Remote Sensing of Fires

Wildfires occur frequently on the Earth's land surface, and biomass burning has important effects on both local and global ecosystems. Biomass burns inefficiently, releasing not only carbon dioxide and water, but also a number of other greenhouse gases that absorb outgoing longwave radiation and enhance the greenhouse effect. Aerosols are another by-product of inefficient combustion that can effect atmospheric processes. Burning mobilizes such nutrients as nitrogen, phosphorus, and sulfur in ash so that they become available for a new generation of plants, but it also carries them upward in smoke and as gases.

Fire affects ecosystems by changing species composition and creating a patchy structure of diversity on the landscape. It can also stimulate runoff and soil erosion where a significant layer of vegetation is lost to fire. For these reasons

8.23 Santa Barbara's Jesusita fire

▲ **MODIS views the fire** This MODIS image, acquired on May 8, 2009, shows the smoke plume from the Jesusita fire blowing southward, across the city of Santa Barbara and Channel Islands. The red outline delimits the area of active fire according to MODIS's thermal detectors. The large urban area in the right-center of the image is Los Angeles.

▲ **Jesusita fire from aircraft** Photographed just after sunrise, the fire covers the mountain slopes above Santa Barbara. Late afternoon "sundowner" winds, strong and hot, drove the fire into the city, burning many homes.

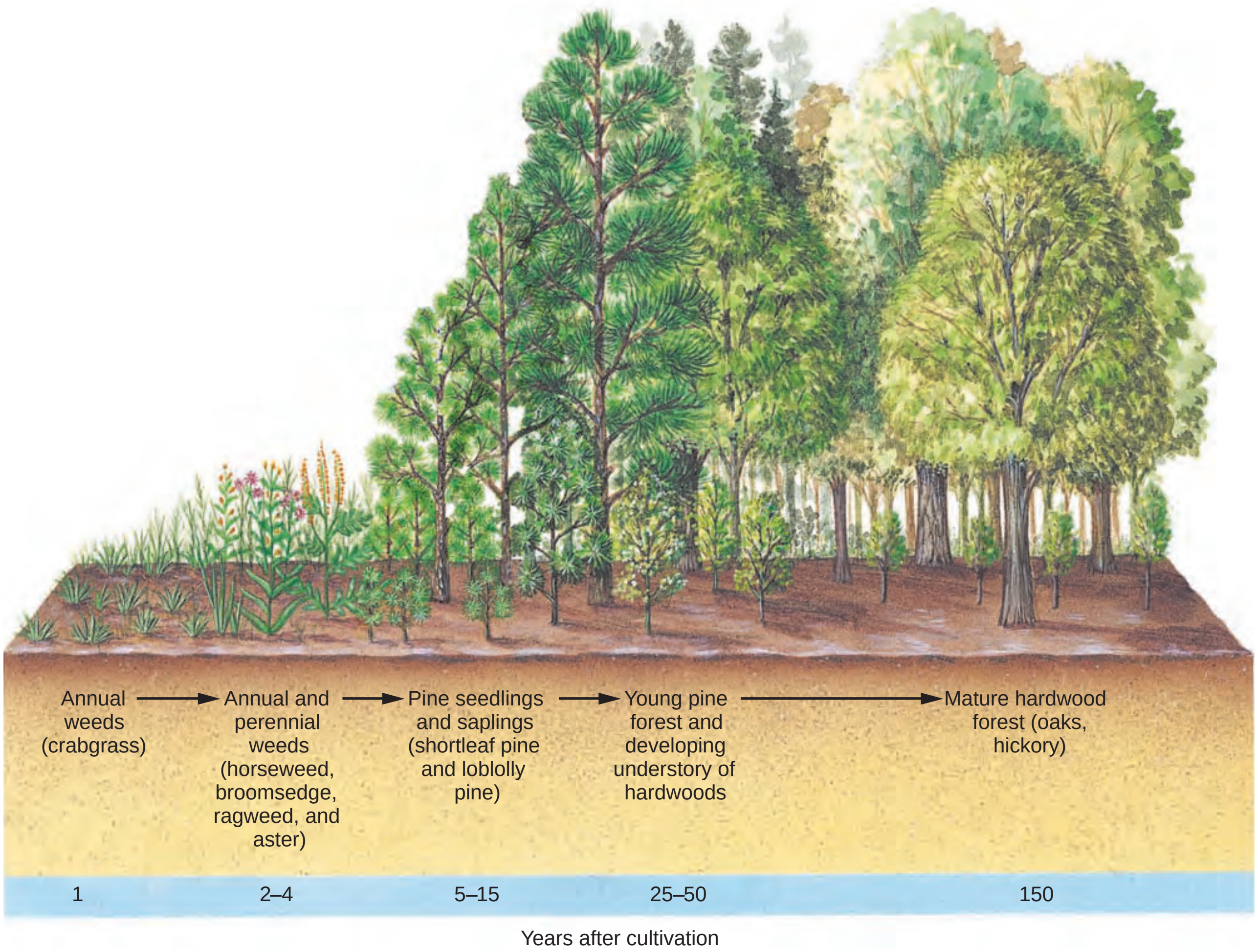
▲ **Burn scar from the Jesusita fire** Five days after the fire, NASA's Advanced Land Imager captured this true color image of the huge burned area, shown in reddish-purple tones. The road at the top of the photo marks the summit of the mountain ridge above the city. The street grid of the city of Santa Barbara is visible in the lower right.

and more, monitoring of fires by remote sensing is a topic of intense interest to global change researchers.

Fires can be remotely sensed in several ways. Thermal imagers detect active fires as bright spots because they emit more heat energy than normal surfaces. However, fires may be obscured under clouds. Smoke plumes can also identify the location of fires but are hard to distinguish from clouds in some images. Burn scars can also be detected after the fire.

Figure 8.23, from May 8, 2009, shows the Jesusita fire, in the hills above Santa Barbara, California, as imaged by NASA's MODIS instrument. Although not a large fire by California standards, this intense blaze destroyed 77 homes, damaged another 22 homes, and caused the evacuation of about 30,000 people.

The photo shown above is an image of the burn scar from this fire, acquired on May 10 by the Advanced Land Imager aboard NASA's Earth Observing-1 satellite platform. This imager uses a newer technology to produce multispectral images that are similar to those of Landsat. In the burned area, little vegetation remains outside of canyon bottoms.



8.24 Old-field succession in the Southeast United States

When cultivation ceases, grasses and forbs colonize the bare soil. The first stages depend on the last use of the land. If row crops were last cultivated, the pioneers will be annuals and biennials. If small grain crops were cultivated, the pioneers are often perennial herbs and grasses. If pasture is abandoned, those pioneers that were not grazed will have a head start. Where mineral soil was freshly exposed by plowing, pines often follow the first stages of succession because pine seeds favor disturbed soil and strong sunlight for germination. The pines eventually shade out the other plants and become dominant. Pine dominance is only temporary because their seeds cannot germinate in shade and litter on the forest floor. Hardwoods such as hickories and oaks, however, can germinate and their seedlings grow quickly to fill holes in the canopy. After several more decades, the deciduous hardwoods shade out the pines, providing the oak-hickory climax forest.

While succession is a reasonable model to explain many of the changes that we see in ecosystems with time, we must also take into account other effects. External forces can reverse or rechannel autogenic change temporarily or permanently. The biotic landscape is a mosaic of distinctive biotic communities with different biological potentials and different histories.

Historical Biogeography

Thus far, we've looked at ecological processes that produce biogeographic patterns at local and regional spatial scales. We now turn to patterns at continental and global scales that develop over longer time periods. *Historical biogeography* focuses on how these spatial distribution patterns arise over space and time through four key processes: evolution, speciation, extinction, and dispersal.

EVOLUTION

An astonishing number of organisms exist on Earth, each adapted to the ecosystem in which it carries out its life cycle (Figure 8.25). About 40,000 species of microorganisms, 350,000 species of plants, and 2.2 million species of animals, including some 800,000 insect species, have been described and identified. This is probably only a fraction of the number of species found on Earth.

How has life gained this astonishing diversity? Through the process of **evolution**, the environment

8.25 Diversity of life-forms on Earth

▼ **Microorganism** A diatom of the genus *Corethron*. Diatoms are a class of algae with over 70,000 known species. They contain silicified skeletons and are extremely abundant in fresh and ocean water (National Geographic Image Collection).

▼ **Reptile** An Australian thorny devil lizard makes its way across an arid landscape. Inhabiting the sand plains of South Australia, this small reptile lives on ants. It drinks dew that condenses on its body and is carried to its mouth in fine grooves between its spines (National Geographic Image Collection).

▼ **Fungus** A stinkworm fungus on the floor of a Costa Rican rainforest. Fungi are plants without chlorophyll that gain their nutrition from dead and decaying organic matter (National Geographic Image Collection).

▼ **Insect** Blue nose caterpillars on a leaf. These placid herbivores are well protected from predation by defensive spines that sting and detachable burrs that work their way into the skin (National Geographic Image Collection).

itself has acted on organisms to create this diversity. You've probably heard of Sir Charles Darwin, whose monumental biological work, *The Origin of Species by Means of Natural Selection*, was published in 1859. Through exhaustive studies, Darwin showed that all life possesses *variation*—the differences that arise between parent and offspring. He proposed that the environment acts on variation in organisms in much the same way that a plant or an animal breeder does, picking out the individuals with qualities that are best suited to their environment. These individuals are more likely to live longer, propagate, and pass on their useful qualities.

Darwin termed this survival and reproduction of the fittest **natural selection**. He saw that, when acted upon by natural selection through time, variation could bring about the formation of new species whose individuals differed greatly from their ancestors.

But how and why does this variation occur in the first place? Although Darwin couldn't provide an explanation, we now know the answer. Variation comes from two interacting sources: *mutation* and *recombination*. A reproductive cell's genetic material (DNA, or deoxyribonucleic acid) can mutate when the cell is exposed to heat, ionizing radiation, or certain types of chemical agents. Chemical bonds in the DNA are broken and reassembled. Most mutations either have no effect or are harmful. But a small proportion of mutations have a positive effect on the individual's genetic makeup. If that positive effect makes the individual organism more likely to survive and reproduce, then the altered gene is likely to survive as well and be passed on to offspring.

Natural selection acts on the variation that occurs within populations of species to produce evolution. Variation is produced by mutation, in which genetic material is altered, and recombination, in which new combinations of existing genetic material arise.

Recombination describes the process by which an offspring receives two slightly different copies, or *alleles*, of each gene from its parents. One allele may be dominant and suppress the other, or the two alleles may act simultaneously. Because each individual receives two alleles of each gene, and there are typically tens of thousands of genes in an organism, the possible number of genetic combinations is very large. Thus, recombination provides a constant source of variation that acts to make every offspring slightly different from the next.

SPECIATION

Mutations change the nature of species through time. But just what is a species? For our purposes, we can define a **species** (plural, species) as a collection of individuals capable of interbreeding to produce fertile offspring. A *genus* (plural, *genera*) is a collection of closely related species that share a similar genetic evolutionary history (Figure 8.26).

Speciation is the process by which species are differentiated and maintained. Actually, speciation is not a single process. It arises from a number of component processes acting together through time. We've already looked at two of these: mutation and natural selection.

Speciation is the process that differentiates and maintains species. Component processes affecting speciation include mutation, natural selection, genetic drift, and gene flow. Isolation, in which breeding populations are separated, enhances speciation.

A third speciation process is *genetic drift*. Chance mutations that don't have any particular benefit can still change the genetic composition of a breeding

8.26 Red and white oaks

Although similar in general appearance, these two species of the genus *Quercus* are easily separated.

▼ **Red oak** The acorns of red oak (*Quercus rubra*) have a flat cap and stubby nut, with pointed bristle tips on the leaf lobes.

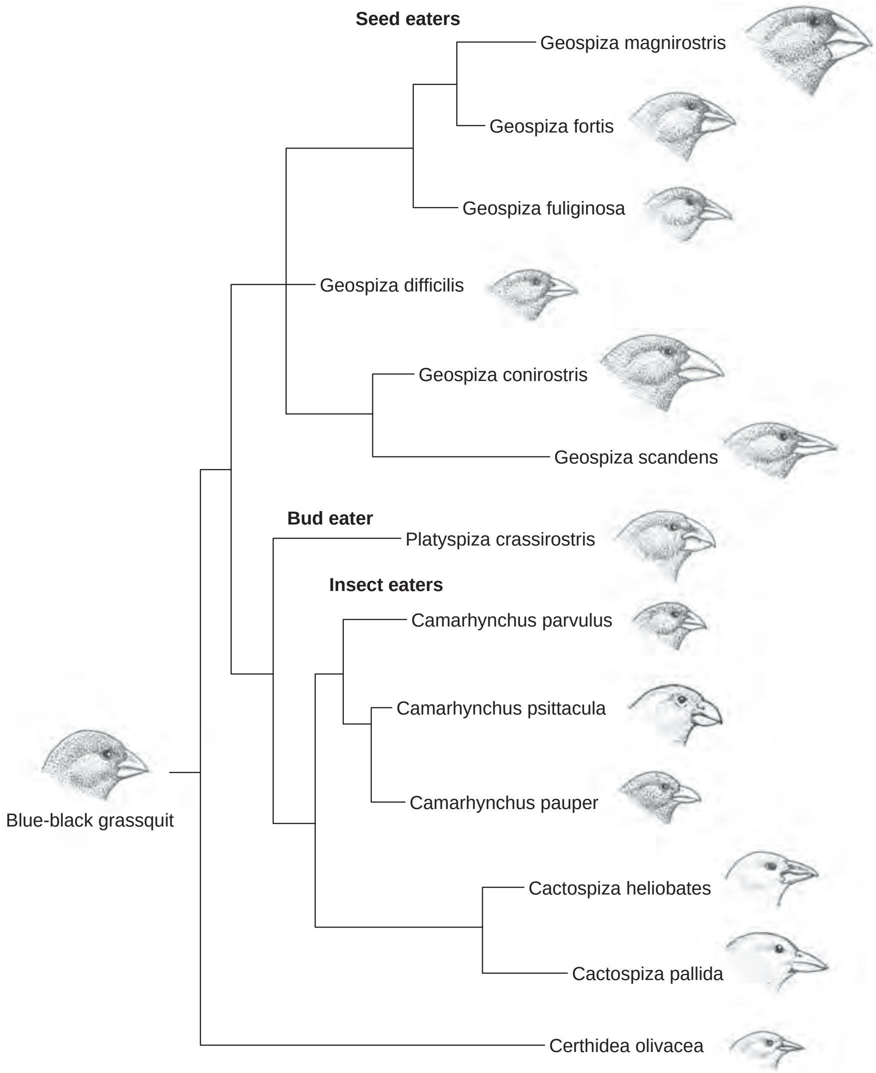
▼ **White oak** The acorns of white oak (*Quercus alba*) have a deeper cap and a pointed nut, with rounded leaf-lobe tips.

population until it diverges from other populations. Genetic drift is a weak factor in large populations. But in small populations, such as a colony of a few pioneers in a new habitat, random mutations are more likely to be preserved. *Gene flow* is the opposite process. Evolving populations exchange alleles as individuals move among populations, keeping the gene pool uniform.

Speciation often occurs when populations become isolated from one another, so there's no gene flow between them. This *geographic isolation* can happen in several ways. For example, geologic forces may uplift a mountain range that separates a population into two different subpopulations by a climatic barrier. Or a chance long-distance dispersal may establish a new population far from the main one. These are examples of *allopatric speciation*. As genetic drift and natural selection proceed, the populations gradually diverge and eventually lose the ability to interbreed.

The evolution of finch species on the Galápagos Islands is a classic example of allopatric speciation (Figure 8.27). Charles Darwin visited this cluster of five major volcanic islands and nine lesser ones, located about 800 km (500 mi) from the coast of Ecuador, and they inspired his ideas about evolution. The famous giant tortoises of the Galápagos are another example (Figure 8.28). Each of the larger islands bears at least one distinctly different population of these reptiles. Like the finches, they are believed to be evolved from a single ancestral stock that colonized the island chain and then diverged into unique types.

Sympatric speciation, by contrast, only occurs within a larger population. Imagine a species that has two different primary food sources. Eventually, mutations will arise that favor one food source over the other. For example, birds could develop two different lengths or shapes of beak, with one beak type better adapted for eating fruit and the other better suited to seeds. As these mutations are exposed to natural selection, they will produce two different populations, each adapted to its own food source. Eventually, the populations can become separate species.



8.27 Allopatric speciation of Galápagos finches

Five genera and 14 species of finch evolved from a single ancestral population. As the story has been reconstructed, the islands were first colonized by a single original finch species, the blue-black grassquit. Over time, individual populations became adapted to conditions on particular islands through natural selection, and, enhanced by their isolation on different islands, evolved into different species. Later, some of these species successfully reinvaded other islands, continuing the speciation and evolution process. The finches' beak shapes are adapted to their primary food source: seeds, buds, or insects.

8.28 Galápagos tortoises

These land-dwellers are the largest living tortoises and have a life expectancy of 100–150 years. In the Galápagos Islands, they diverged by allopatric speciation into 12 subspecies, of which 10 still exist. The subspecies generally have shells of two distinctive shapes: dome-back and saddle-back.

▼ **Dome-back shell** On the wetter islands with abundant ground vegetation, the tortoises maintain dome-shaped shells and shorter necks and legs suited to ground grazing.

▼ **Saddle-back shell** On the drier islands with less ground vegetation, the tortoises evolved saddle-shaped shells with wide openings and longer necks and legs to allow grazing on low trees and shrubs.

Another mechanism of sympatric speciation that is quite important in plants is *polyploidy*. Normal organisms have two sets of genes and chromosomes—that is, they are *diploid*. Through accidents in the reproduction process, two closely related species can cross in such a way that the offspring has both sets of genes from both parents. These *tetraploids* are fertile but can't reproduce with the populations from which they arose, and so they are instantly isolated as new species. About 70 to 80 percent of higher plant species probably arose in this fashion.

EXTINCTION

Over geologic time, all species are doomed to **extinction**. When conditions change more quickly than populations can evolve new adaptations, population size falls. When that happens, the population is more vulnerable to chance occurrences, such as a fire, a rare climatic event, or an outbreak of disease. Ultimately, the population is wiped out.

Extinction occurs when all individuals of a species die in response to rapid environmental change. Extreme events, such as the collision of a meteorite with the Earth about 65 million years ago, can cause mass extinctions.

Some extinctions occur very rapidly, particularly those induced by human activity, such as in the classic example of the passenger pigeon (Figure 8.29). Rare but extreme events can also cause extinctions. Strong evidence suggests that the Earth was struck by a large meteorite about 65 million years ago, wiping out the dinosaurs and many other groups of terrestrial and marine organisms (Figure 8.30). The impact sent huge volumes of dust into the atmosphere that choked off sunlight globally for several years and froze many plants and animals to death.

DISPERSAL

Nearly all types of organisms can move from a location of origin to new sites. Often this *dispersal* is confined to one life stage, as in the dispersal of higher plants as seeds. Even for animals, there is often a developmental stage when the animals are more likely to move from one site to the next.

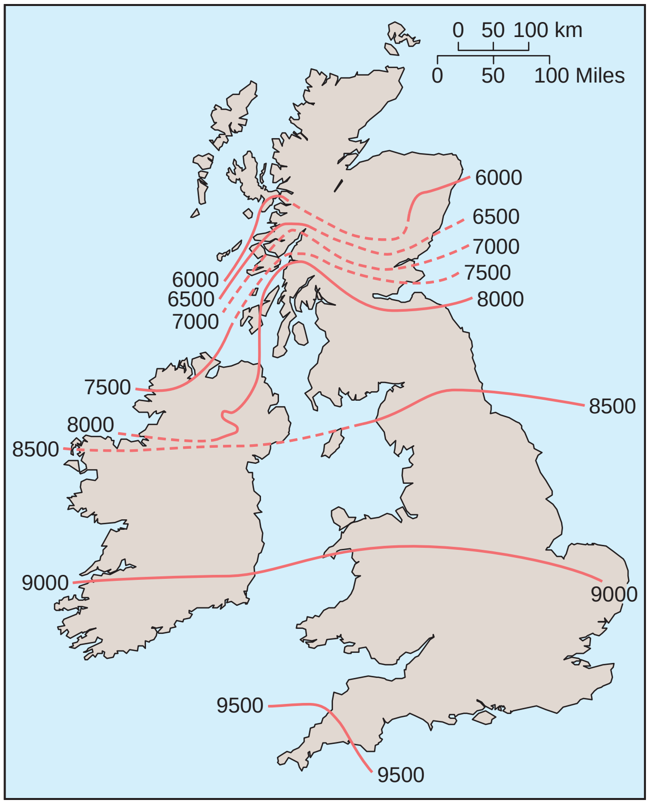
8.29 Passenger pigeon

The passenger pigeon was a dominant bird of eastern North America in the late nineteenth century. But these birds were easily captured in nets and shipped to markets for food. By 1890, they were virtually gone. The last known passenger pigeon died in the Cincinnati Zoo in 1914 (National Geographic Image Collection).

8.30 Chicxulub crater

When a large meteorite hit the Earth about 65 million years ago, it created a huge crater centered near Chicxulub, Mexico, on the Yucatan Peninsula. The curving shoreline here, created by a jutting shelf of limestone, is thought to be a remnant of the crater. Many scientists now believe that the impact of this meteorite was responsible for the extinction of dinosaurs and many other species (National Geographic Image Collection).

Normally, dispersal doesn't change the species' geographic range. Seeds fall near their sources, and animals seek out nearby habitats to which they are adjusted. Dispersal is thus largely a method for gene flow that helps to encourage the cross-breeding of organisms



8.31 Diffusion of oaks

Following the retreat and melting of continental glaciers at the close of the Ice Age, oak species diffused northward across the British Isles. Contours indicate northern borders at times in years before present. Dashed lines are less certain. The oaks took about 3500 years, from about 9500 years before present to 6000 years before present, to reach their northern limit.

throughout a population. When land is cleared or new land is formed, dispersal moves colonists into the new environment, as we saw when we discussed succession. Species also disperse by *diffusion*—slowly extending their range from year to year. An example of diffusion is the northward colonization of the British Isles by oaks at the end of the Ice Age (Figure 8.31).

A rare, long-distance dispersal event can be very significant, as we saw with the Galápagos finches. Some species, such as the ubiquitous coconut, are especially well adapted to long-distance dispersal. Among the animals, birds, bats, and insects are frequent long-distance travelers (Figure 8.32). Generally, nonflying mammals, freshwater fishes, and amphibians are less likely to make long leaps, with rats and tortoises the exceptions.

Dispersal often means surmounting barriers. That might mean bridging an ocean or an ice sheet by an unlikely accident. But other barriers are not so obvious. For example, the basin and range country of Utah, Nevada, and California is a sea of desert with islands of forest. Birds and bats can easily move from one

8.32 Dispersal

This small red-footed falcon was sighted for the first time in the western hemisphere in August 2004 at a grassy meadow airstrip on Martha's Vineyard Island, Massachusetts. The species normally winters in Africa and summers in eastern Europe. Munching happily on butterflies, grasshoppers, and small voles, it remained at the airstrip for about two weeks before heading for parts unknown.

8.33 Wooly mammoth

A reconstruction of the wooly mammoth, a huge tusked mammal that inhabited North America throughout the Ice Age and became extinct about 10,000 years ago, most likely from hunting by prehistoric humans.

island to the next, but a small mammal would not be likely to cross the desert sea under its own power. In this case, it's beyond the species' physiological limits to cross the barrier. But there may be ecological barriers as well—for example, a zone filled with predators or a region occupied by strongly and successfully competing species.

Dispersal is the capacity to move from a location of origin to new sites. In diffusion, species extend their range slowly from year to year. In long-distance dispersal, unlikely events establish breeding populations at remote locations.

There are also corridors that help dispersal. For example, Central America forms a present-day land bridge, connecting North and South America, that has been in place for about 3.5 million years. Other corridors existed in the recent past. The Bering Strait region between Alaska and easternmost Siberia was dry land during the early Cenozoic Era (about 60 million years ago) and during the Ice Age, when sea level dropped by more than 100 m (325 ft). Many plant and animal species of Asia are known to have crossed this bridge and then spread southward into the Americas. One notable migrant species of the last continental glaciation was the aboriginal human, and evidence suggests that these skilled hunters caused the extinction of many of the large animals, including wooly mammoths and ground sloths, that disappeared from the Americas about 10,000 years ago (Figure 8.33).

DISTRIBUTION PATTERNS

Over time, evolution, speciation, extinction, and dispersal have distributed many species across the Earth, creating a number of spatial distribution patterns. An **endemic** species is found in one region or location and nowhere else. An endemic distribution can arise in two ways—the species simply stays within a small range of its original location, or it contracts from a broader range. Some endemic species are ancient relics of biological strains that have otherwise gone extinct (Figure 8.34).

In contrast to endemics are *cosmopolitan species*, which are distributed very widely (Figure 8.34). Very small organisms, or organisms with very small propagating forms, are often cosmopolitan because they can be distributed widely by atmospheric and oceanic circulations. *Disjunction* is another interesting pattern, in which one or more closely related species are found in widely separated regions.

8.34 Endemic and cosmopolitan species

▼ **Cosmopolitan species** Shown here are two cosmopolitan species—the peregrine falcon (*Falco peregrinus*) and the human (*Homo sapiens*). Both are found widely over the globe. The human, a scientist, is attaching a band to the leg of the bird as part of a study of how the falcon is affected by chemical contamination.

▶ **Endemic species** The gingko tree was widespread throughout the Mesozoic Era (245 to 60 million years ago) but until recently was endemic to a small region in eastern China. Thanks to human activity, it is now much more widely distributed around the world. It is widely planted in North America as an urban street tree, known for its hardiness.

BIOGEOGRAPHIC REGIONS

When we examine the spatial distributions of species on a global scale, we find common patterns. Closely related species tend to be nearby or to occupy similar regions. But larger groups of organisms, such as families and orders, often have disjunct distribution patterns. For example, the South America–Africa–Australia–New Zealand pattern for the ratite birds, described in Figure 8.35, also fits the distribution of many other ancient families of plants and animals. This reflects their common ancestry on the supercontinent of Gondwana, which existed about 210 million years ago and then gradually split apart (see Chapter 11).

Cosmopolitan species are found very widely. Endemic species are restricted to a single region or location. Disjunctions occur when closely related species are found in widely separated regions.

Global climate also plays an important role. Often, members of the same lineage have similar adaptations to environment, and so they are found in similar climatic regions.

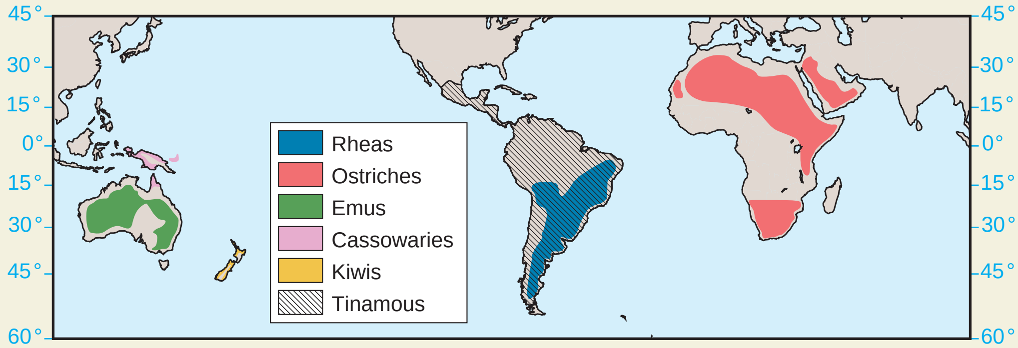
We can define **biogeographic regions** as areas in which the same or closely related plants and animals tend to be found together. When we cross the boundary between two biogeographic regions, we pass from one group of distinctive plants and animals to another. Figure 8.36 shows the major biogeographic regions for plants and animals.

Biodiversity

Today, global **biodiversity**—the variety of biological life on Earth—is rapidly decreasing. Two out of every five species on the planet that have been assessed by scientists

8.35 Disjunct distribution

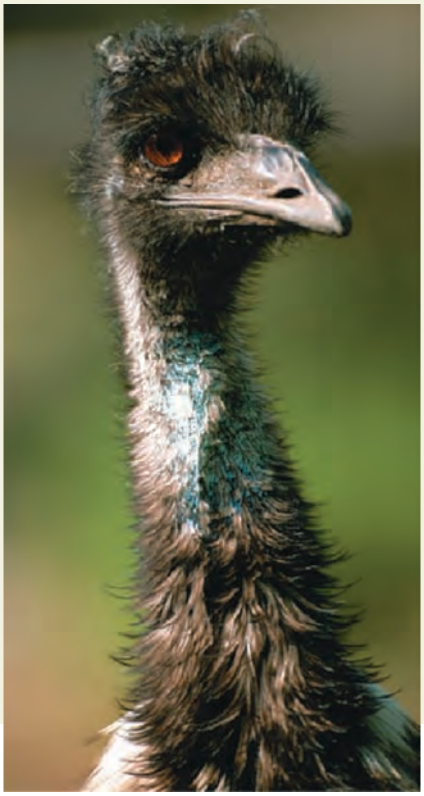
▶ The flightless ratite birds and tinamous descended from common ancestors that once roamed the ancient continent of Gondwana. As Gondwana split into South America, Africa, Australia, and New Zealand, populations were isolated, allowing separate but related species to evolve.



▼ **Cassowary** The cassowary hails from New Guinea and northeastern Australia. It is a rainforest dweller (National Geographic Image Collection).

▼ **Ostrich** The ostrich is restricted to Africa and the Middle East, although it was formerly found in Asia (National Geographic Image Collection).

▼ **Emu** The emu inhabits most of Australia and is commonly encountered in the wild (National Geographic Image Collection).

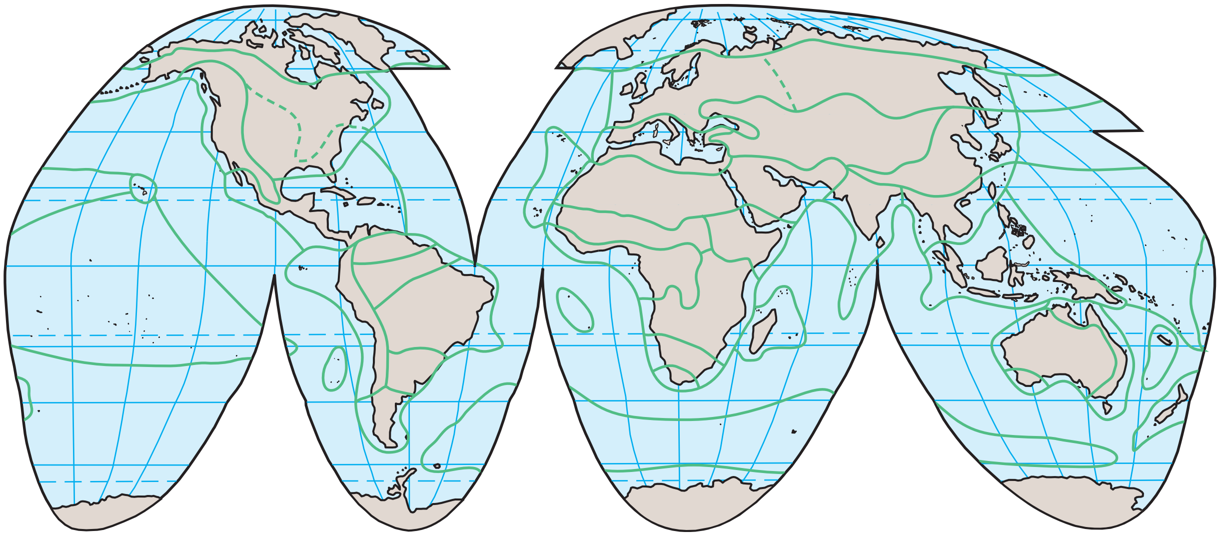


face extinction, according to the International Union for Conservation of Nature and Natural Resources (Figure 8.37).

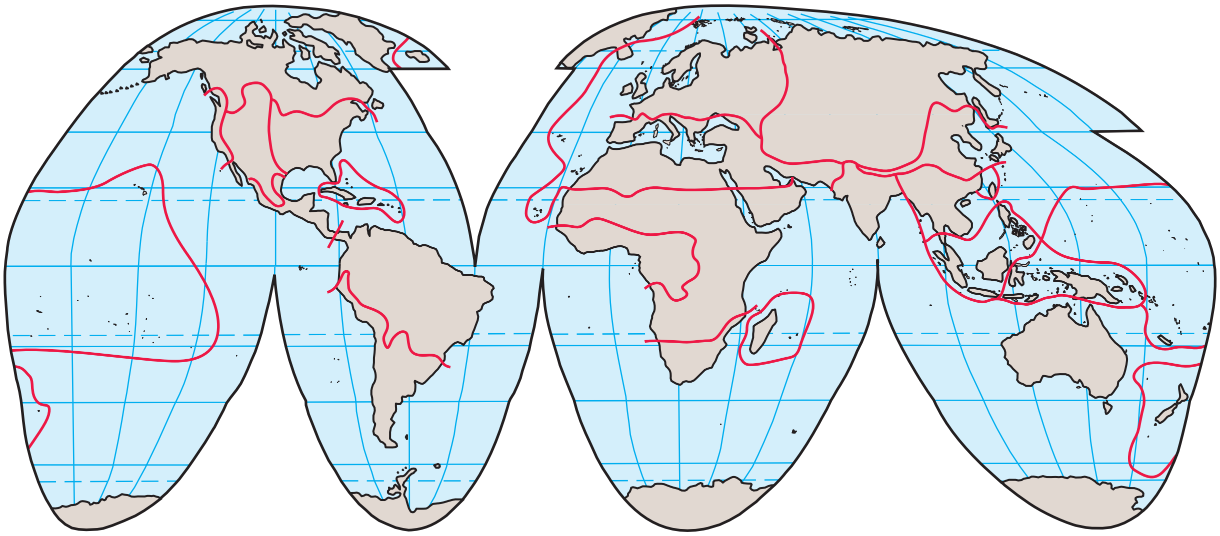
Our species, *Homo sapiens*, has ushered in a wave of extinctions unlike any that has been seen for millions of years. In the last 40 years, several hundred land animal species have disappeared. Aquatic species have also been severely affected, with 40 species or subspecies of freshwater fish lost in North America alone in the last few decades. In the plant kingdom, botanists estimate that over 600 species have become extinct in the past four centuries. These documented extinctions may be only the tip of the iceberg. Many species haven't been discovered yet and so

Biodiversity expresses the variety of biological life. Human activity has reduced biodiversity by modifying natural habitats and causing extinctions.

▼ Biogeographic regions of land plants.



▼ Biogeographic regions of land animals.



8.36 Biogeographic regions

Note that many of the boundaries on the two maps are fairly close, indicating that at the global scale, plants and animals have similar and related histories of evolution and environmental affinity.

may become extinct without ever being described. Figure 8.38 shows the conservation status of some important groups of plants and animals of the United States. Many species are extinct or imperiled.

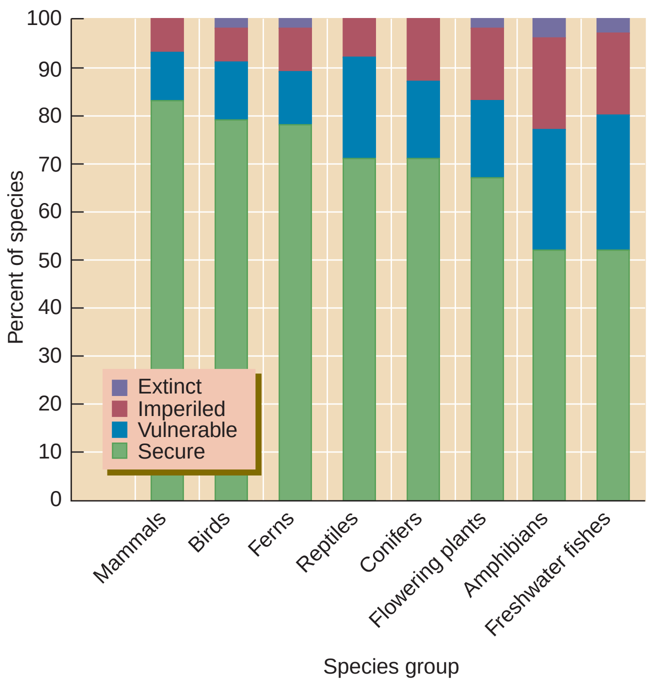
How has human activity created extinctions? Over our history, we've dispersed new organisms to regions where they outcompete or prey on existing organisms. Many islands were subjected to waves of invading species, ranging from rats to weeds, brought first by prehistoric humans and later by explorers and conquerors. Hunting by prehistoric humans alone was sufficient to exterminate many species. As humans learned to use fire, large areas became subject to periodic burning. And human alteration and fragmentation of habitats have isolated plant and animal populations, causing populations to shrink and sometimes become extinct.

Biodiversity is not uniform over the Earth's surface. In general, tropical and equatorial regions have more species and more variation in species composition between different habitats. Geographic areas in which

8.37 Endangered species

▼ **Manatee** The West Indian manatee is a large aquatic mammal found year round in the West Indies and southern Florida, and in the winter, as far north as coastal Virginia. Loss of habitat and collisions with boats and barges reduced the population until it reached endangered-species status.

▲ **Black-footed ferret** This small mammal, related to otters and badgers, was driven nearly to extinction as its prey, the prairie dog, was hunted and poisoned throughout the western United States.



8.38 Degree of endangerment of plant and animal groups in the United States

These bar graphs show the proportion of species within each group as secure, vulnerable, imperiled, or extinct. (Data from Nature Conservancy.)

biodiversity is especially high and also threatened are referred to as *hotspots* (Figure 8.39). An important strategy for preservation of global biodiversity is to identify hotspots and take conservation measures to protect them. In this way, conservation efforts can be most effective.

Why is biodiversity important? Nature has provided an incredibly rich array of organisms that interact with each other in a seamless web of organic life. When we cause the extinction of a species, we break a link in that web. Ultimately, the web will thin, with unknown consequences for both the human species and continued life on Earth.

GEODISCOVERIES Web Quiz

Take a quick quiz on the key concepts of this chapter.

8.39 Biodiversity hotspots

Conservation International identified 34 "hotspots" of biodiversity, defined as habitats holding at least 1500 endemic plant species and having lost 70 percent of their original extent. Many of these are in the six major regions identified on the map (National Geographic Image Collection).

A Look Ahead

In this chapter we've focused on the processes that determine the spatial patterns of biota at scales ranging from local to global. We've examined how energy and matter flow in local ecosystems and how different ecosystems have different levels of productivity. We have seen how organisms adjust to their individual environments and how natural selection works in response to environmental pressures. We have also seen how the processes of evolution, dispersal, and extinction generate patterns of species distribution and determine biodiversity at continental and global scales. Our next chapter takes a more functional view of the life layer by inventorying the global *biomes*—major divisions of ecosystems that are based largely on the dominant life-form of their vegetation covers—and where they occur on Earth.

GEODISCOVERIES Web Links

Food webs, carbon dioxide cycling, wildfires, and more are waiting at the web sites on this chapter's web links list. Explore evolution and extinction and pay a virtual visit to the Galapágos islands.

IN REVIEW BIOGEOGRAPHIC PROCESSES

- Fossil fuel burning releases large amounts of carbon to the atmosphere as CO_2. Less than half of that carbon is removed by oceanic and land processes, leaving the remainder to accumulate and increase global warming.
- Oceans take up atmospheric CO_2 by solution and in the photosynthesis of phytoplankton. Land ecosystems release CO_2 by land clearing, biomass burning, and oxidation of organic matter in soils, but take up CO_2 as forests grow and forest area expands to cover abandoned lands.
- **Biogeography** focuses on the distribution of plants and animals over the Earth. *Ecological biogeography* examines how relationships between organisms and environment help determine when and where organisms are found. *Historical biogeography* examines how, where, and when species have evolved and how they are distributed over longer times and broader scales.
- **Ecology** is the science of interactions among organisms and their environment. Its focus is the **ecosystem**, which by interaction among components

provides pathways for flows of energy and cycles of matter. The **food web** of an ecosystem details how food energy flows from *primary producers* through *consumers* and on to *decomposers*. Because energy is lost at each level, only a relatively few top-level consumers are normally present.

- *Photosynthesis* is the production of carbohydrate from water, carbon dioxide, and light energy by primary producers. *Respiration* is the opposite process, in which carbohydrate is broken down into carbon dioxide and water to yield chemical energy and thus power organisms. *Net photosynthesis* is the amount of carbohydrate remaining after respiration has reduced *gross photosynthesis*. Net photosynthesis increases with increasing light and temperature, up to a point.
- **Biomass** is the accumulated net production of an ecosystem. Forests and wetlands are ecosystems with high rates of *net primary production*, while grasslands and agricultural lands are generally lower. Oceans are most productive in coastal and upwelling zones near continents. Among climate types, those with abundant rainfall and warm temperatures are most productive.
- **Biogeochemical cycles** consist of *active* and *storage* pools linked by flow paths. The **carbon cycle** includes an active pool of biospheric carbon and atmospheric atmospheric CO_2, with a large storage pool of carbonate in sediments. Human activities have provided a pathway from storage to active pools by the burning of fossil fuel.
- The *nitrogen cycle* also has an atmospheric pool, but the nitrogen is largely held in the form of N_2, which cannot be used directly by most organisms. *Nitrogen fixation* occurs when N_2 is converted to more useful forms by bacteria or blue-green algae, often in symbiosis with higher plants. Human activity has doubled the rate of nitrogen fixation, largely through fertilizer manufacture.
- A *community* of organisms occupies a particular environment, or **habitat**. *Associations* are recurring types of communities that are often defined by characteristic species. Environmental factors influencing the distribution patterns of organisms include moisture, temperature, light, and wind.
- Organisms require water to live, and so they are limited by the availability of water. **Xerophytes** are adapted to arid habitats. They reduce water loss by having waxy leaves, spines instead of leaves, or no leaves at all. *Phreatophytes* have deep roots; *succulents* store water in spongy tissues. *Tropophytes* are deciduous during the dry season. *Sclerophylls* have thick, leathery leaves that resist drying during the Mediterranean summer climate.
- *Xeric animals* include vertebrates that are nocturnal and have various adaptations to conserve water. Invertebrates such as brine shrimp can adjust their life cycle to prolonged drought.
- Temperature acts on plants to trigger and control stages of plant growth as well as to limit growth at temperature extremes. Survival below freezing requires special adaptations, and so only a small proportion of plants are frost-tolerant. *Cold-blooded animals* have body temperatures that follow the environment, but they can moderate these temperatures by seeking warm or cool places. Mammals and birds maintain constant internal temperatures through a variety of adaptation mechanisms.
- The light available to a plant depends on its position in the structure of the community. Duration and intensity of light vary with latitude and season and serve as a cue to initiate growth stages in many plants. The day–night cycle regulates much of animal behavior, as does *photoperiod* (daylight length). Wind deforms plant growth by desiccating buds and young growth on the windward side of the plant.
- A *bioclimatic frontier* marks the potential distribution boundary of a species. Other factors may also limit the distribution of a species.
- *Geomorphic factors* of slope steepness and orientation affect both the moisture and temperature environment of the habitat and serve to differentiate the microclimate of each community.
- Soil, or *edaphic, factors* can also limit the distribution patterns of organisms or affect community composition.
- *Disturbance* includes catastrophic events that damage or destroy ecosystems. Fire is a very common type of disturbance that influences forests, grasslands, and shrublands. Floods, high winds, and storm waves are others. Many ecosystems include specialized species that are well adapted to disturbance.
- Species interact in a number of ways, including **competition**, *predation* and *parasitism*, and *herbivory*. In *allelopathy*, plant species literally poison the soil environment against competing species. Positive (beneficial) interaction between species is termed **symbiosis**.
- Fire contributes greenhouse gases to the atmosphere as well as changing species composition, stimulating runoff, and increasing soil erosion.
- **Ecological succession** comes about as ecosystems change in predictable ways through time. A series of stable communities follows a *sere* to a *climax*. *Primary succession* occurs on new soil substrate, while *secondary succession* occurs on disturbed habitats. Succession on coastal sand dunes follows a series of stages from dune grass to an oak and holly forest. *Old-field succession*, which occurs on abandoned farmland, also leads to a deciduous forest climax. Although succession is a natural tendency for

ecosystems to change with time, it is opposed by natural disturbances and limited by local environmental conditions.

- *Historical biogeography* focuses on evolution, speciation, extinction, and dispersal as they influence the distribution patterns of species.
- Life has attained its astonishing diversity through **evolution**. In this process, **natural selection** acts on *variation* to produce populations that are progressively better adjusted to their environment. Variation arises from *mutation* and *recombination*.
- A **species** is best defined as a population of organisms that are capable of interbreeding successfully. **Speciation** is the process by which species are differentiated and maintained. It includes mutation, natural selection, *genetic drift*, and *gene flow*.
- *Geographic isolation* acts to isolate subpopulations of a species, allowing genetic divergence and speciation to occur. The finches of the Galápagos Islands provide an example of *allopatric speciation* by geographic isolation. In *sympatric speciation*, adaptive pressures force a breeding population to separate into different subpopulations that may become species. Sympatric speciation of plants has included *polyploidy*, which is an important mechanism of evolution for higher plants.
- **Extinction** occurs when populations become very small and thus are vulnerable to chance occurrences of fire, disease, or climate anomaly. Rare but very extreme events can cause mass extinctions. An example is the meteorite impact that the Earth suffered about 65 million years ago. The global dust cloud that lingered for several years caused extreme cold temperatures, which wiped out many important lineages of plants and animals.
- Species expand and contract their ranges by **dispersal**. Plants are generally dispersed by seeds, whereas animals often disperse under their own power. Since most dispersal happens within the range of a species, it acts primarily to encourage gene flow between subpopulations. Long-distance dispersal, though very rare, may still be very important in establishing biogeographic patterns. *Barriers*, often climatic or topographic, inhibit dispersal and induce geographic isolation. Corridors provide pathways that facilitate dispersal.
- **Endemic** species are found in one region or location and nowhere else. They arise by either a contraction of the range of a species or by a recent speciation event. *Cosmopolitan* species are widely dispersed and nearly universal. *Disjunction* occurs when one or more closely related species appear in widely separated regions.
- **Biogeographic regions** capture patterns of occurrence in which the same or closely related plants and animals tend to be found together. They result because their species have common histories and similar environmental preferences.
- **Biodiversity** is rapidly decreasing as human activity progressively affects the Earth. Extinction rates for many groups of plants and animals are as high or higher today than they have been at any time in the past. Humans act to disperse predators, parasites, and competitors widely, disrupting long-established evolutionary adjustments of species with their environments. Hunting and burning have exterminated many species. Habitat alteration and fragmentation also produce extinctions. Preservation of global biodiversity includes a strategy of protecting *hotspots* where diversity is greatest.

KEY TERMS

biogeography, p. 268
ecology, p. 268
ecosystem, p. 268
food web, p. 268
biomass, p. 271
biogeochemical cycle, p. 273
pool, p. 273
carbon cycle, p. 274
habitat, p. 275
xerophytes, p. 277
competition, p. 282
symbiosis, p. 283
ecological succession, p. 284
evolution, p. 288
natural selection, p. 289
species, p. 290
speciation, p. 290
extinction, p. 292
endemic, p. 294
biogeographic region, p. 295
biodiversity, p. 295

REVIEW QUESTIONS

1. What is the fate of carbon released by fossil fuel burning to the atmosphere?
2. Describe the processes that move CO_2 between the ocean and atmosphere and between land ecosystems and the atmosphere.
3. How do changes in land cover affect the global carbon budget? What is the role of soil carbon?
4. Define the terms *biogeography*, *ecology*, and *ecosystem*.

5. What is a *food web* or *food chain*? What are its essential components? How does energy flow through the food web of an ecosystem?
6. Compare and contrast the processes of photosynthesis and respiration. What classes of organisms are associated with each?
7. How is net primary production related to biomass? Identify some types of terrestrial ecosystems that have a high rate of net primary production and some with a low rate.
8. Which areas of oceans and land are associated with high net primary productivity? How is net primary production on land related to climate?
9. What is a *biogeochemical cycle*? What are its essential features?
10. What are the essential features and flow pathways of the carbon cycle? How have human activities impacted the carbon cycle?
11. What are the essential features and flow pathways of the nitrogen cycle? What role do bacteria play? How has human activity modified the nitrogen cycle?
12. What is a *habitat*? What are some of the characteristics that differentiate habitats? Compare habitat with *ecological niche*.
13. Contrast the terms *ecosystem*, *community*, and *association*.
14. Although water is a necessity for terrestrial life, many organisms have adapted to arid environments. Describe some of the adaptations that plants and animals have evolved to cope with the desert.
15. Terrestrial temperatures vary widely. How does the annual variation in temperature influence plant growth, development, and distribution? How do animals cope with variation in temperature?
16. How does the ecological factor of light affect plants and animals? How does wind affect plants?
17. How do geomorphic and edaphic factors influence the habitat of a community?
18. Identify several types of disturbance experienced by ecosystems. How does fire affect forests and grasslands?
19. Contrast the terms used to describe interactions among species. Provide an example of beneficial predation.
20. What are the effects of fire on the atmosphere and on ecosystems?
21. Describe ecological succession using the terms *sere*, *seral stage*, *pioneer*, and *climax*. Use dune succession as an example.
22. How do primary succession and secondary succession differ? Describe old-field succession as an example of secondary succession.
23. How does the pattern of ecosystems on the landscape reflect a balance between succession and disturbance?
24. Explain Darwin's theory of evolution by means of natural selection. What key point was Darwin unable to explain?
25. What two sources of variation act to differentiate offspring from parents?
26. What is *speciation*? Identify and describe four component processes of speciation.
27. What is the effect of geographic isolation on speciation? Provide an example of allopatric speciation.
28. How does sympatric speciation differ from allopatric speciation? Provide an example of sympatric speciation.
29. What is *extinction*? Provide some examples of extinctions of species.
30. Describe the process of dispersal. Provide a few examples of plants and animals suited to long-distance dispersal.
31. Contrast barriers and corridors in the dispersal process.
32. How does an endemic distribution pattern differ from a cosmopolitan pattern? What is *disjunction*?
33. How are biogeographic regions differentiated?
34. What is *biodiversity*? How has human activity impacted biodiversity?

VISUALIZING EXERCISES

1. Sketch a graph showing the relationship among gross photosynthesis, net photosynthesis, respiration, and temperature. How is net photosynthesis obtained from gross photosynthesis and respiration for each temperature?
2. Diagram the general features of a biogeochemical cycle in which storage pools and active pools are linked by life processes and physical processes.
3. Draw a timeline illustrating old-field succession. Between the stages, indicate the environmental changes that occur.
4. Carefully compare the two maps of Figure 8.36. Which boundaries are similar, and which are different? Speculate on possible reasons for the similarities and differences.

ESSAY QUESTIONS

1. Suppose atmospheric carbon dioxide concentration doubles. What will be the effect on the carbon cycle? How will flows change? Which pools will increase? decrease?
2. Select three distinctive habitats for plants and animals that occur nearby and with which you are familiar. Organize a field trip (real or virtual) to visit the habitats. Compare their physical environments and describe the basic characteristics of the ecosystems found there.
3. Invent a biological history of the Galápagos Islands, describing how and when organisms such as finches and tortoises evolved using the processes of speciation.

Chapter 9
Global Biogeography

These large marine mammals are brown fur seals—members of the species *Arctocephalus pusillus*, which is found along the African coast from Namibia to South Africa as well as along the south coast of eastern Australia and Tasmania. Adult males measure about 2 m (about 6 ft) in length and weigh around 250 kg (about 550 lb). Females are smaller, weighing about 120 kg (260 lb) with a length of about 1.6 m (about 5.2 ft).

Fur seals are individual swimmers and foragers that feed on fish, squid, rock lobster, and other marine animals. But from time to time they “haul out,” gathering together in groups on land or ice to rest, avoid predators, and engage in social activity.

In November and December, a herd will haul out to reproduce. Male fur seals fight to establish territories and gather harems of females in noisy rituals of growling, honking, and roaring. Females bear single pups and then soon after mate with the males, remaining pregnant until the following year’s haul out.

Although once widely hunted for the warm, soft fur of its pups, the brown fur seal is now protected and no longer endangered.

Fur seals on a rock, Western Cape Province, Republic of South Africa.

Global Biogeography

The Earth's land environments are home to a vast diversity of plants and animals. How do biogeographers and ecologists classify the ecological realms of the land into biomes and vegetation formation classes? What are the five biomes of the world? How do they compare? Where are they found? What important formation classes do they contain? How is the global and continental pattern of biomes and formation classes related to climate? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Exploitation of the Low-Latitude Rainforest Ecosystem

Many of the world's equatorial and tropical regions are home to the *rainforest ecosystem*. This ecosystem is perhaps the most diverse on Earth, possessing more species of plants and animals than any other. Very large tracts of rainforest still exist in South America, south Asia, and some parts of Africa. Ecologists regard this ecosystem as a genetic reservoir of many species of plants and animals. But as human populations expand and the quest for agricultural land continues, low-latitude rainforests are being threatened by clearing, logging, cultivation of cash crops, and animal grazing.

In the past, low-latitude rainforests were farmed by native peoples using the *slash-and-burn* method—cutting down all the vegetation in a small area, then burning it (Figure 9.1). In a rainforest ecosystem, most of the nutrients are held within living plants rather than in the soil. Burning the vegetation on the site releases the trapped nutrients, returning a portion of them to the soil where they are available to growing crops.

The supply of nutrients derived from the original vegetation cover is small, however, and the harvesting of crops rapidly depletes the nutrients. After a few seasons of cultivation, the old field is abandoned, and a new field is cleared. Nearby rainforest plants soon reestablish their hold on the abandoned area. Eventually, the rainforest returns to its original state.

The rainforest ecosystem, home of the world's most diverse collection of plants and animals, is threatened by deforestation and conversion to cropland and rangeland.

9.1 Slash-and-burn clearing

This rainforest in Maranhão, Brazil, has been felled and burned in preparation for cultivation.

In contrast, modern intensive agriculture uses large areas of land and is not compatible with the rainforest ecosystem. When large areas are abandoned, seed sources are so far away that the original forest species cannot take hold. Instead, secondary species dominate, often accompanied by good invaders from other vegetation types. Once these invaders enter an area, they tend to stay, and their dominance is permanent, at least on the human time scale. The rainforest ecosystem is thus a resource that, once cleared, will never return in quite the same way. The loss of low-latitude rainforest will result in the disappearance of thousands of species of organisms from the rainforest environment—a loss of millions of years of evolution, together with the destruction of the most complex ecosystem on Earth.

In Amazonia, transformation of large areas of rainforest into agricultural land uses heavy machinery to carve out major highways and innumerable secondary roads and trails. Large fields for cattle pasture or commercial crops are created by cutting, bulldozing, clearing, and burning the vegetation. In some regions, the great broad-leaved rainforest trees are removed for commercial lumber.

According to a recent report issued by the United Nations Food and Agriculture Organization, about 0.6 percent of the world's rainforest is lost annually by conversion to other uses. More rainforest land, 2.2 million hectares (about 8500 mi^2), is lost annually in Asia than in Latin America and the Caribbean, where 1.9 million hectares (about 7300 mi^2) are converted every year. Africa's loss of rainforest was estimated at about 470,000 hectares per year (1800 mi^2). Among individual countries, Brazil and Indonesia are the loss leaders, accounting for nearly half of the rainforest area converted to other uses. These values do not include even larger losses of moist deciduous forests in these regions. Deforestation in low-latitude dry deciduous forests and hill and montane forests is also very serious.

Although deforestation rates are very rapid in some regions, many nations are now working to reduce the rate of loss of rainforest environment. However, because the rainforest can provide agricultural land, minerals, and timber, the pressure to allow deforestation continues.

Natural Vegetation

Over the last few thousand years, human societies have come to dominate much of the land area of our planet. We've changed the natural vegetation—sometimes drastically—of many regions. What exactly do we mean by natural vegetation? **Natural vegetation** is a plant cover that develops with little or no human interference. It is subject to natural forces, storms, or fires that can modify or even destroy it. Natural vegetation can still be seen over vast areas of the wet equatorial climate ①, although the rainforests there are being slowly cleared. Much of the arctic tundra and the boreal forest of the subarctic zones is in a natural state.

In contrast, there is also *human-influenced vegetation*. Much of the midlatitude land surface is totally under human control, through intensive agriculture, grazing, or urbanization. Other areas appear to be untouched but may actually be dominated by human activity in a subtle manner. For example, most national parks and national forests have been protected from fire for many decades. As a result, dead branches and debris have accumulated on the forest floor, creating fuel loads that encourage hot, damaging, crown fires rather than cooler, sparser, understory fires that leave the larger, healthier, trees alive (Figure 9.2).

Most of the Earth's land surface is influenced subtly or strongly by human activities, including clearing for agriculture and grazing, fire suppression, and introduction of alien plants and animals.

9.2 The great Yellowstone fire

Yellowstone National Park is a priceless forest ecosystem, little disturbed by natural catastrophe or human interference for at least the past two centuries. But through August and September of 1988, 45 forest fires—mostly started by lightning strikes—burned out of control in the park. The number of fires was not unusually high. However, they followed the driest summer of more than a century, and so the fires were able to spread more rapidly than usual. The fires were most destructive in long-unburned areas where dead wood and branches had accumulated for decades.

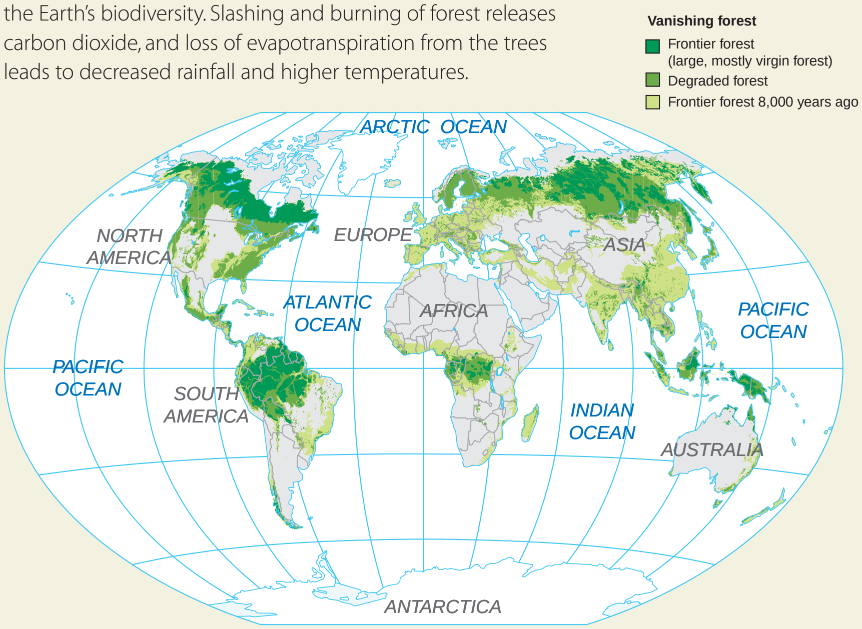
▼ **After the burn** This stand of lodgepole pines in Yellowstone was killed by an intensely hot, crown fire.

▼ **Ten years later** After 10 years, regeneration has started a new pine forest.

9.3 Deforestation and desertification

Forest clearing, if carried out unsustainably, reduces global biomass and biodiversity while contributing to global warming. Desertification, or land degradation, reduces productivity by overusing the land for grazing, wood gathering, and other consumptive activities.

▼ **Deforestation** Since humans took up agriculture, the Earth's forests have been diminishing. At present, about 13 million hectares (32 million acres) of forest is lost each year, largely to agriculture. More than half of this area is in South America, Africa, and equatorial Asia. Loss of habitat in these species-rich areas takes a toll on the Earth's biodiversity. Slashing and burning of forest releases carbon dioxide, and loss of evapotranspiration from the trees leads to decreased rainfall and higher temperatures.



▲ **Clear-cutting** Clear-cutting of large tracts of timber, without sustainable replanting, contributes to deforestation, erosion, and loss of habitat (National Geographic Image Collection).

▶ **Wood gathering** Where fuel is in short supply, firewood is stripped from living trees, reducing the vegetation cover. When trees are gone, dung is burned, further impoverishing the soil (National Geographic Image Collection).

Humans have also moved plant species from their original habitats to foreign lands and foreign environments. Sometimes exported plants thrive like weeds, forcing out natural species and becoming a major nuisance. Other human activities such as clear-cutting, slash-and-burn agriculture, overgrazing, and wood-gathering have had profound effects on the plant species and the productivity of the land (Figure 9.3).

STRUCTURE AND LIFE-FORM OF PLANTS

Plants come in many types, shapes, and sizes. Botanists recognize and classify plants by species. However, the biogeographer is less concerned with individual species and more interested in plant cover as a whole. So, when talking about plant cover, plant geographers discuss the **life-form** of the plant—its physical structure, size, and shape. Most life-form names are in common use, and you're probably familiar with them already, but we'll quickly review them now.

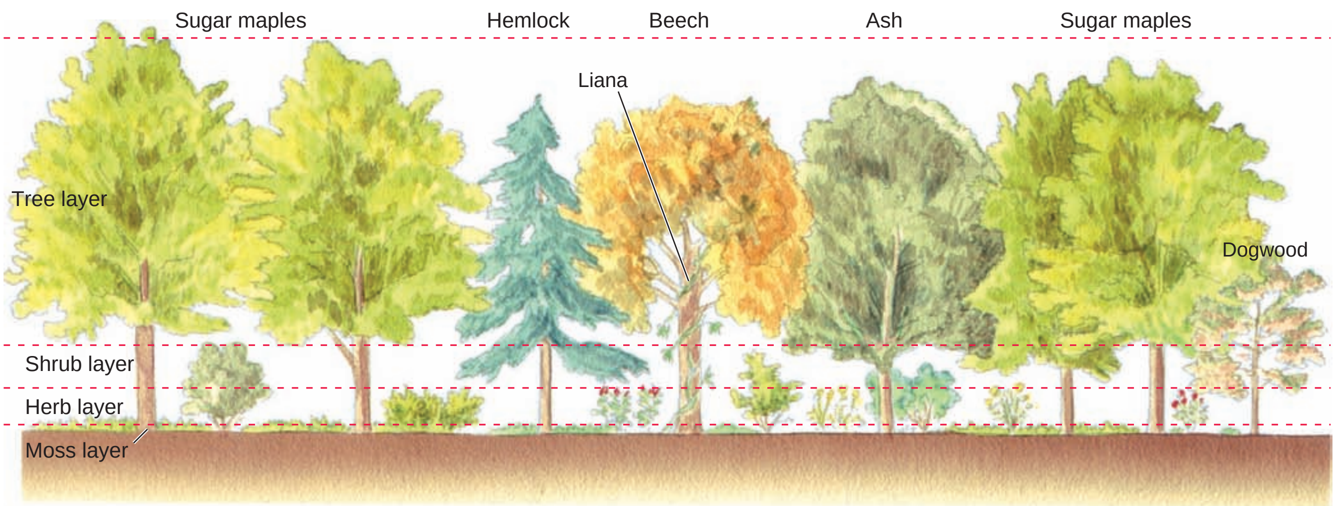
Figure 9.4 illustrates various plant life-forms. Trees and shrubs are erect, woody plants. They are *perennial*, meaning that their woody tissues endure from year to year. Most have life spans of many years. *Trees* are large plants with a single upright main trunk, often with few branches in the lower part but branching in the upper part to form a crown. *Shrubs* have several stems branching from a base near the soil surface, creating a mass of foliage close to ground level.

Lianas are also woody plants, but they take the form of vines supported on trees and shrubs. Lianas include tall, heavy vines in the wet equatorial and tropical rainforests and also some woody vines of midlatitude forests. English ivy, poison ivy or oak, and Virginia creeper are familiar North American examples of lianas.

▶ **Slash-and-burn** Large areas of equatorial rainforest in the Amazon Basin are now being converted to grazing land and agriculture. The first step in this process is cutting the forest for timber and burning the debris to release nutrients to soil. The nutrients are soon exhausted, leaving the land impoverished and unproductive (National Geographic Image Collection).

▲ **Desertification** Climate variability and human activities such as grazing and conversion of natural areas to agricultural use are leading causes of desertification—the degradation of land in arid, semiarid, and dry subhumid areas. Desertification brings loss of topsoil, increased soil salinity, damaged vegetation, regional climate change, and a decline in biodiversity.

▼ **Overgrazing** Overgrazing strips vegetation from the land, reducing evapotranspiration, increasing temperatures, and leaving the soil without cover.



9.4 Layers of a beech–maple–hemlock forest

Tree crowns form the uppermost layer, shrubs an intermediate layer, and herbs a lower layer. Mosses and lichen grow very close to the ground. In this schematic diagram, the vertical dimensions of the lower layers are greatly exaggerated.

9.5 Lichens

Lichens are plant forms that combine algae and fungi in a single symbiotic organism. They are abundant in some boreal and arctic habitats. Pictured here are reindeer lichen (dark gray) and caribou moss (light green) in Lac La Ronge Provincial Park, Saskatchewan (National Geographic Image Collection).

Herbs make up a major class of plant life-forms. They lack woody stems and so are usually small, tender plants. They occur in a wide range of shapes and leaf types. Some are *annuals*, living only for a single season. Some herbs are broad-leaved, and others are narrow-leaved, such as grasses. Herbs share few characteristics with each other, except that they usually form a lower layer than shrubs and trees. *Lichens* also grow close to the ground (Figure 9.5). They are life-forms in which algae and fungi live together, forming a single plant structure. Lichens dominate the vegetation in some alpine and arctic environments.

Forest is a vegetation structure in which trees grow close together. The crowns of forest trees often touch, so that their foliage largely shades the ground. Many forests in moist climates show at least three layers of life-forms—the tree, shrub, and herb layers. There is sometimes a fourth, lowermost layer of mosses and related very small plants. In *woodland*, tree crowns are separated by open areas that usually have a low herb or shrub layer.

Terrestrial Ecosystems—The Biomes

For humans, ecosystems are great natural factories producing food, fiber, fuel, and structural material. These useful products are manufactured by organisms using energy from the Sun, and we harvest that energy by using these ecosystem products. The products and productivity of ecosystems depend on their climate. Where temperature and rainfall cycles permit, ecosystems provide a rich bounty. Where temperature or rainfall cycles restrict ecosystems, human activities can also be limited. Of course, humans are also part of the ecosystems that we modify for our own benefit.

Ecosystems fall into two major groups—aquatic and terrestrial. *Aquatic ecosystems* include marine environments and the freshwater environments of the lands. Marine ecosystems include the open ocean, coastal estuaries, and coral reefs. Freshwater ecosystems include lakes, ponds, streams, marshes, and bogs. In this book, we'll focus on the **terrestrial ecosystems**, which are dominated by land plants spread widely over the upland surfaces of the continents. The terrestrial ecosystems are directly influenced by climate, so they are closely woven into the fabric of physical geography.

We divide terrestrial ecosystems into **biomes**. Although the biome includes both plant and animal life, green plants dominate the biome simply because of their enormous biomass. Plant geographers concentrate on the characteristic life-form of the green plants within the biome—principally trees, shrubs, lianas, and herbs—but also other life-forms in certain biomes.

There are five principal biomes. The **forest biome** is dominated by trees, which form a closed or nearly closed canopy. Forest requires an abundance of soil water, so forests are found in moist climates. Temperatures must also be suitable, requiring at least a warm season, if not warm temperatures the year round. The **savanna biome** is transitional between forest and grassland. It exhibits an open cover of trees with grasses and herbs underneath. The **grassland biome** develops in regions with moderate shortages of soil water. The semiarid regions of the dry tropical, dry subtropical, and dry midlatitude climates are the home of the grassland biome. Temperatures must also provide adequate warmth during the growing season.

The **desert biome** includes organisms that can survive a moderate to severe water shortage for most, if not all, of the year. Temperatures can range from very hot to cool. Plants are often xerophytes, showing adaptations to the dry environment. The **tundra biome** is limited by cold temperatures. Only small plants that can grow quickly when temperatures warm above freezing in the warmest month or two can survive.

Biogeographers recognize five principal biomes: forest, grassland, savanna, desert, and tundra. Formation classes are subdivisions of biomes based on vegetation structure and life-form.

Biogeographers break the biomes down farther into smaller vegetation units, called *formation classes*, using the life-form of the plants. For example, at least four and perhaps as many as six kinds of forests can be distinguished within the forest biome. At least three kinds of grasslands are easily recognizable. Deserts, too, span a wide range in terms of the abundance and life-form of plants. The formation classes described in the remaining portion of this chapter are major, widespread types that are clearly associated with specific climate types.

GEODISCOVERIES **Natural Vegetation Regions of the World**

Take a second look at the world map of vegetation regions and click on a formation class or biome to see a characteristic photo. An animation.

BIOMES, FORMATION CLASSES, AND CLIMATE

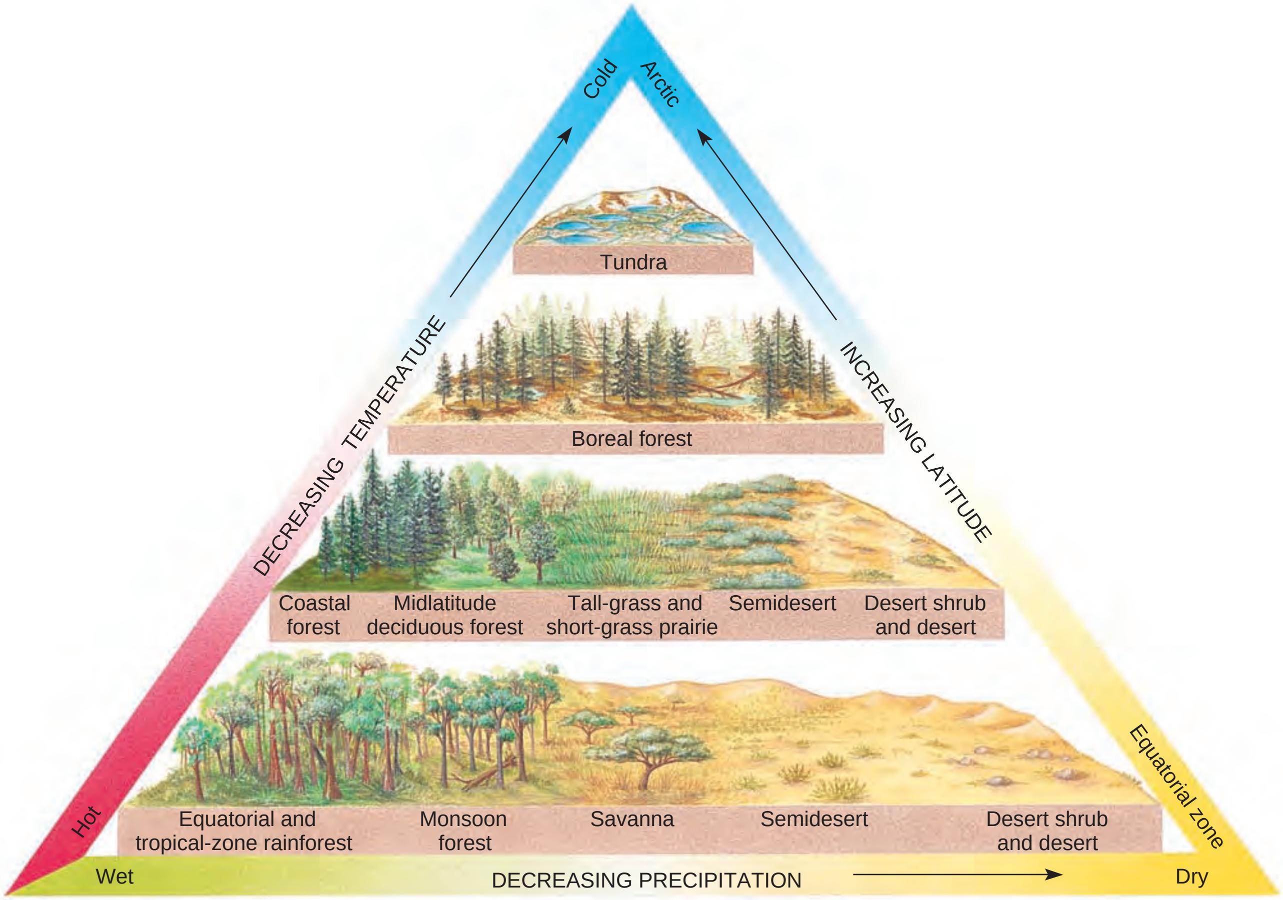
The pattern of formation classes depends heavily on climate. As climate changes with latitude or longitude, vegetation will also change. Figure 9.6 shows how vegetation formation classes respond to temperature and precipitation gradients. In both low- and midlatitude environments, strong precipitation gradients produce vegetation types grading from forest to desert. At high latitudes, decreasing temperatures control the transition from forest to tundra.

The diagram does not include seasonality. In low latitudes, savanna and grassland formation classes are found in regions with a distinct dry season. In the midlatitudes, west coasts are marked with a strong summer dry period, providing sclerophyll vegetation (not shown) in coastal regions and, farther poleward, encouraging the growth of lush coastal forests of conifers.

Figure 9.7 is a generalized world map of vegetation formation classes. It simplifies the very complex patterns of natural vegetation to show large uniform regions in which a given formation class might be expected to occur. Although the boundaries between vegetation types are shown as distinct lines, many real boundaries are gradational and located approximately.

GEODISCOVERIES **Interaction of Climate, Vegetation, and Soil**

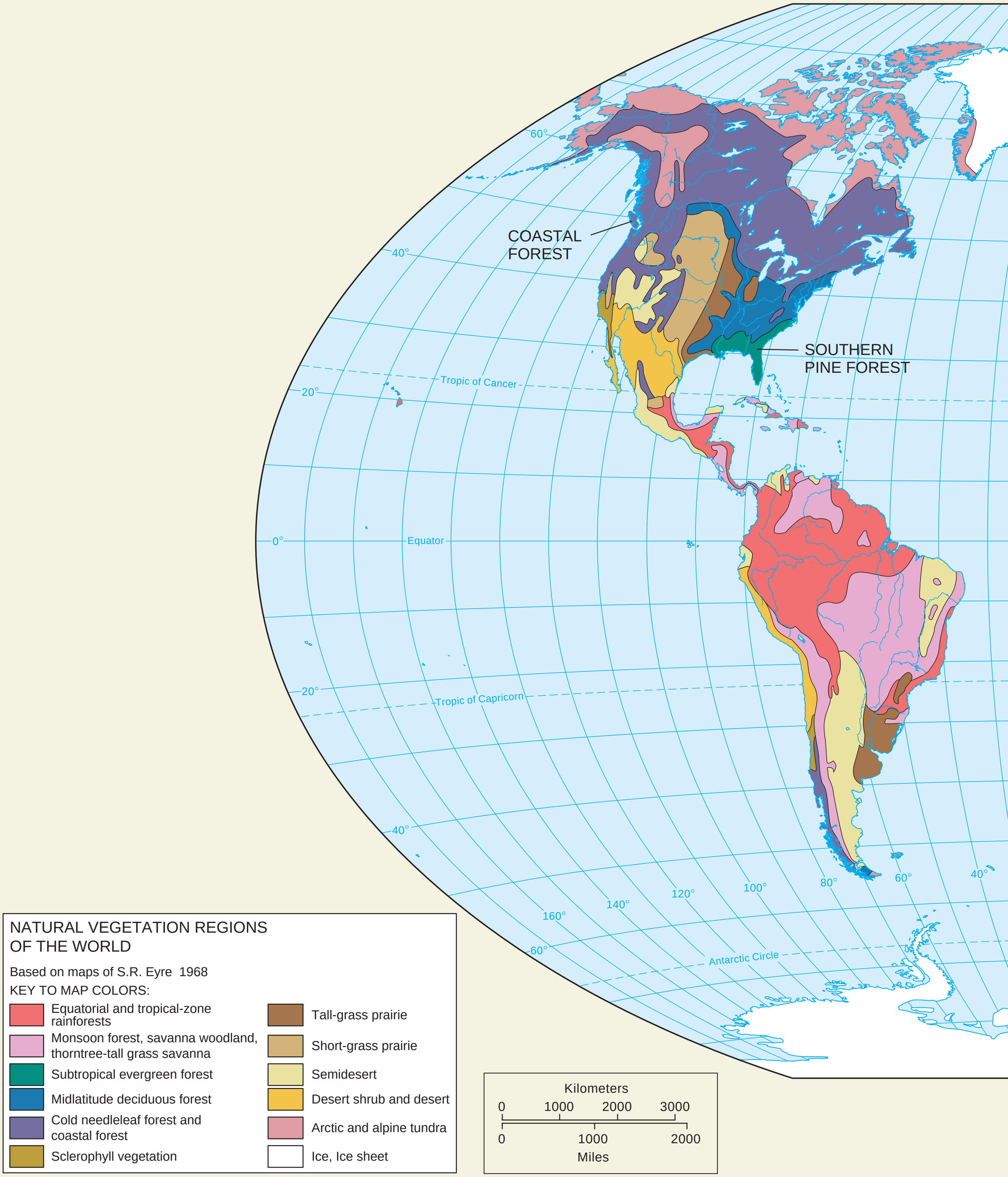
Return to the animations for Chapter 7 to view climate, vegetation, and soils maps superimposed to see common patterns. One animation for each of five global regions.

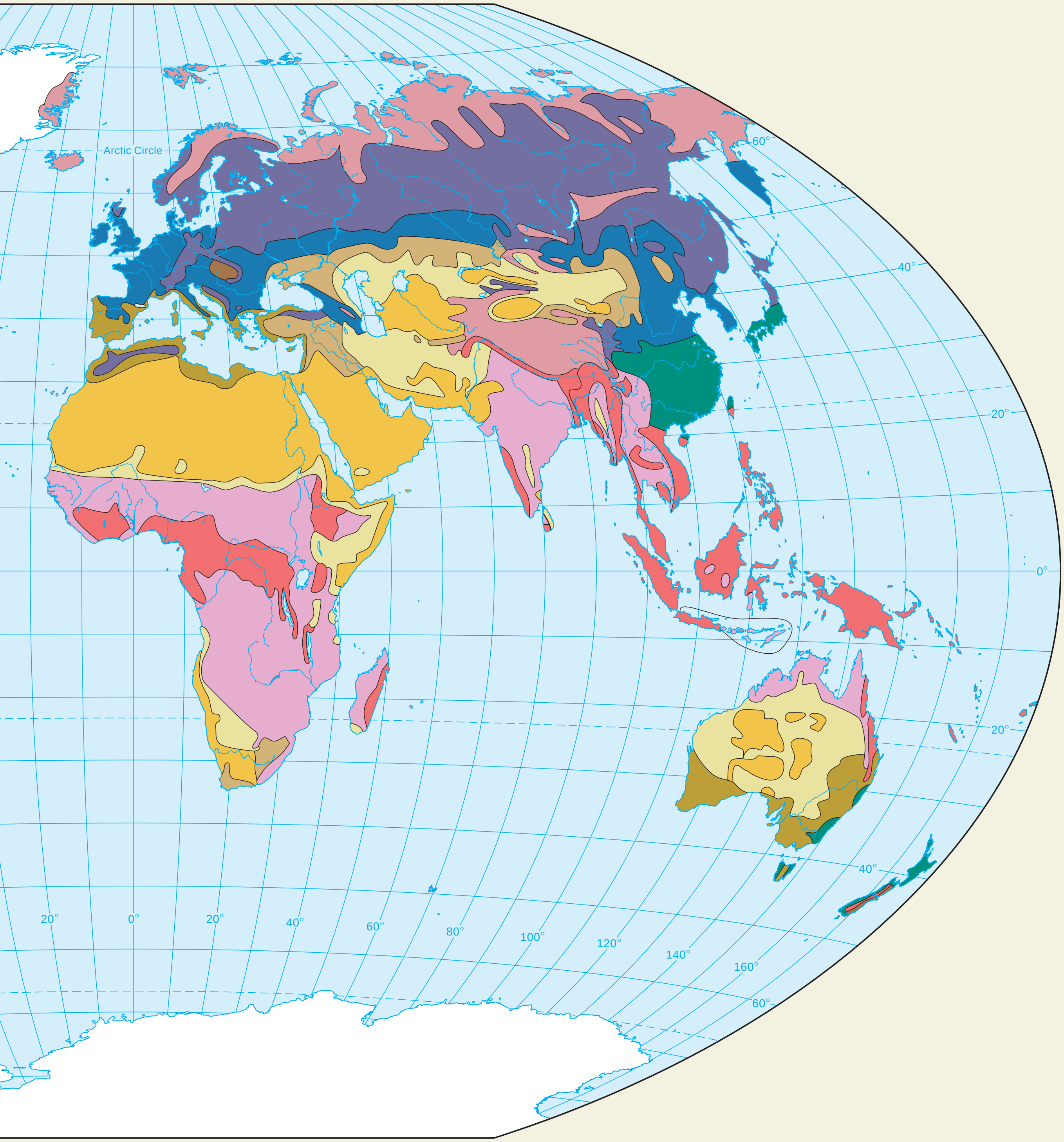


9.6 Vegetation types and climate

Temperature and precipitation are the two most important factors in determining the pattern of natural vegetation types.

9.7 Natural vegetation regions of the world




Arctic Circle
60°
40°
20°
0°
20°
40°
20°
0°
20°
40°
60°
80°
100°
120°
140°
160°
60°

Forest Biome

Within the **forest biome**, we can recognize six major formations: low-latitude rainforest, monsoon forest, subtropical evergreen forest, midlatitude deciduous forest, needleleaf forest, and sclerophyll forest. Ecologists sometimes recognize three principal types of forest as separate biomes, based on their widespread nature and occurrence in different latitude belts: low-latitude rainforest, midlatitude deciduous and evergreen forest, and boreal forest.

LOW-LATITUDE RAINFOREST

Low-latitude rainforest, found in the equatorial and tropical latitude zones, consists of tall, closely spaced trees (Figure 9.8). Equatorial and tropical rainforests are not jungles of impenetrable plant thickets. Rather, the floor of the low-latitude rainforest is usually so densely shaded by a canopy of tree crowns that plant foliage is sparse close to the ground. The trees define a number of distinct rainforest layers (Figure 9.9).

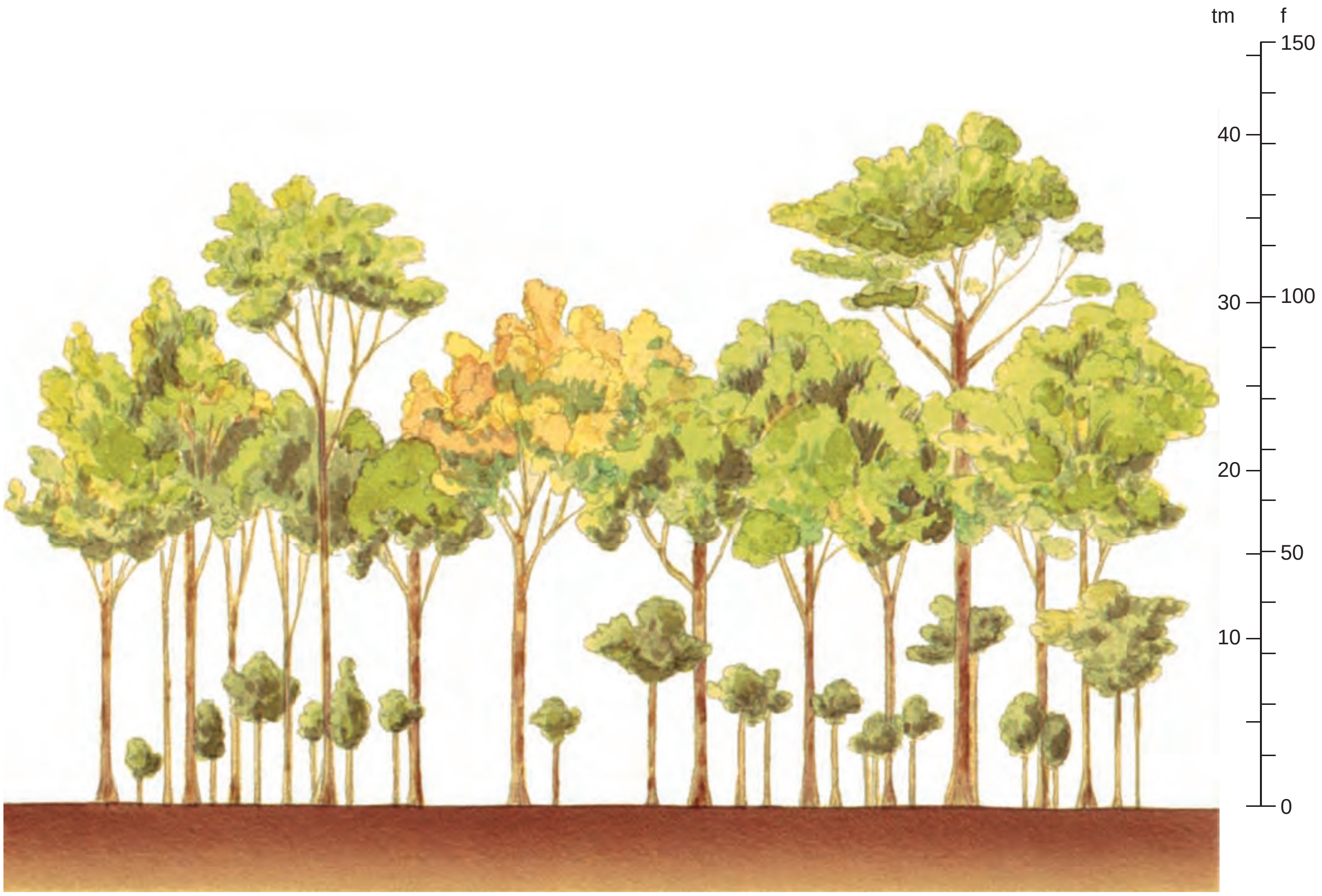
Typical of the low-latitude rainforest are thick, woody lianas supported by the trunks and branches of trees. They climb to the upper canopy, where light is available, and develop numerous branches of their own. *Epiphytes* ("air plants") are also common in low-latitude rainforest (Figure 9.8). These plants attach themselves to the trunk, branches, or foliage of trees and lianas. Their host is used solely as a means of physical support. Epiphytes include plants of many different types—ferns, orchids, mosses, and lichens.

9.8 Rainforest

▶ **Rain forest interior** Crowns form a continuous canopy shading lower layers. The lower two-thirds of the trees are characteristically smooth-barked and unbranched. Many rainforest species, especially in low or wet areas, have buttress roots extending out from the base of the tree. Kalimantan, Borneo, Indonesia (National Geographic Image Collection).

◀ **Epiphytes** In this photo from the El Yunque rainforest, Caribbean National Forest, Puerto Rico, red-flowering epiphytes adorn the trunks of Sierra palms.

▼ **Rainforest dweller** Many animal species of the rainforest are adapted to arborescent life. Here an orangutan in Gunung Palung National Park, Borneo, snacks upon *Polyalthia* fruit high above the forest floor. Toucans, parrots, and fruit-eating bats also exploit the resources of the rainforest canopy.



9.9 Rainforest layers

Crowns of the trees of the low-latitude rainforest tend to form two or three layers. The highest layer consists of scattered "emergent" crowns that protrude from the closed canopy below, often rising to 40 m (130 ft). Some emergent species develop wide buttress roots, which aid in their physical support. Below the layer of emergents is a second, continuous layer, which is 15 to 30 m (about 50 to 100 ft) high. A third, lower layer consists of small, slender trees 5 to 15 m (about 15 to 50 ft) high with narrow crowns.

Figure 9.10 shows the world distribution of low-latitude rainforests. These rainforests develop in a climate that is continuously warm, frost-free, and has abundant precipitation in all months of the year (or, at most, has only one or two dry months). These conditions occur in the wet equatorial climate ① and the monsoon and trade-wind coastal climate ②. Plants grow continuously throughout the year.

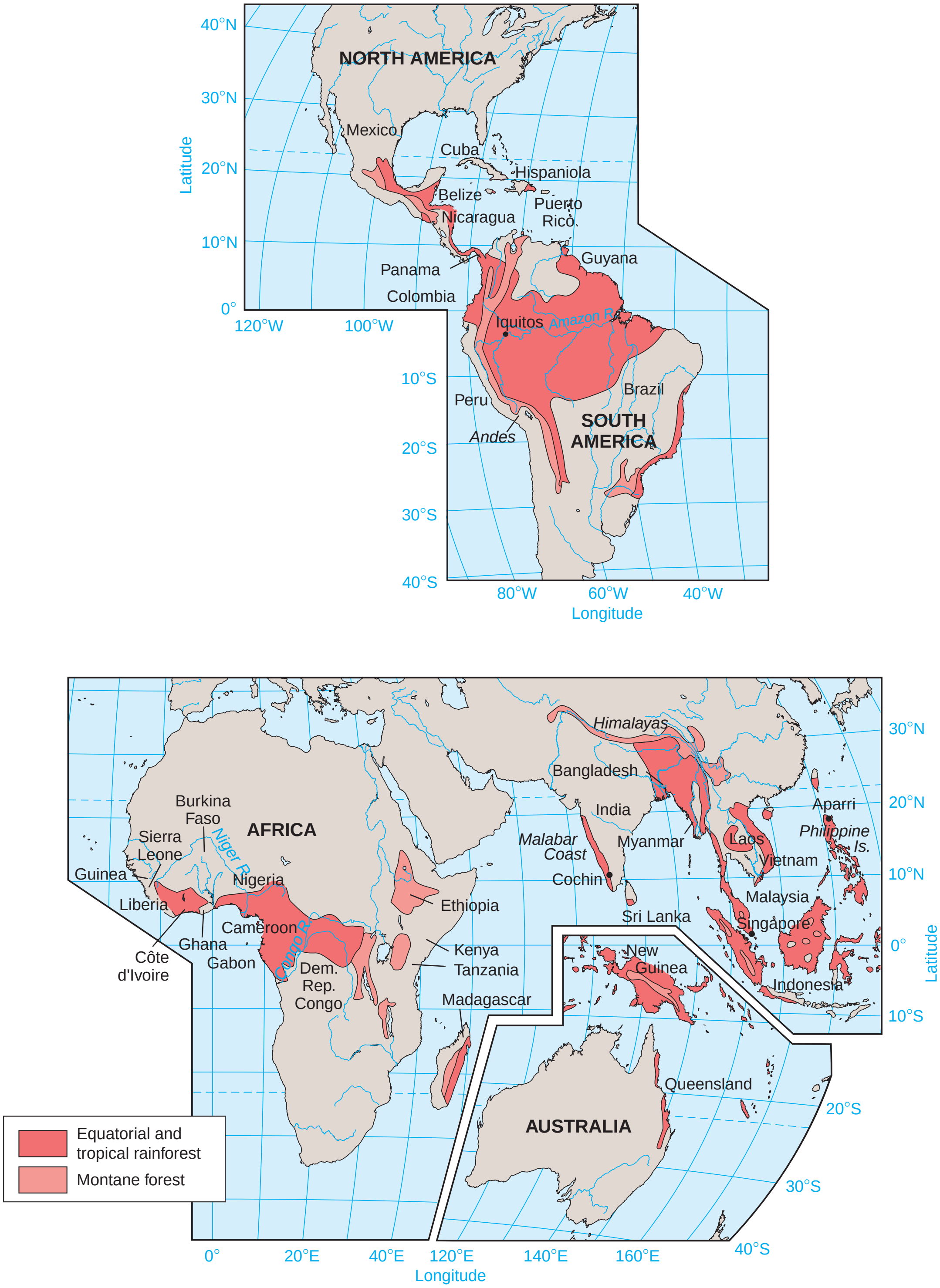
Low-latitude rainforests are very diverse, containing large numbers of plant and animal species. Broadleaf evergreen trees dominate the vegetation cover. The rainforest climate is wet all year or has a short dry season.

A particularly important characteristic of the low-latitude rainforest is the large number of species of plants and animals that coexist. Equatorial rainforests contain as many as 3000 tree species within a few square kilometers.

Large herbivores are uncommon in the low-latitude rainforest. They include the African okapi and the tapir of South America and Asia. Most herbivores are climbers, and they include many primates—monkeys and apes (Figure 9.8). Tree sloths spend their lifetimes hanging upside down as they browse the forest canopy. There are only a few large predators. Notable are the leopards of African and Asian forests and the jaguars and ocelots of the South American forests.

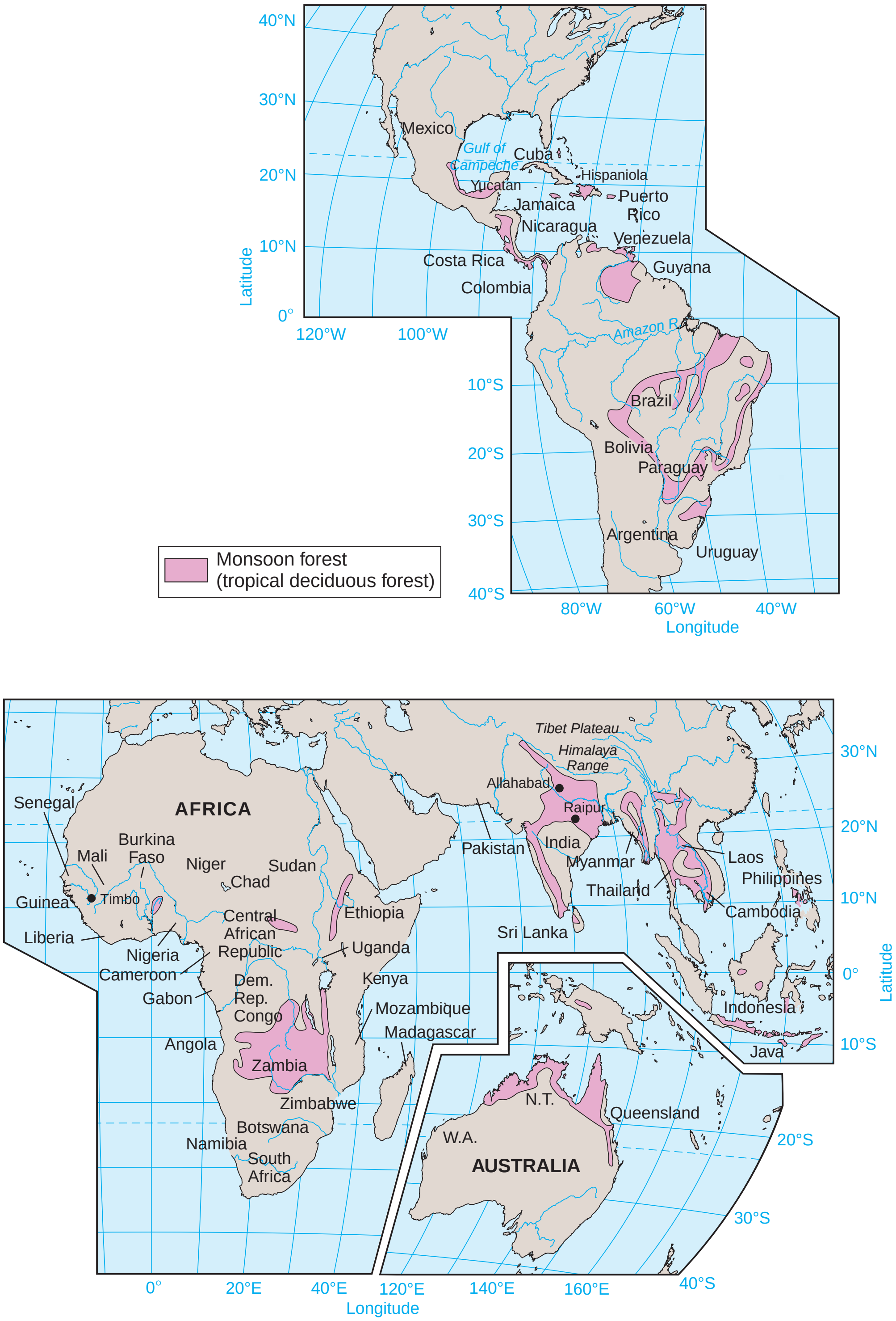
MONSOON FOREST

Figure 9.11 is a world map of the *monsoon forest*. It is typically open, but grades into woodland, with open areas occupied by shrubs and grasses (Figure 9.12). Monsoon forest of the tropical latitude zone differs from tropical rainforest because it is *deciduous*; that is, most of the trees of the monsoon forest shed their leaves because of stress during the long dry season that occurs at the time of low sun and cool temperatures.



9.10 Low-latitude rainforest

World map of low-latitude rainforest, showing equatorial and tropical rainforest types. A large area of rainforest lies astride the Equator and extends poleward through the tropical zone (lat. 10° to 25° N and S) along monsoon and trade-wind coasts. Within the low-latitude rainforest are many highland regions where temperatures are cooler and rainfall is increased by the orographic effect. The canopy of this *montane forest* is more open, with lower trees and smaller plants that luxuriate in the abundant rainfall.



9.11 World map of monsoon forest

9.12 Monsoon woodland

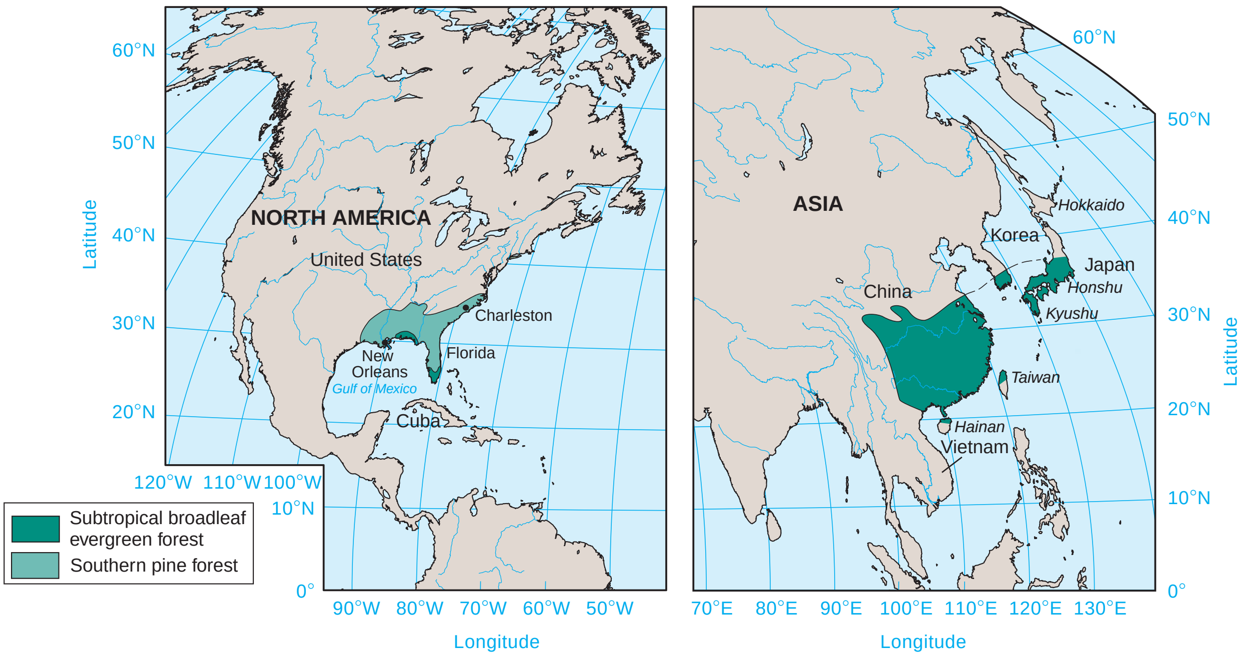
Monsoon woodland is a open forest of trees that are deciduous in the dry season. Tree crowns are lower and more rounded than in the low-latitude rainforest. Because sunlight penetrates the lower layers more easily, the understory is usually better developed. This photo is taken in the rainy season, with trees in full leaf. Bandipur National Park, Karnataka, India.

This forest develops in the wet-dry tropical climate ③, where a long rainy season alternates with a dry, rather cool season. The typical regions of monsoon forest are in Myanmar, Thailand, and Cambodia. In the monsoon forest of southern Asia, the teakwood tree was once abundant and was widely exported to the Western world to make furniture, paneling, and decking. Now this great tree is logged out. Large areas of monsoon forest also occur in south-central Africa and in Central and South America, bordering the equatorial and tropical rainforests.

Monsoon forest is an open cover of deciduous trees that shed their leaves during a pronounced dry season. It occurs in the wet-dry tropical climate ③, ranging from South America to Africa and southern Asia.

SUBTROPICAL EVERGREEN FOREST

Subtropical evergreen forest is generally found in regions of moist subtropical climate ⑥, where winters are



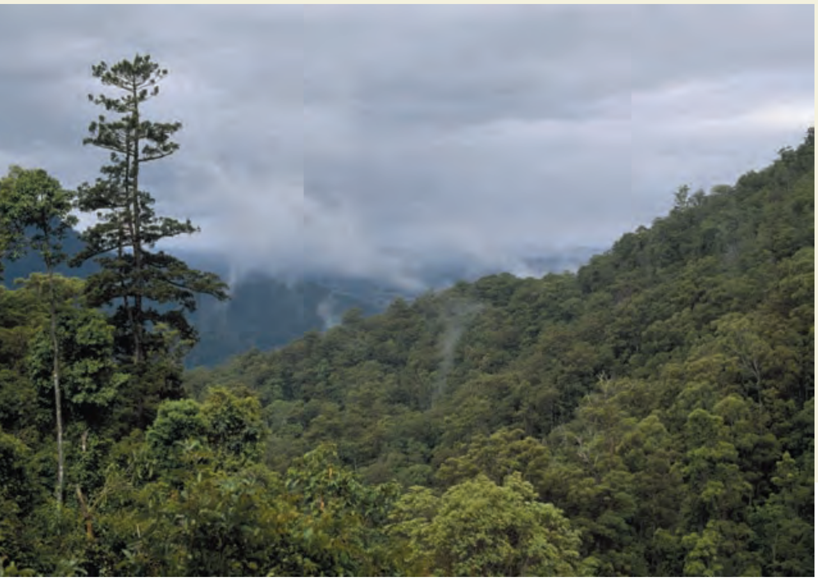
9.13 Map of subtropical evergreen forest

Northern hemisphere map of subtropical evergreen forests, including the needleleaf southern pine forest. Broadleaf evergreen forest includes trees of the laurel and magnolia families, so it is also termed "laurel forest." Because the laurel forest region is intensely cultivated, little natural laurel forest remains.

9.14 Subtropical evergreen forest

This forest of mild and moist climates includes both broadleaf and needleleaf types.

▼ **Broadleaf** Here broad-leaved species dominate over a lower layer of smaller plants. This example is from New South Wales, Australia, and includes many species of eucalyptus (National Geographic Image Collection).



▼ **Needleleaf** The subtropical needleleaf evergreen forest inhabits dry, sandy soils, and it experiences occasional droughts that lead to fires. Pines are well-adapted to these conditions and form a stable vegetation cover in many areas. Where fire is less frequent, a layer of broadleaf shrubs and small trees often occurs beneath the pines. Shown here is a longleaf pine stand near Aiken, South Carolina (National Geographic Image Collection).

mild and there is ample rainfall throughout the year (Figure 9.13). This forest occurs in two forms: broadleaf and needleleaf (Figure 9.14).

The subtropical evergreen forest includes both broadleaf and needleleaf types and is found in moist subtropical climate ⑥ regions of southeastern North America and Southeast Asia. Most of this formation class has been lost to cultivation.

The *subtropical broadleaf evergreen forest* has fewer tree species than the low-latitude rainforests, which are also broadleaf evergreen types. Trees are also not as tall as in the low-latitude rainforests. Their leaves tend to be smaller and more leathery, and the leaf canopy is less dense. The subtropical broadleaf evergreen forest often has a well-developed lower layer of vegetation. Depending on the location, this layer may include tree ferns, small palms, bamboos, shrubs, and herbaceous plants. There are also many lianas and epiphytes. The subtropical broadleaf evergreen forest is associated with the moist subtropical climate ⑥ in the southeastern United States, southern China, and southern Japan. In these areas, the land has been cleared of natural vegetation and replaced by agriculture for centuries.

Figure 9.14 shows the subtropical evergreen forests of the northern hemisphere. The *subtropical needleleaf evergreen forest* occurs only in the southeastern United States. Here it is referred to as the southern pine forest, since it is dominated by species of pine. Much of this area is now in commercial pine plantations that produce lumber, kraft paper, cardboard, and related wood products.

MIDLATITUDE DECIDUOUS FOREST

Midlatitude deciduous forest is the native forest type of eastern North America and western Europe (Figure 9.15). It is dominated by tall, broadleaf trees that provide a continuous and dense canopy in summer but shed their leaves completely in the winter. Lower layers of small trees and shrubs are weakly developed. In the spring, a lush layer of low herbs quickly develops but soon fades after the trees reach full foliage and shade the ground. The deciduous forest includes a great variety of animal life, stratified according to canopy layers.

Figure 9.16 is a map of midlatitude deciduous forests, which are found almost entirely in the northern hemisphere. This forest type is associated with the moist continental climate ⑩, which receives adequate

9.15 Deciduous forest

▼ **Trees of the forest** Shown here is a forest of maple, oak, and hickory in fall colors. Monongahela National Forest, West Virginia (National Geographic Image Collection).

▲ **White-tailed deer** Among the large herbivores that graze in the deciduous forest are the white-tailed deer of North America and the red deer and roe deer of Eurasia (National Geographic Image Collection).

◀ **Fox squirrel** Scampering freely from the trees to the forest floor, the fox squirrel feeds primarily on nuts and seeds of the deciduous forest. In the canopy, squirrels are joined by many species of birds and insects (National Geographic Image Collection).

▶ **Woodchuck** Many small mammals burrow in forest soils for shelter or food, including the woodchuck, or groundhog, shown here. They are joined by ground squirrels, mice, and shrews (National Geographic Image Collection).

precipitation in all months, normally with a summer maximum. There is a strong annual temperature cycle with a cold winter season and a warm summer.

Common trees of the deciduous forest of eastern North America, southeastern Europe, and eastern Asia are oak, beech, birch, hickory, walnut, maple, elm, and ash. Where the deciduous forests have been cleared by lumbering, pines readily develop as second-growth forest.

In western Europe, the midlatitude deciduous forest is associated with the marine west-coast climate ⑧. Here the dominant trees are mostly oak and ash, with beech in cooler and moister areas. In Asia, the midlatitude deciduous forest occurs as a belt between the boreal forest to the north and steppelands to the south. A small area of deciduous forest is found in Patagonia, near the southern tip of South America.

Midlatitude deciduous forest consists largely of trees that drop their leaves during the cold season. It is characteristic of the marine west-coast ⑧ and moist continental ⑩ climates.

NEEDLELEAF FOREST

Needleleaf forest is composed largely of *conifers*—straight-trunked, cone-shaped trees with relatively short branches and small, narrow, needle-like leaves. Most conifers are evergreen, retaining their needles for several years before shedding them. At any location, species are usually few in number. In fact, large tracts of needleleaf forest consist

9.16 Map of midlatitude deciduous forest

almost entirely of only one or two species. When the needleleaf forest is dense, it provides continuous and deep shade to the ground. Lower layers of vegetation are sparse or absent, except for possibly a thick carpet of mosses.

Boreal forest is the cold-climate needleleaf forest of high latitudes (Figure 9.17). It occurs in two great continental belts, one in North America and one in Eurasia (Figure 9.18). These belts span their land masses from west to east in latitudes 45° N to 75° N, and they closely correspond to the region of boreal forest climate ⑪.

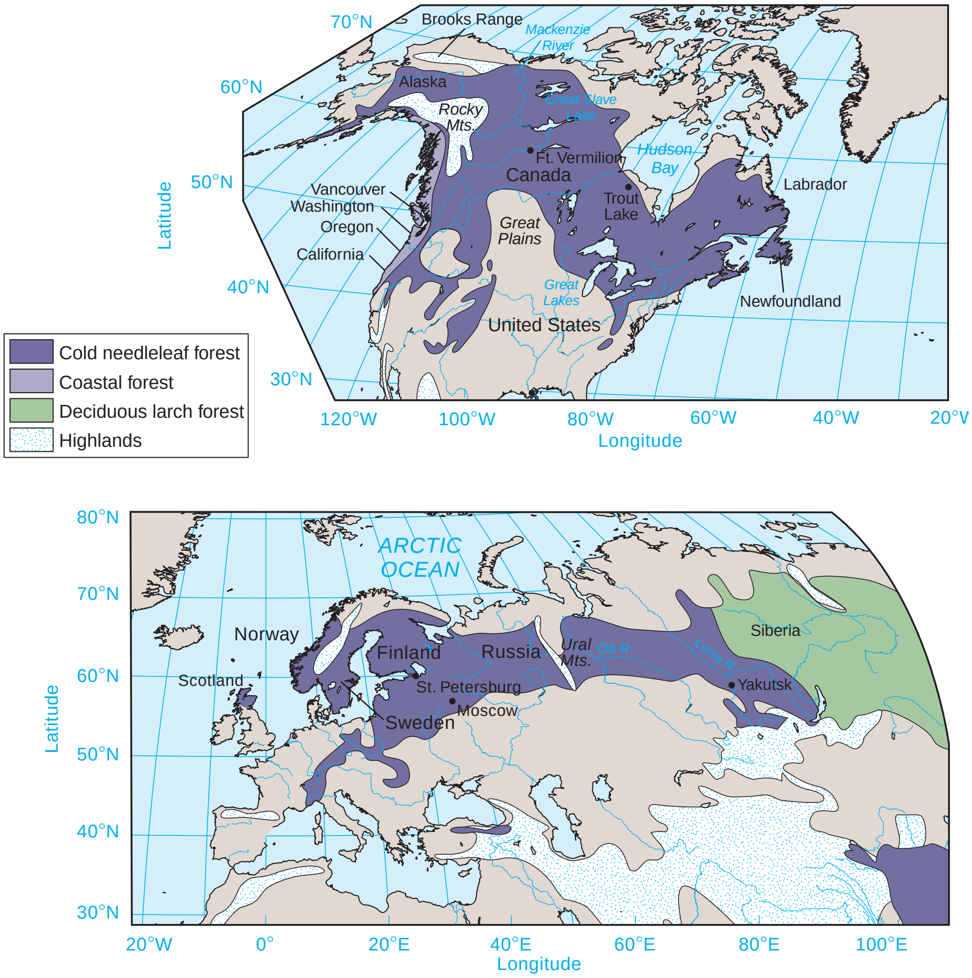
The boreal forest of North America, Europe, and western Siberia is composed of such evergreen conifers as spruce and fir, while the boreal forest of north-central and eastern Siberia is dominated by larch. The larch tree sheds its needles in winter and is thus a deciduous needleleaf tree. Broadleaf deciduous trees, such as aspen, balsam poplar, willow, and birch, tend to take over rapidly in areas of needleleaf forest that have been burned over. These species can also be found bordering streams and in open places. Between the boreal forest and the midlatitude deciduous forest lies a broad transition zone of mixed boreal and deciduous forest.

Coastal forest is a distinctive needleleaf evergreen forest of the Pacific Northwest coastal belt, ranging in latitude from northern California to southern Alaska. Here, in a band of heavy orographic precipitation, mild temperatures, and high humidity, are perhaps the densest of all conifer forests, with magnificent specimens of cedar, spruce, and Douglas fir. At the extreme southern end, coastal forest includes the world's largest trees—redwoods (Figure 9.19).

Needleleaf forest includes boreal and coastal forest. Boreal forest stretches across the northern reaches of North America and Eurasia. Coastal forest is restricted to the coast ranges of the Pacific Northwest region.

9.17 Boreal forest

The view of the boreal forest, the Denali National Park, Alaska, pictured here just after the first snowfall of the season. At this location, near the northern limits of the boreal forest, the tree cover is sparse. The golden leaves of aspen mark the presence of this deciduous species.



9.18 Map of needleleaf forest

Northern hemisphere map of cold-climate needleleaf forests, including coastal forest.

9.19 Coastal forest

Along the western coast of North America from central California to Alaska is a forest dominated by many unique species of needleleaf trees. Shown here is a stand of coast redwoods, *Sequoia sempervirens*, a species found at the southern end of this range. It is generally considered the tallest of tree species, attaining a height of 115 m (377 ft) and diameter of 7 m (23 ft) at the base. These redwoods are at Muir Woods National Monument, not far from San Francisco (National Geographic Image Collection).

Individual redwood trees attain heights of over 115 m (377 ft) and diameters of over 7 m (23 ft) at the base.

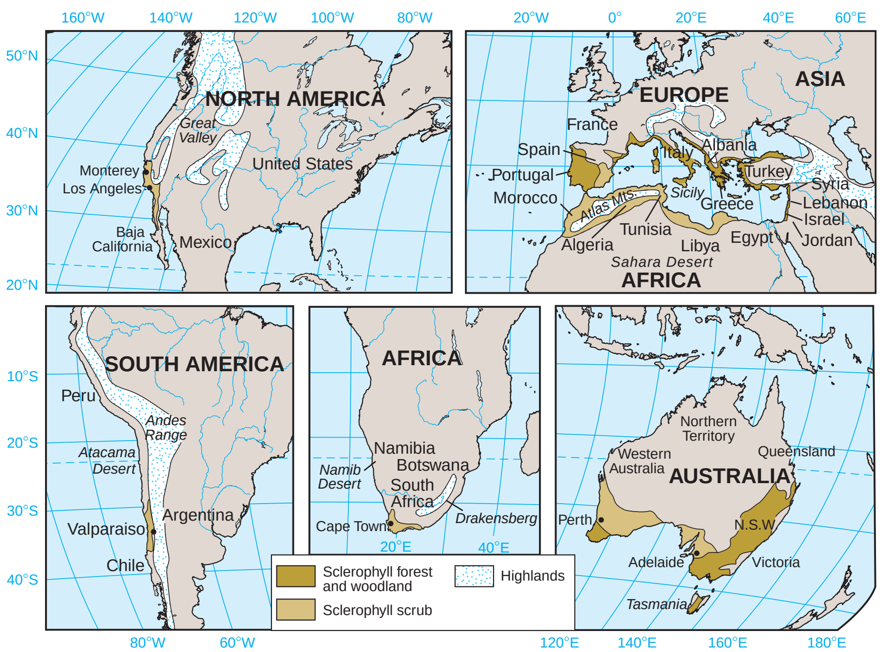
SCLEROPHYLL FOREST

The native vegetation of the Mediterranean climate ⑦ is adapted to survival through the long summer drought. Shrubs and trees that can survive such drought are equipped with small, hard, or thick leaves that resist water loss through transpiration. These plants are called *sclerophylls*.

Sclerophyll forest is made up of trees with small, hard, leathery leaves. The trees are often low-branched and gnarled, with thick bark. The formation class includes *sclerophyll woodland*, an open forest in which only 25 to 60 percent of the ground is covered by trees. Also included are extensive areas of *scrub*, a plant formation type consisting of shrubs covering somewhat less than half of the ground area. The trees and shrubs are evergreen, retaining their thickened leaves despite a severe annual drought. Our map of sclerophyll vegetation, Figure 9.20, includes forest, woodland, and scrub types.

Sclerophyll forest is dominated by low trees with thick, leathery leaves that are well-adapted to the long summer drought of the Mediterranean climate ⑦. Southern California's chaparral, found on coast-range slopes, is a form of sclerophyll scrub.

Sclerophyll forest is limited to west coasts between 30° and 40°–45° N and S latitude. In the California coastal ranges, the sclerophyll forest or woodland is typically dominated by live oak and white oak. Grassland occupies the open ground between the



9.20 Map of sclerophyll forest

9.21 Chaparral

Chaparral varies in composition with elevation and exposure. It may contain wild lilac, manzanita, mountain mahogany, poison oak, and live oak.

scattered oaks. Much of the remaining vegetation is sclerophyll scrub known as *chaparral* (Figure 9.21).

In the Mediterranean lands, the sclerophyll forest forms a narrow coastal belt ringing the Mediterranean Sea. Here, the Mediterranean forest consists of such trees as cork oak, live oak, Aleppo pine, stone pine, and olive. Important areas of sclerophyll forest, woodland, and scrub are found in southeast, south-central, and southwest Australia, Chile, and the Cape region of South Africa.

Over the centuries, human activity has reduced the sclerophyll forest to woodland or destroyed it entirely. Today, large areas of this former forest consist of dense scrub.

Savanna and Grassland Biomes

SAVANNA BIOME

The **savanna biome** is usually associated with the tropical wet-dry climate ③ of Africa and South America. Its vegetation ranges from woodland to grassland. In *savanna woodland*, the trees are spaced rather widely apart because there is not enough soil moisture during the dry season to support a full tree cover (Figure 9.22). The open spacing lets a dense lower layer develop, which usually consists of grasses. The woodland has an open, park-like appearance. Savanna woodland usually lies in a broad belt adjacent to equatorial rainforest.

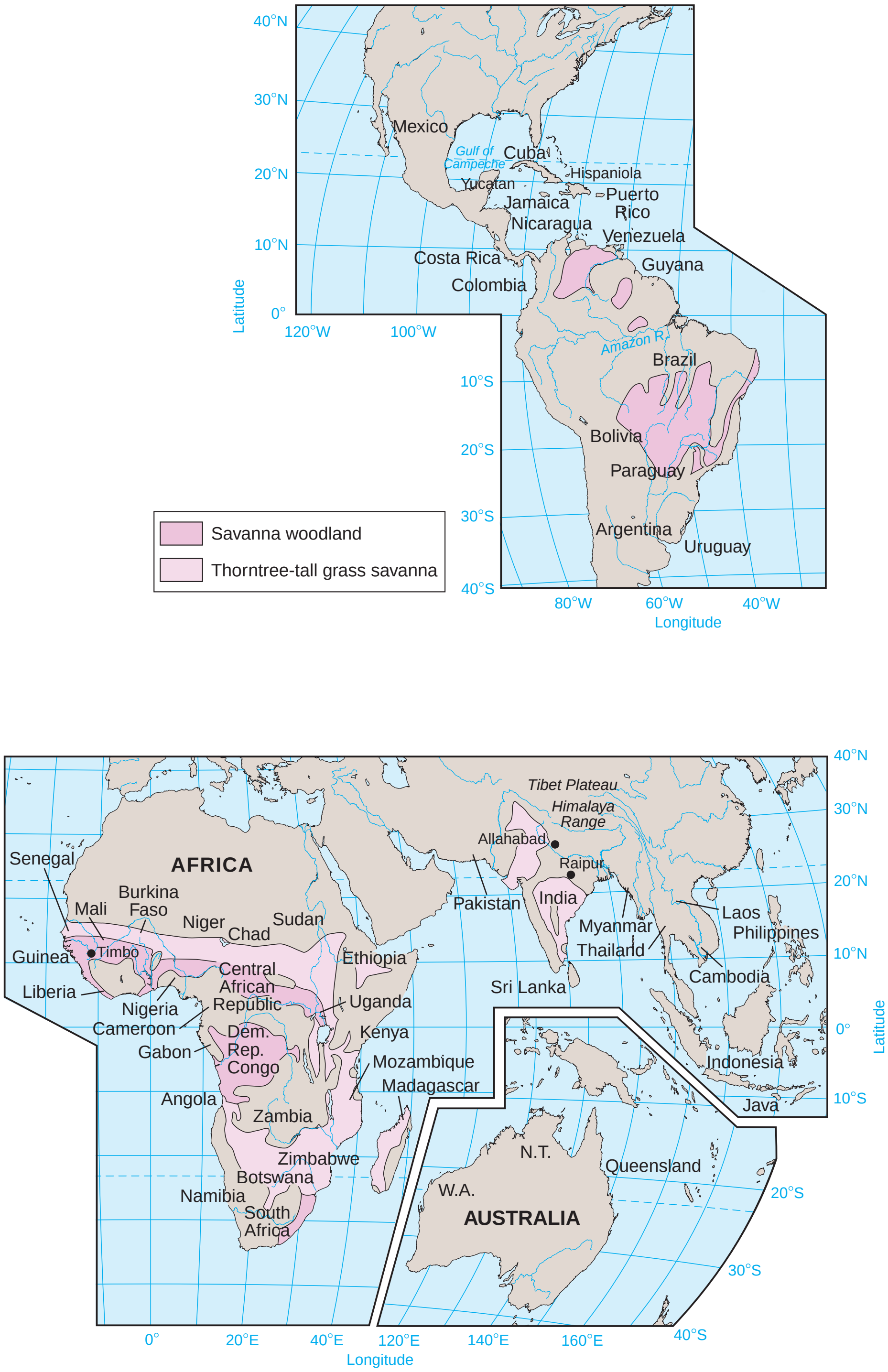
In the tropical savanna woodland of Africa, the trees are of medium height. Tree crowns are flattened or umbrella-shaped, and the trunks have thick, rough bark. Some species of trees are xerophytic forms—adapted to the dry environment with small leaves and thorns. Others are broad-leaved deciduous species that shed their leaves in the dry season. In this respect, savanna woodland resembles monsoon forest.

Fires occur frequently in the savanna woodland during the dry season, but the tree species are particularly resistant to fire. Many geographers think that periodic burning of the savanna grasses keeps forest

9.22 Savanna

▼ **Savanna woodland** Where the trees are more closely spaced, we have savanna woodland. This example is from the central Kalahari Desert, Botswana. The rich green of the landscape identifies the time of year as just after the rainy season.

▼ **Thorntree-tall-grass savanna** The long dry season of the tropical wet-dry climate ③ restricts the vegetation to grasses with an open canopy of drought-resistant trees, such as the acacia shown in this photo. The zebras are one of more than a dozen species of antelope that graze the savanna. Serengeti National Park, Tanzania (National Geographic Image Collection).



9.23 World map of savanna woodland and thorntree-tall-grass savanna

from invading the grassland. Fire doesn't kill the underground parts of grass plants, but it limits tree growth to fire-resistant species. So, many rainforest tree species that might otherwise grow in the wet-dry climate regime are suppressed by fires. Browsing animals also kill many young trees, helping maintain grassland at the expense of forest.

The regions of savanna woodland are shown in Figure 9.23. In Africa, the savanna woodland grades into a belt of *thorntree-tall-grass savanna*, a formation class transitional to the desert biome (Figure 9.22). The trees are largely of thorny species. They are more widely scattered, and the open grassland is more extensive than in the savanna woodland. One characteristic tree is the

9.24 Animals of the African savanna

▲ **Lions** The abundance of large grazing herbivores brings predators, including the lion. Shown here is a pride of lions out for a sunset stroll through the tall grass of Masai Mara National Reserve, Kenya (National Geographic Image Collection).

▼ **Wildebeest** These strange-looking animals are actually antelopes. More than a dozen antelope species graze on the savanna. Each one has a particular preference for eating either the grass blade, sheath, or stem. Grazing stimulates the grasses to continue to grow, and so the ecosystem is more productive when grazed than when left alone (National Geographic Image Collection).

◀ **Spotted hyena** Another savanna predator is the hyena, which does not attack its prey directly like the lion, but runs it to exhaustion. Small packs of 6 to 12 animals do the hunting, employing different strategies for different antelope prey. They fear only the big cats, such as lions. Shown here is a hyena carrying a newborn Thomson's gazelle. Serengeti National Park, Tanzania. (National Geographic Image Collection).

flat-topped acacia. Elephant grass is a common species. It can grow to a height of 5 m (16 ft) to form an impenetrable thicket.

Savanna biome vegetation is described as rain-green. That's because the thorntree-tall-grass savanna is closely identified with the semiarid subtype of the dry tropical and subtropical climates (④s, ⑤s). In the semiarid climate, soil-water storage is only enough for plants during the brief rainy season. After rains begin, the trees and grasses quickly green up. Vegetation of the monsoon forest is also rain-green.

The savanna biome is adapted to a strong wet-dry annual cycle. Grazing by large mammals and periodic burning in the dry season maintain the openness of the savanna by suppressing tree seedlings.

The African savanna is widely known for the diversity of its large grazing mammals (Figure 9.24). With these grazers come a large variety of predators—lions, leopards, cheetahs, hyenas, and jackals. Elephants are the largest animals of the savanna and adjacent woodland regions.

GRASSLAND BIOME

The **grassland biome** includes two major formation classes—tall-grass prairie and steppe (Figure 9.25). *Tall-grass prairie* is a ground cover of tall grasses with also some broad-leaved herbs, named *forbs*. Like the savanna biome, grasslands are maintained by frequent burning, which kills trees and shrubs that might otherwise dominate the grasses. As a result, trees and shrubs are not found on the prairie, but they do occur

9.25 Grasslands

▼ **Tall-grass prairie** In addition to grasses, tall-grass prairie vegetation includes many forbs, such as the wildflowers shown in this photo. The grasses are deeply rooted and form a thick and continuous turf (National Geographic Image Collection).

▼ **Steppe** Buffalo grass is typical of the American steppe, as are sunflowers and loco weeds. There may also be some scattered shrubs and low trees. Because the plant cover is poor, much of the bare soil is exposed.

in narrow bands and patches of forest in and along stream valleys.

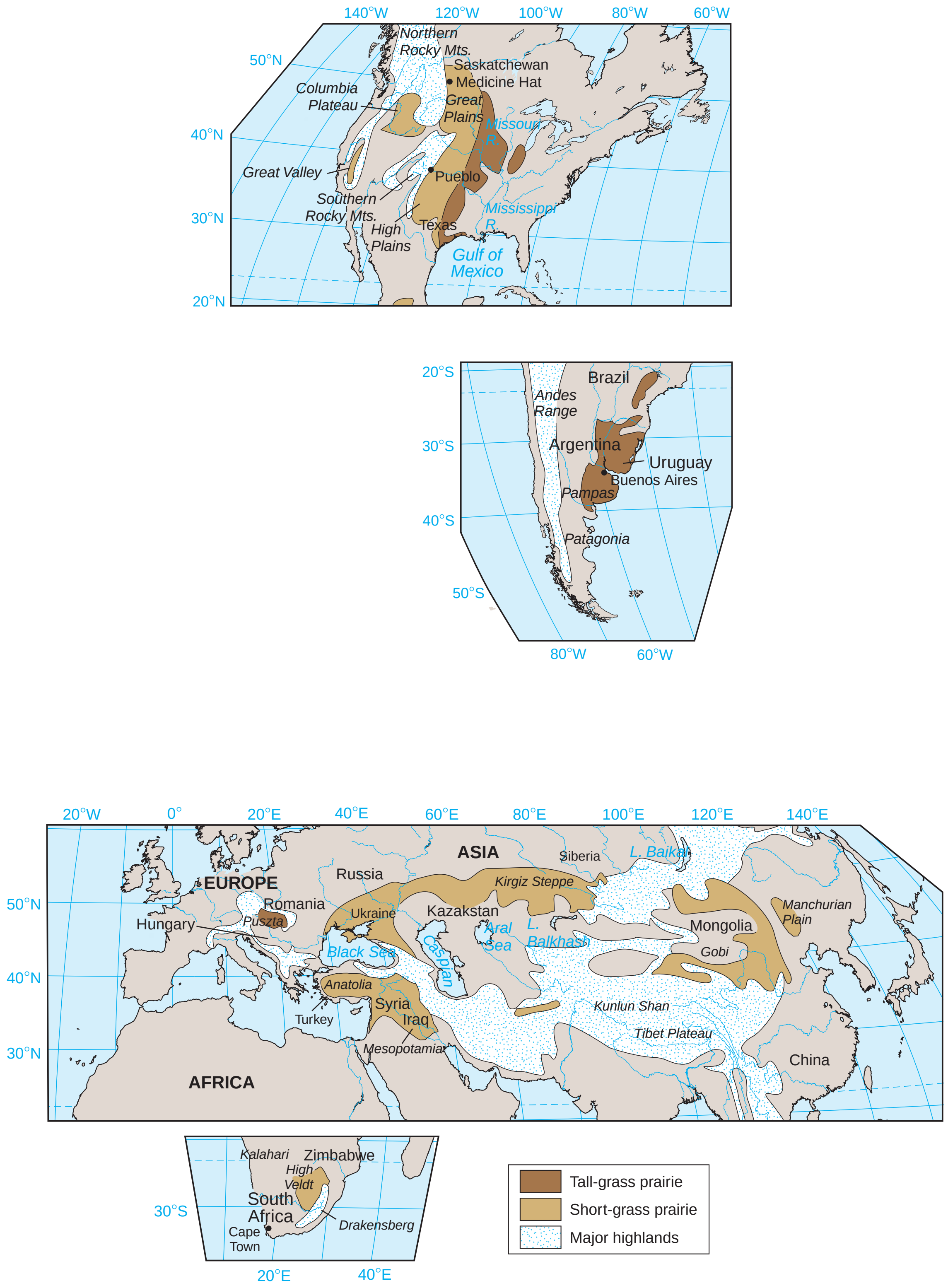
Figure 9.26 shows the distribution of grassland around the world. Prairie grasslands are associated with the drier areas of moist continental climate ⑩, and steppe grasslands correspond well with the semiarid subtype of the dry continental climate ⑨s.

North American tall-grass prairies once lay in a belt from the Texas Gulf coast to southern Saskatchewan, and extended eastward into Illinois. Now they have been converted almost entirely to agricultural land. Another major area of tall-grass prairie is the Pampa region of South America, which occupies parts of Uruguay and eastern Argentina. The Pampa region falls into the moist subtropical climate ⑥ with mild winters and abundant precipitation.

Steppe, or *short-grass prairie*, consists of sparse clumps of short grasses. Steppe grades into semidesert in dry environments and into prairie where rainfall is higher. Steppe grassland is concentrated largely in the midlatitude areas of North America and Eurasia.

The animals of the grassland are distinctive, including many grazing mammals. The grassland ecosystem supports some rather unique adaptations to life (Figure 9.27). Animals have learned to jump or leap, to get an unimpeded view of their surroundings. We see jackrabbits and jumping mice, and the pronghorn combines the leap with great speed, which allows it to avoid predators and fire. Many animals burrow because the soil provides the only shelter in the exposed grasslands. Examples are burrowing rodents, including prairie dogs, gophers, and field mice. Rabbits exploit old burrows, using them for nesting or shelter. Invertebrates also seek shelter in the soil, and many are adapted to living within the burrows of rodents, where extremes of moisture and temperature are substantially moderated.

The grassland biome includes tall-grass prairie and short-grass prairie (steppe). Tall-grass prairie provides rich agricultural land suited to cultivation and cropping. Short-grass prairie occupies vast regions of semidesert and is suited to grazing.



9.26 World map of the grassland biome in subtropical and midlatitude zones

9.27 Grassland animals

▼ **American bison** Prairie grasslands are the home of many types of grazing animals, including the American bison, also known as the buffalo. Once extremely widespread throughout the Great Plains, it was hunted to near extinction in the nineteenth century. These animals are part of a managed herd in Kentucky. Other prairie grazers include the elk and the pronghorn antelope (National Geographic Image Collection).

▼ **Prairie dog** Many animals burrow into the prairie soil for shelter, such as the prairie dog. These highly social animals live in colonies or "dogtowns" of hundreds of animals. They feed on grasses, forbs, and insects (National Geographic Image Collection).

◀ **Jackrabbit** The jackrabbit is a common grazer of the prairies and steppes. It has developed a leaping habit, along with the pronghorn and jumping mouse, that allows it to see above the grass as it moves (National Geographic Image Collection).

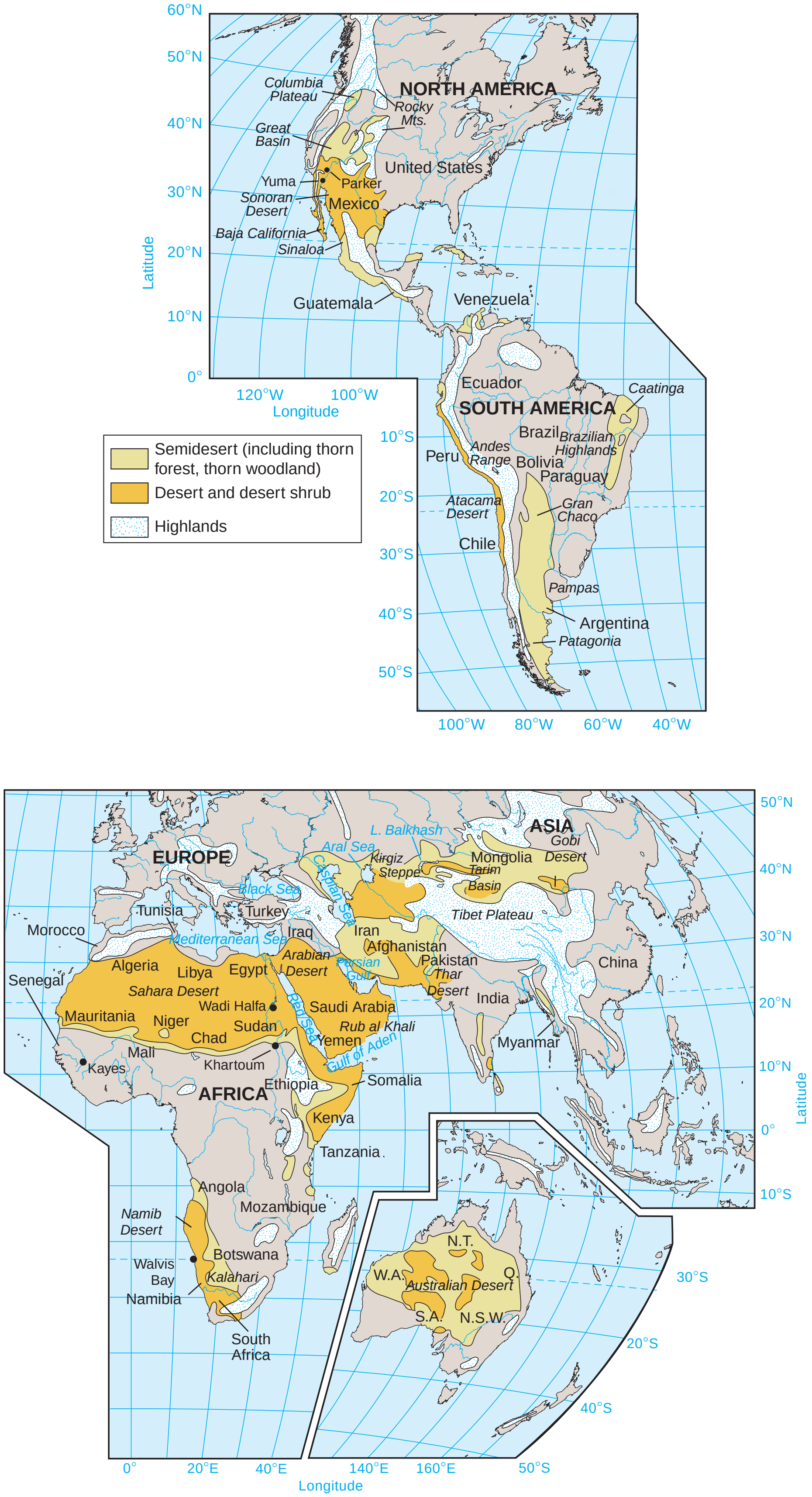
Desert and Tundra Biomes

DESERT BIOME

The **desert biome** includes several formation classes that are transitional from grassland and savanna biomes into vegetation of the arid desert. Our map of the desert biome (Figure 9.28) recognizes two basic formation classes: semidesert and dry desert.

Semidesert is a transitional formation class found in a wide latitude range—from the tropical zone to the midlatitude zone (Figure 9.29). It is identified primarily with the arid subtypes of all three dry climates. Semidesert consists primarily of sparse xerophytic shrubs. One example is the sagebrush vegetation of the middle and southern Rocky Mountain region and Colorado Plateau. In recent times, overgrazing and trampling by livestock have helped semidesert shrub vegetation expand widely into areas of the western United States that used to be steppe grasslands.

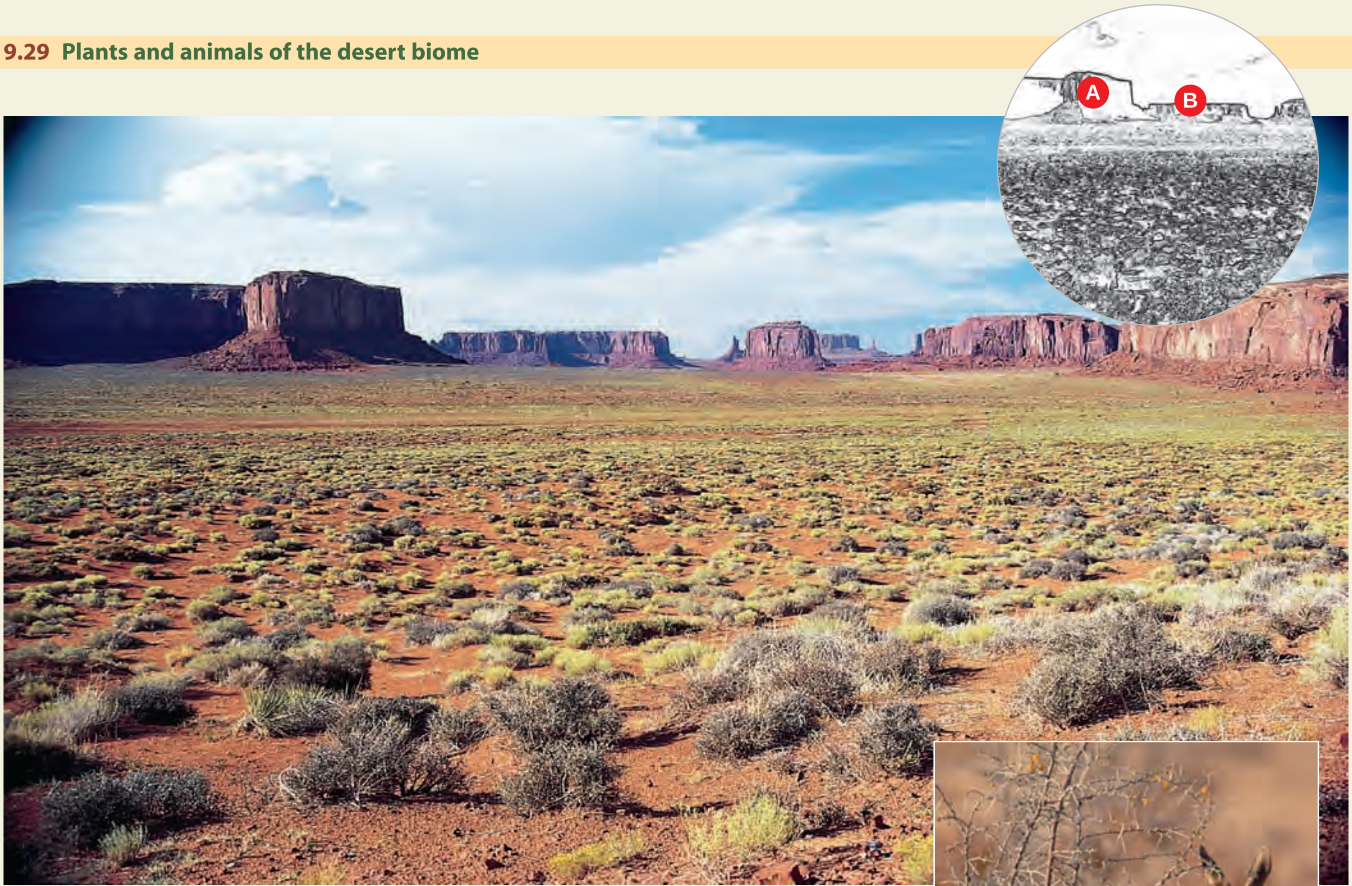
Thorntree semidesert of the tropical zone is made up of xerophytic trees and shrubs that are adapted to a climate



9.28 Map of the desert biome

World map of the desert biome, including desert and semidesert formation classes.

9.29 Plants and animals of the desert biome



▲ **Sagebrush semidesert** Sparse grasses and shrubs, largely sagebrush, provide the vegetation cover near Monument Valley, Arizona.

EYE ON THE LANDSCAPE **What else would the geographer see?** These tall, columnar landforms are buttes (A). Mesas are larger, isolated rock platforms (B). Here in Monument Valley, they are formed by a thick layer of uniform sandstone, which breaks up into rectangular blocks as it weathers. The blocks fall away, leaving a vertical cliff face behind.

▶ **Thorntree semidesert** The thorntree semidesert formation is found in tropical climates with very long dry seasons and short, but intense, rainy seasons. It consists of a sparse vegetation cover of grasses and thorny shrubs that are dormant for much of the year. This photo shows a steenbok (a small african Antelope) in Etosha National Park, Namibia.

with a very long, hot dry season and only a very brief, but intense, rainy season. We find these conditions in the semiarid and arid subtypes of the dry tropical ④ and dry subtropical ⑤ climates. The thorny trees and shrubs are known locally as thorn forest, thornbush, or thornwoods. In some places, cactus plants are abundant.

Dry desert is a formation class of plants that are widely dispersed over the ground. It consists of small, hard-leaved, or spiny shrubs, succulent plants (such as cactus), or hard grasses. Many species of small annual plants only appear after rare and heavy downpours. In fact, many of the areas mapped as desert vegetation have no plant cover at all because the surface consists of shifting dune sands or sterile salt flats.

The desert biome includes semidesert and dry desert and occupies the tropical, subtropical, and midlatitude dry climates (④, ⑤, and ⑨). Desert plants vary widely in appearance and in adaptation to the dry environment.

Desert plants around the world look very different from each other. In the Mojave and Sonoran deserts of the southwestern United States, plants are often large, giving the appearance of a woodland (Figure 9.30).

Desert animals, like the plants, are typically adapted to the dry conditions of the desert (Figure 9.31). Important herbivores in American deserts include kangaroo rats,

9.30 Desert plants

A desert scene near Phoenix, Arizona. The tall, columnar plant is saguaro cactus; the delicate wand-like plant is ocotillo. Small clumps of prickly pear cactus are seen between groups of hard-leaved shrubs.

EYE ON THE LANDSCAPE **What else would the geographer see?** This sky of puffy altocumulus clouds and layered altostratus (A) indicates moisture at higher levels in the troposphere. The photo, taken in July, reflects conditions of the local "monsoon" season, in which moist air from the Gulf of California moves into southern Arizona, often generating intense thunderstorms and flash floods. The gravel-covered ground surface (B) is characteristic of deserts, where wind and storm runoff remove fine particles and leave coarser rock fragments behind.

9.31 Desert animals

▼ **Kangaroo rat** This small, nocturnal desert dweller is well adapted to the desert environment. Rarely drinking water, it has a metabolism that is very efficient at retaining water and excreting salty wastes. Not a true rat, it is closely related to the pocket gopher. It gets its name from its powerful hind feet and its jumping habit (National Geographic Image Collection).

▼ **Meerkat** The meerkat is a denizen of the Kalahari Desert, related to the mongoose. Meerkats are very social animals, living in large colonies in underground burrows. They are immune to many of the poisons and stingers of desert reptiles, such as scorpions and snakes. This photo shows a young meerkat snacking on a lizard.

jackrabbits, and grasshopper mice. Insects are abundant, as are insect-eating bats and birds such as the cactus wren. Reptiles, especially lizards, are also common.

TUNDRA BIOME

Arctic tundra is a formation class of the **tundra biome**, with a tundra climate ⑫. In this climate, plants grow during the brief summer of long days and short (or absent) nights. At this time of year, air temperatures rise above freezing, and a shallow surface layer of ground ice thaws. The permafrost beneath, however, remains frozen, keeping the meltwater at the surface. These conditions create a marshy environment for a short time over wide areas. Because plant remains decay very slowly within the cold meltwater, layers of organic matter build up in the marshy ground. Frost action in the soil fractures and breaks large roots, keeping tundra plants small (Figure 9.32). In winter, wind-driven snow

The tundra biome includes low plants that are adapted to survival through a harsh, cold winter. They grow, bloom, and set seed during a short summer thaw.

9.32 Arctic tundra in Lapland

Found in areas of extreme winter cold with little or no true summer, arctic tundra consists of low perennial grasses, sedges, herbs, and dwarf shrubs, accompanied by lichens and mosses. This photo shows tundra in fall colors in Lapland, Finland. In the background, a sparse stand of trees grows in a sheltered spot.

9.33 Animals of the tundra

▼ **Caribou** Barren-ground caribou roam the tundra, constantly grazing the lichens and plants of the tundra and boreal zone. They migrate long distances between calving and feeding grounds (National Geographic Image Collection).

▲ **Musk oxen** These wooly tundra-grazers are more closely related to goats than cattle. They feed on grasses, sedges, and other ground plants, scratching their way through the snow to find them in winter. Hunted close to extinction, they are now protected. Originally restricted to Alaska, Canada, and Greenland, they have been introduced to northern Europe (National Geographic Image Collection).

◀ **Sandpiper** This small migratory bird, a dunlin sandpiper, travels long distances to return to the tundra to nest and fledge its young. It probes the tundra with its sensitive beak, searching for insects. The boggy tundra presents an ideal summer environment for many other migratory birds such as waterfowl and plovers (National Geographic Image Collection).

and extreme cold also injure plant parts that project above the snow.

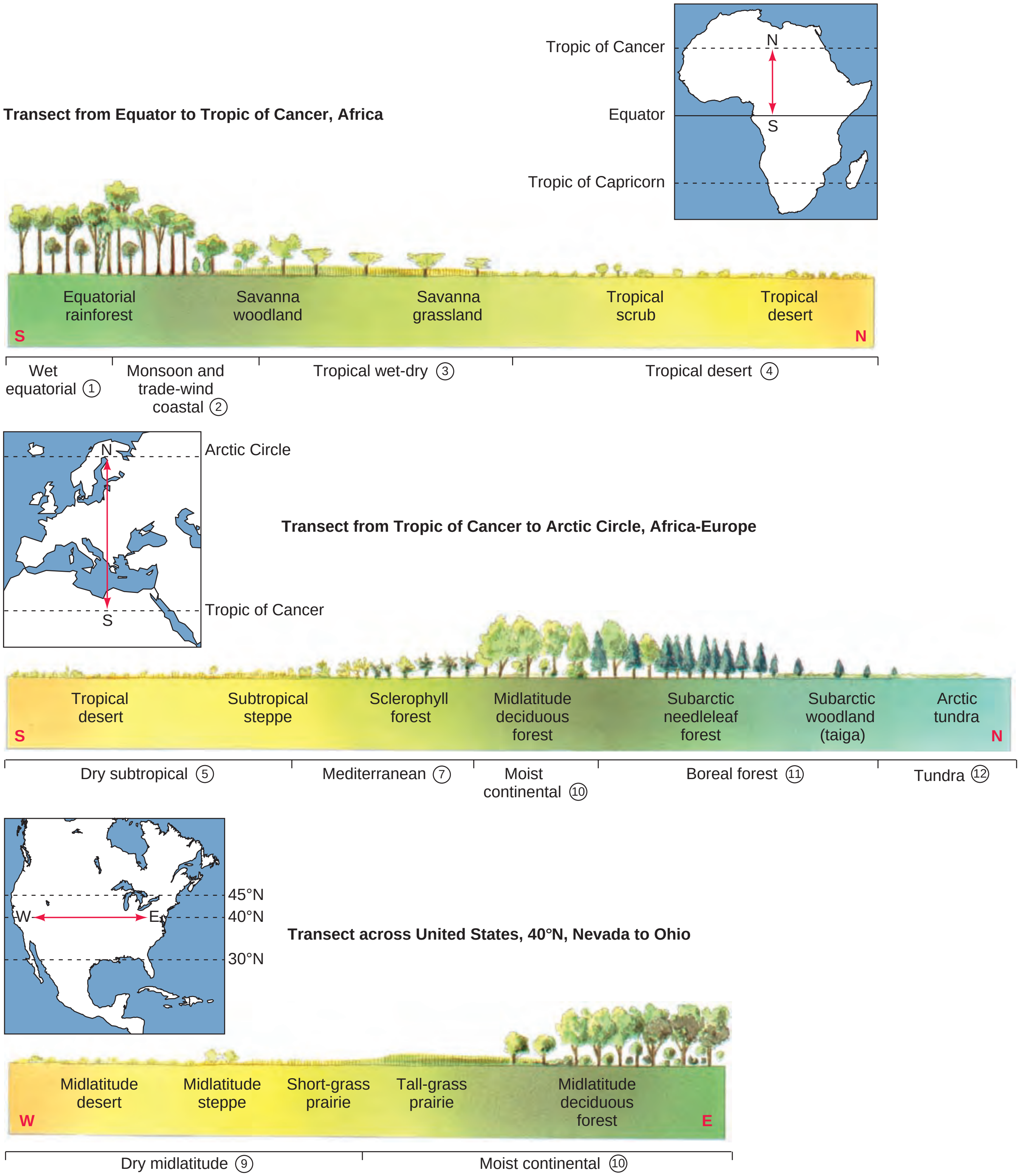
Tundra vegetation is also found at high elevations, above the limit of tree growth and below the vegetation-free zone of bare rock and perpetual snow. This *alpine tundra* resembles arctic tundra in many physical respects.

Although only a few plant and animal species are suited to the tundra, they are often represented by a large number of individuals (Figure 9.33). The food web of the tundra ecosystem is simple and direct. The important producer is reindeer moss, the lichen *Cladonia rangifera*. Caribou, reindeer, lemmings, ptarmigan (arctic grouse), and snowshoe rabbits all graze on this lichen. Foxes, wolves, and lynxes prey on those animals, although they may all feed directly on plants as well. During the summer, the abundant insects help support the migratory waterfowl populations.

Climate and Altitude Gradients

CLIMATE GRADIENTS AND BIOME TYPES

As we have seen, biomes and formation classes change along with climate. Figure 9.34 shows three continental transects that illustrate this principle.



9.34 Vegetation transects

Three continental transects showing the sequence of plant formation classes across climatic gradients. Effects of mountains or highland regions are not shown.

FOCUS ON REMOTE SENSING

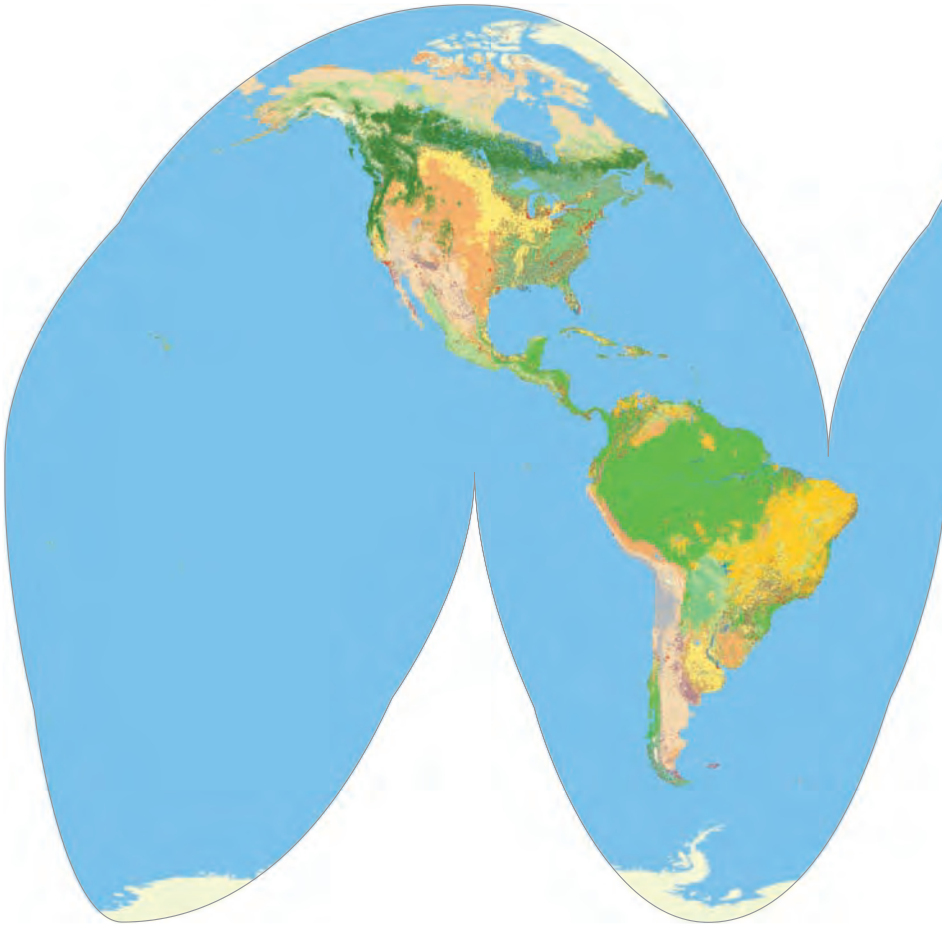
Mapping Global Land Cover by Satellite

Imagine yourself as an astronaut living on an orbiting space station, watching the Earth turn underneath you. One of the first things that would strike you about the land surface is its color and how it changes from place to place and time to time. Deserts are in shades of brown, dotted with white salty playas and the black spots and streaks of recent volcanic activity. Equatorial forests are green and lush, dissected by branching lines of dark rivers. Shrublands are marked by earth colors, but with a greenish tinge.

Some regions show substantial change throughout the year. In the midlatitude zone, forests and agricultural lands go from intense green in the summer to brown as leaves drop and crops are harvested. Snow expands equatorward in the fall and winter and retreats poleward in the spring and summer. In the tropical zones, grasslands and savannas go from brown to green to brown again as the rainy season comes and goes. Some features, such as lakes, remain nearly unchanged throughout the year.

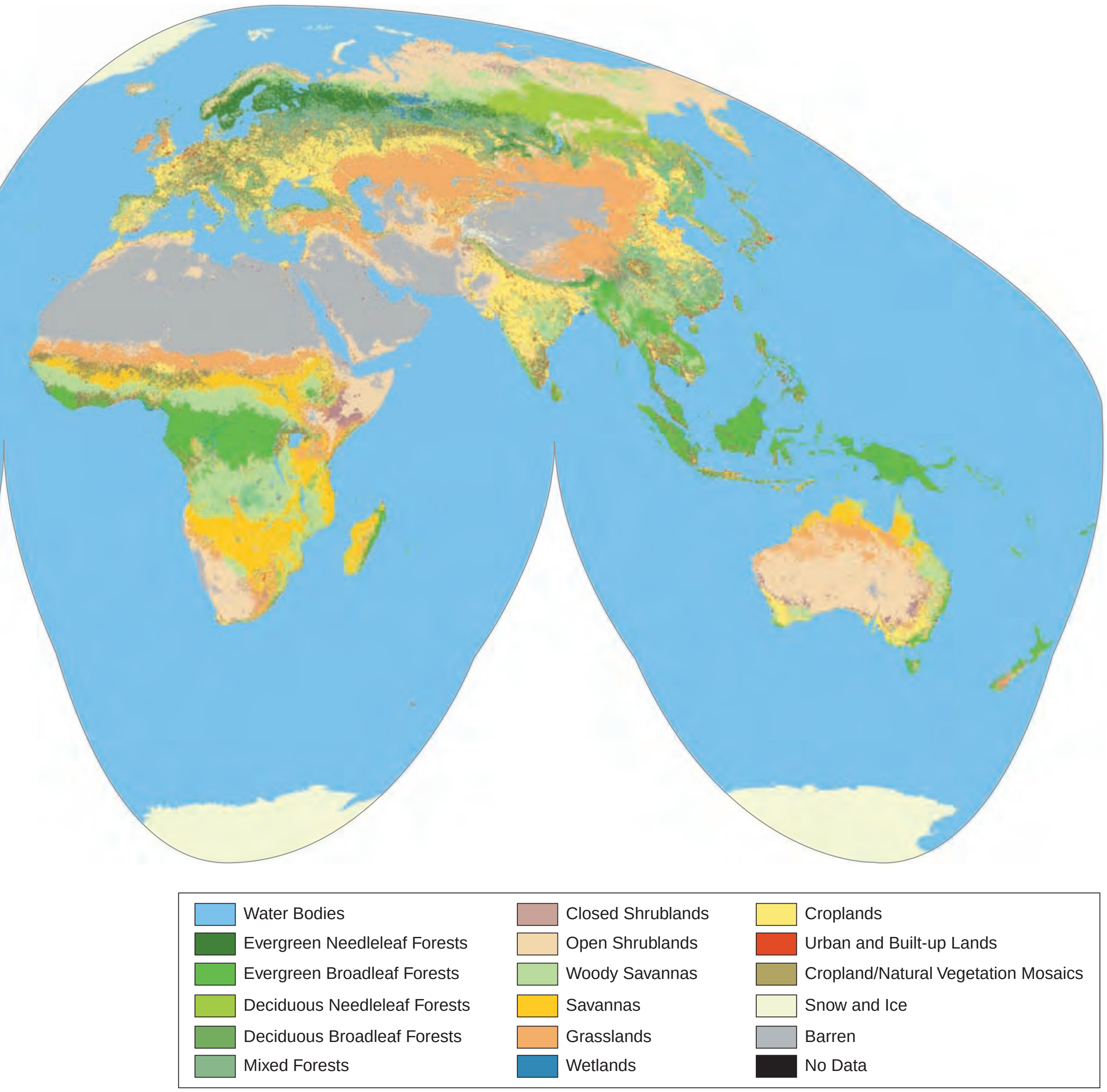
Ever since the first satellite images of the Earth were received, scientists have used color—and the change of color with time—as an indicator of land-cover type. For example, there is a 30-year history of producing land-cover maps for local areas using individual Landsat images from cloud-free dates. But global-scale mapping of land cover requires instruments like MODIS that can observe the surface on a daily or near-daily basis to acquire cloud-free images of regions that are frequently cloud-covered.

Figure 9.35 is a map of global land cover produced from MODIS images for the year 2005. The legend recognizes 17 types of land covers, including forests, shrublands, savannas, grasslands, and wetlands. The global pattern of land-cover types is rather similar to Figure 9.7. Evergreen broadleaf forest dominates the equatorial belt, stretching from South America, through Central Africa, to south Asia. Adjoining the equatorial forest belt are regions of savannas and grasslands, which have strong wet-dry climates. The vast desert region running from the Sahara to the Gobi is barren or sparsely vegetated. It is flanked by grasslands on the west, north, and east. Broadleaf deciduous forests are prominent in eastern North America, western Europe, and eastern Asia. Evergreen needleleaf forests span the boreal zone from Alaska and northwest Canada to Siberia. Croplands are found throughout most regions of human habitation, except for dry desert regions and cold boreal zones.



9.35 Global land cover from MODIS

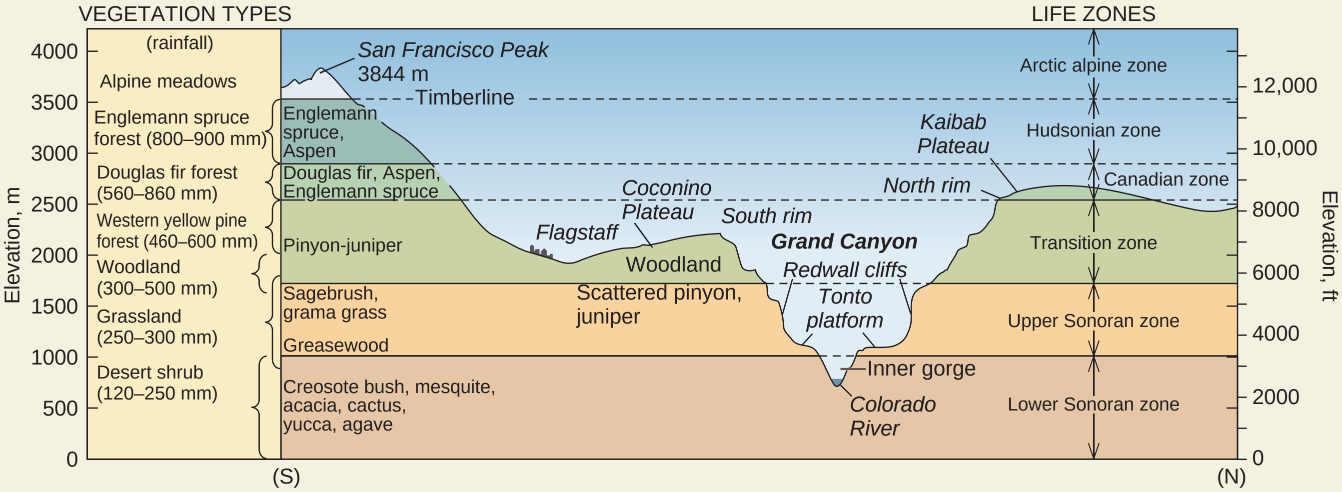
This map of global land-cover types was constructed from MODIS data acquired during 2005. The map has a spatial resolution of 1 km^2—that is, each square kilometer of the Earth's land surface is independently assigned a land-cover type label.



The MODIS map was constructed from both color (spectral) and time-based (temporal) information using a process called classification. In short, a computer program is presented with many images of each land-cover type. It then "learns" the examples and uses them to classify pixels depending on their spectral and temporal pattern. The MODIS global landcover map shown was prepared with more than 2500 examples of the 17 land-cover types. It is estimated to be 75 to 80 percent accurate.

Land-cover mapping is a common application of remote sensing. Given the ability of spaceborne instruments to image the Earth consistently and repeatedly, classification of remotely sensed data is a natural way of extending our knowledge from the specific to the general to provide valuable new geographic information.

9.36 Altitude zones of vegetation near Grand Canyon, Arizona



▲ **Life-zones of the Colorado Plateau** A series of life-zones identified by biogeographers describes the zonation of ecosystems with altitude in this region. They are named for geographic regions that have similar vegetation from the Sonoran Desert to Hudson's Bay.

▲ **Transition zone** At intermediate elevations, we find a woodland of pinyon pine and juniper with sparse grasses between the trees.

▲ **Lower Sonoran life zone** Cactus is often part of desert shrub communities near the floor of the Grand Canyon.

▼ **Arctic-alpine life zone** At the highest elevations we find an alpine tundra of sparse low plants and angular rock fragments.

The upper transect stretches from the Equator to the Tropic of Cancer in Africa. Across this region, climate ranges through all four low-latitude climates: wet equatorial ①, monsoon and trade-wind coastal ②, wet-dry tropical ③, and dry tropical ④. Vegetation grades from equatorial rainforest, savanna woodland, and savanna grassland to tropical scrub and tropical desert.

The middle transect is a composite from the Tropic of Cancer to the Arctic Circle in Africa and Eurasia. Climates include many of the mid- and high-latitude types: dry subtropical ⑤, Mediterranean ⑦, moist continental ⑩, boreal forest ⑪, and tundra ⑫. The vegetation cover grades from tropical desert through subtropical steppe to sclerophyll forest in the Mediterranean. Farther north is the midlatitude deciduous forest in the region of moist continental climate ⑩, which grades into boreal needleleaf forest, subarctic woodland, and finally tundra.

> **Because climate factors of temperature and precipitation vary with elevation and over space, vegetation patterns often show zonation with altitude and systematic variation on long transects.**

The lower transect ranges across the United States, from Nevada to Ohio. On this transect, the climate begins as dry midlatitude ⑨. Precipitation gradually increases eastward, reaching moist continental ⑩ near the Mississippi River. The vegetation changes from midlatitude desert and steppe to short-grass prairie, tallgrass prairie, and midlatitude deciduous forest.

ALTITUDE GRADIENTS

While climate varies with latitude and longitude, it also varies with elevation. At higher elevations, temperatures are cooler and precipitation is usually greater. This can produce a zonation of ecosystems with elevation that resembles a poleward transect.

The vegetation zones of the Colorado Plateau region in northern Arizona and adjacent states provide a striking example of altitude zonation. Figure 9.36 shows a cross section of the land surface in this region along with photos of typical vegetation types you might see at different elevations. Rainfall ranges from about 120 mm to 900 mm as elevation increases from about 700 m (about 2300 ft) at the bottom of the Grand Canyon to 3844 m (12,608 ft) at the top of San Francisco Peak. Temperature also decreases substantially with elevation.

Noting the variation in vegetation cover with altitude, biogeographers working in this region developed a series of *life-zones* to refer to these cover types. They relate the appearance of the vegetation cover to regions you might encounter on a transect from Mexico to the Arctic Ocean.

A Look Ahead

As we've seen, global and continental patterns of biomes and formation classes are strongly related to corresponding patterns of climate. The key ingredients of climate are temperature, moisture, and the variation of temperature and moisture through the year. These same factors are also important in the formation of soils, which is the subject of the next chapter. The vegetation cover also influences soil formation. For example, soils developed on grasslands are very different from those developed under conifer forests. Other important determinants of soil formation are the nature of the soil's parent material as it is derived from weathered rock and the time allowed for soil formation to proceed.

IN REVIEW GLOBAL BIOGEOGRAPHY

- The *rainforest ecosystem* can rapidly rebound from the low-intensity, slash-and-burn agriculture of native peoples, but it is threatened by deforestation and conversion of forest to agricultural and grazing land.
- **Natural vegetation** is a plant cover that develops with little or no human interference. Although much vegetation appears to be in a natural state, humans influence the vegetation cover by fire suppression and introduction of new species.
- The **life-form** of a plant refers to its physical structure, size, and shape. Life-forms include *trees*, *shrubs*, *lianas*, *herbs*, and *lichens*.
- The largest unit of terrestrial ecosystems is the **biome**: forest, grassland, savanna, desert, and tundra. Within biomes are vegetation formation classes. At the global and continental scale, the distribution of biomes and formation classes is determined by climate.
- The **forest biome** includes six important forest formation classes. The *low-latitude rainforest* exhibits a dense canopy and open floor with a very large number of species. *Subtropical evergreen forest* occurs in *broadleaf* and *needleleaf* forms in the moist subtropical climate ⑥. *Monsoon forest* is largely deciduous, with most species shedding their leaves after the wet season.
- *Midlatitude deciduous forest* is associated with the moist continental climate ⑩. Its species shed their leaves before the cold season. *Needleleaf forest* consists largely of evergreen conifers. It includes the *coastal forest* of

the Pacific Northwest, the *boreal forest* of high latitudes, and needle-leaved mountain forests. *Sclerophyll forest* is comprised of trees with small, hard, leathery leaves and is found in the Mediterranean climate ⑦ region.

- The **savanna biome** consists of widely spaced trees with an understory, often of grasses. It is associated with the tropical wet-dry climate ③. Dry-season fire is frequent in the savanna biome, limiting the number of trees and encouraging the growth of grasses.
- The **grassland biome** of midlatitude regions includes *tall-grass prairie* in moister environments and *short-grass prairie*, or **steppe**, in semiarid areas. Like the savanna biome, it is partly maintained by fire. Most of the tall-grass prairie is now agricultural land.
- Vegetation of the **desert biome** ranges from a *semidesert* of xerophytic or thorny shrubs and small trees to a *dry desert* comprised of species adapted to the driest of environments.
- **Tundra biome** vegetation is limited largely to low herbs and a few shrubs that are adapted to the severe drying cold and frost action experienced on the fringes of the Arctic Ocean.
- Continental transects clearly demonstrate how patterns of climate are related to patterns of biomes and formation classes.
- Time series of satellite images of the Earth's land surface can provide maps of land over at global and continental scales.

KEY TERMS

natural vegetation, p. 307
life-form, p. 308
forest, p. 310
terrestrial ecosystems, p. 310
biome, p. 310
forest biome, p. 310
savanna biome, p. 310
grassland biome, p. 310
desert biome, p. 310
tundra biome, p. 310
steppe, p. 327

REVIEW QUESTIONS

1. How do traditional agricultural practices in the low-latitude rainforest compare to present-day practices? What are the implications for the rainforest environment?
2. What global regions of the rainforest ecosystem are most threatened by deforestation?
3. What is *natural vegetation*? How do humans influence vegetation?
4. Define and differentiate the following terms: *tree, shrub, herb, liana, perennial, deciduous, evergreen, broadleaf, needleleaf, forest, woodland.*
5. What are the five main biome types that ecologists and biogeographers recognize? Describe each briefly.
6. Low-latitude rainforests occupy a large region of the Earth's land surface. What are the characteristics of these forests? Include forest structure, types of plants, diversity, and climate in your answer.
7. Monsoon forest and midlatitude deciduous forest are both deciduous but for different reasons. Compare the characteristics of these two formation classes and their climates.
8. Subtropical broadleaf evergreen forest and tall-grass prairie are two vegetation formation classes that have been greatly altered by human activities. How was this done and why?
9. Distinguish among the types of needleleaf forest. What characteristics do they share? How are they different? How do their climates compare?
10. Which type of forest, with related woodland and scrub types, is associated with the Mediterranean climate? What are the features of these vegetation types? How are they adapted to the Mediterranean climate?
11. Describe the formation classes of the savanna biome. Where is this biome found and in what climate types? What role does fire play in the savanna biome?
12. Compare the two formation classes of the grassland biome. How do their climates differ?
13. Describe the vegetation types of the desert biome.
14. What are the features of arctic and alpine tundra? How does the cold tundra climate influence the vegetation cover?

VISUALIZING EXERCISES

1. Forests often contain plants of many different life-forms. Sketch a cross section of a forest including typical life-forms, and identify them with labels.
2. Figure 9.6 shows a triangular diagram of the relationship between natural vegetation, temperature, precipitation, and latitude. Make a copy of the

figure, and indicate the climate types by name and number associated with the vegetation types in each block. Consult the global maps of climate, vegetation, and the transects shown in Figure 9.34.

3. How does elevation influence vegetation? Sketch a hypothetical mountain peak in the southwestern American desert that rises from a plain at about 500 m (about 1600 ft) to a summit at about 4000 m (about 13,000 ft) and label the vegetation zones you might expect to find on its flanks.

ESSAY QUESTIONS

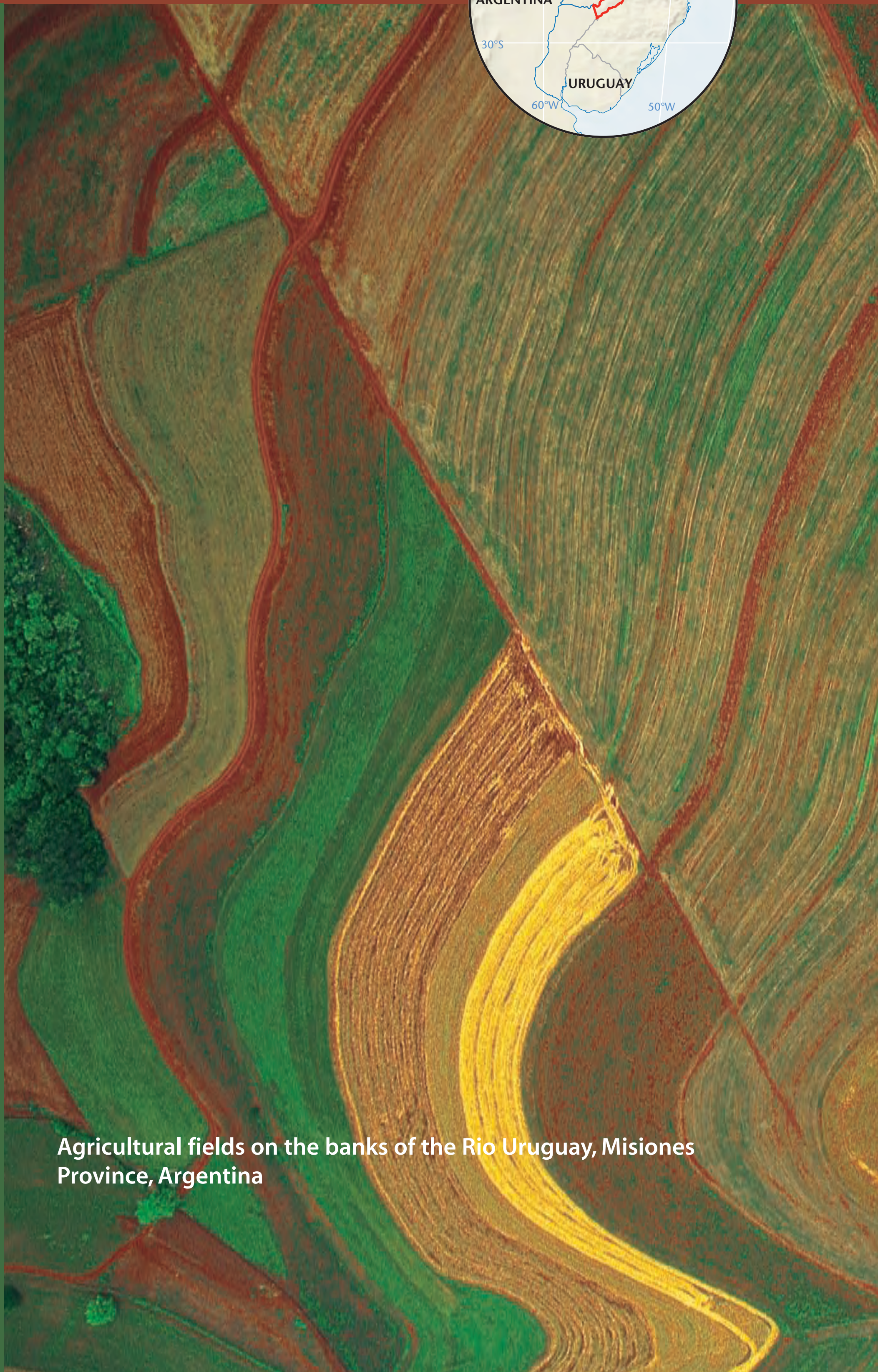
1. Figure 9.34 presents a vegetation transect from Nevada to Ohio. Expand the transect on the west so that it begins in Los Angeles. On the east, extend it northeast from Ohio through Pennsylvania, New York, western Massachusetts, and New Hampshire, to end in Maine. Sketch the vegetation types in your additions and label them, as in the diagram. Below your vegetation transect, draw a long bar subdivided to show the climate types.
2. Construct a similar transect of climate and vegetation from Miami to St. Louis, Minneapolis, and Winnipeg.

Chapter 10
Global Soils

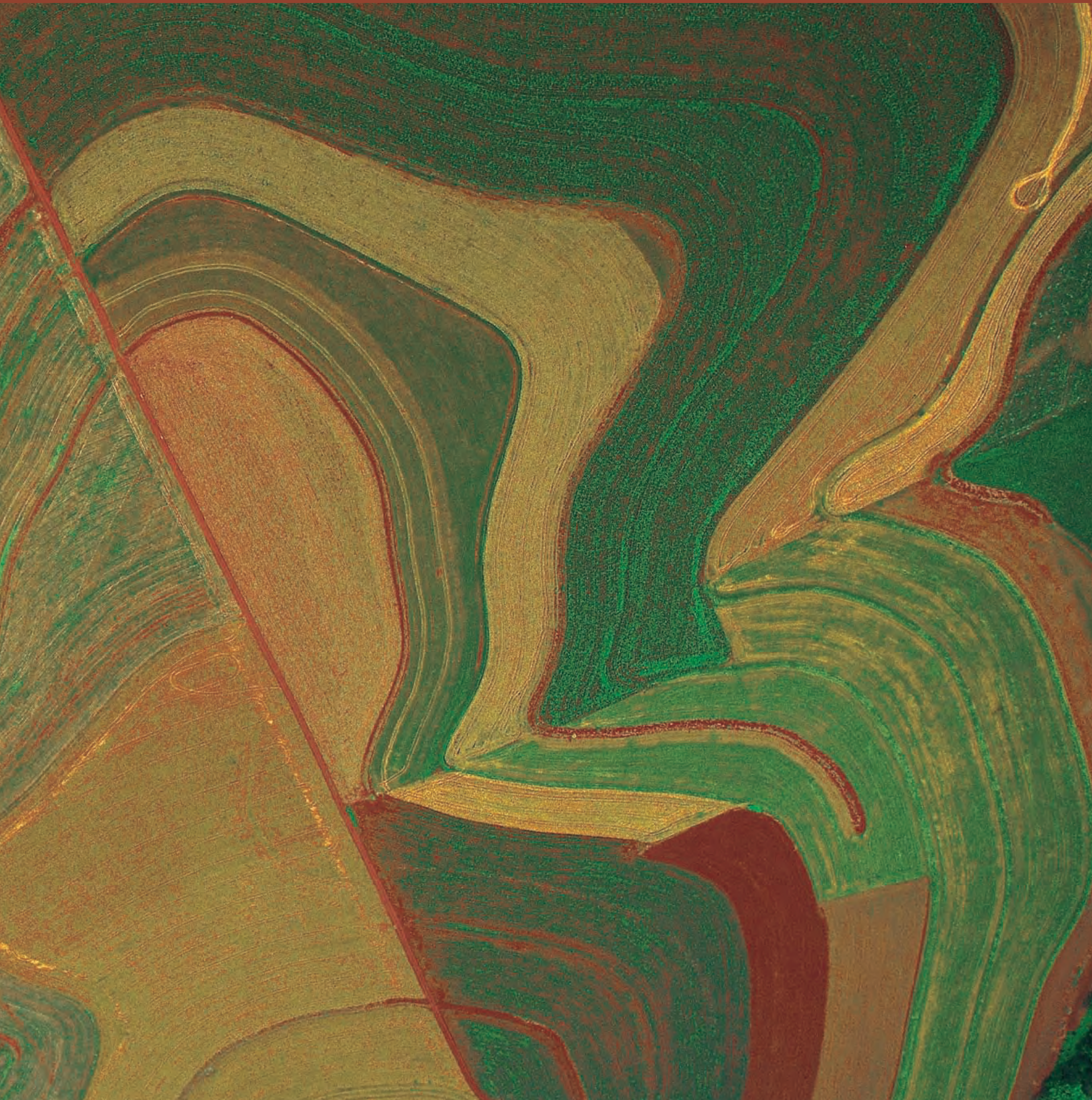
The crops of Misiones Province, Argentina, in various states of maturity, provide an abstract painting of striking yellows and greens on a canvas of red soil. The narrow, curving fields follow the slope contours, a method of cultivation that reduces soil erosion. The straight lines crossing the image are dirt tracks, probably following land ownership boundaries.

The rust-red color of the soil is produced by iron oxides. This region is an upland plateau underlain by ancient flows of basalt—a volcanic rock, rich in iron, that weathers easily in the warm, humid climate of this province.

The soils of Misiones are Ultisols—soils that have developed over very long periods of time. Under many thousands of years of exposure to warm temperatures, abundant rainfall, and organic acids produced by the decay of forest litter, the original minerals of the surface rock have broken down and combined with atmospheric oxygen and water to form mineral oxides, including iron oxide, and some types of very stable clay minerals. No trace of the original minerals remains. Bright-red Ultisols are also found at some locations in the southeastern United States—a region with a similar climate history.



Agricultural fields on the banks of the Rio Uruguay, Misiones Province, Argentina



Global Soils

The soil layer supports the world's natural vegetation, land animals, and its human population through agriculture. How is soil formed? What processes break up and alter the minerals of surface material? How do soils develop distinctive layers, known as horizons? How does climate affect soil development? What are the major types of world soils, and where are they found? What impact will global change have on agriculture? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Global Change and Agriculture

For the remainder of the twenty-first century, and probably well beyond, our global climate will change. The Earth will become warmer, especially in mid- and high latitudes. Most areas will have more precipitation, although higher temperatures will often bring more summer drought stress. Extreme events—heavy rainfalls and high winds—will be more frequent. How will global climate change impact agriculture? (Figure 10.1)

In general, higher temperatures will increase the productivity of most mid- and high-latitude crops by lengthening their growing season. But once temperatures get too high, the effects will be negative as heat stress reduces growth. Global warming is also expected to reduce minimum temperatures. This will be beneficial for many mid- and high-latitude crops but detrimental to some tropical and equatorial crops.

On the other hand, a significant CO_2 fertilization effect will occur as atmospheric CO_2 concentrations double. Because CO_2 is present in the atmosphere only in low concentrations, CO_2 limits photosynthesis in many situations. With higher CO_2 concentrations, plants become more productive. This fertilization effect is well documented in many studies, both in greenhouses and by free-air release of CO_2 gas upwind from agricultural fields.

What are the combined effects of rising temperatures and increasing CO_2 on crop yields? In general, recent studies show that if warming is less than about 2.5°C (4.5°F), yields increase, but if greater, yields decrease. However, the predicted changes for different crops and regions vary significantly.

An important factor affecting yields is adaptation. Adaptation describes actions that respond to climate change, such as changing planting and harvesting dates, selecting different strains of crops, changing the crops that are planted, adding or modifying irrigation, and using more or different fertilizers and pesticides. Studies show that adaptation can mitigate many, but not all, of the negative effects of predicted changes in temperature and rainfall.

Other factors are also important. Soil degradation, which includes erosion of productive soil layers and chemical depletion of nutrients, is a major challenge. Irrigated land is increasing, but so is irrigated land that is degraded by salt accumulation and waterlogging. Soil erosion will increase as more frequent high-rainfall events induce rilling and gullying. Wind deflation of productive soils will also increase if global warming enhances wind speeds. Insect pests will migrate with climate change, inflicting new regions but possibly leaving old ones. Weeds are stimulated by warm temperatures and higher levels of CO_2, and in some cases, will compete more effectively with crops. For livestock, climate change will affect the nature and availability of forage and grain, as well as animal diseases and parasites.

What are the likely effects of global climate change on food availability and food prices? So far, agricultural production has expanded to meet the needs of the world's expanding population. Will it keep pace with demand? Most studies predict that with global warming greater than 2.5°C (4.5°F), demand will exceed supply and food prices will rise. Vulnerable populations, such as marginal farmers and poor urban dwellers, will be placed at greater risk of hunger. However, if adaptation to climate change is effective, these risks will be reduced.

Agriculture is a human activity that is essential to us all, and the effects of global change on agriculture will be significant as our climate warms and CO_2 levels rise. Let's hope that our species is smart enough to adapt to the changes and provide an abundance of food for all.

At first, global warming will generally enhance crop production. But as temperature increases continue, agriculture will be negatively affected. Adaptation will mitigate some of the effects.

10.1 Agriculture and climate change

▼ **Young corn field, Iowa** Climate change will impact how crops grow. Earlier seasonal warming will allow a longer growing season, but hotter summers with higher drought potential may reduce later growth. However, increasing atmospheric CO_2 will tend to increase growth.

▲ **Soil erosion** Soil erosion, which strips off the most fertile part of the soil, presents an important challenge to increasing crop production and yield. More frequent and more intense rainfall events, which are predicted for midlatitude summers, will enhance soil loss by rilling and gullying of unprotected surfaces.

▲ **Cereal crop harvest, Novosibirsk region, Russia** With a changing climate, crop yields will change, but how they change will depend on the crop, the region, and the degree of adaptation employed by growers.

▼ **Vegetable vendor, Cairo, Egypt** Climate change will affect the price and availability of food from region to region. With global warming greater than 2.5°C (4.5°F), most studies predict that future supply will not meet future demand at present levels and prices will rise.

The Nature of the Soil

This chapter is devoted to soil systems. **Soil** is the uppermost layer of the land surface that plants use and depend on for nutrients, water, and physical support. Soils can vary greatly from continent to continent, from region to region, and even from field to field. This is because they are influenced by factors and processes that can vary widely from place to place. In this chapter, we'll look at each factor in turn in order to understand the many different types of soil found over the globe.

Vegetation is an important factor in determining soil qualities. For example, some of America's richest soils developed in the Middle West under a cover of thick grass (Figure 10.2). The deep roots of the grass, in a cycle of growth and decay, deposited nutrients and organic matter throughout the thick soil layer. In the Northeast, conifer forests provided a surface layer of decaying needles that kept the soil quite acid. This acidity allowed nutrients to be washed below root depth, out of the reach of plants. When farmed today, these soils need applications of lime to reduce their acidity and enhance their fertility.

Climate, measured by precipitation and temperature, is also an important determinant of soil properties. Precipitation controls the downward movement of nutrients and other chemical compounds in soils. If precipitation is abundant, water tends to wash soluble compounds, including nutrients, deeper into the soil and out of reach of plant roots.

Soil is the uppermost layer of the land surface. Plants depend on soil for nutrients, water, and physical support. Vegetation, climate, time, and parent material are important factors in soil development.

Temperature acts to control the rate of decay of organic matter that falls to the soil from the plant cover or that is provided to the soil by the death of roots. When conditions are warm and moist, decay organisms work efficiently, consuming organic matter readily. Thus, organic matter and

10.2 Soils and agriculture

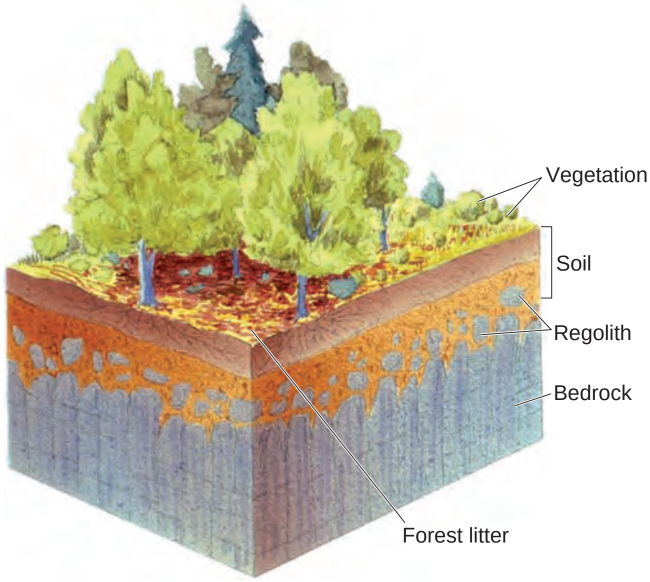
North American prairies are famous for their fertile soils. This farm in Grand Coulee, near Regina, Saskatchewan, specializes in growing crop seeds (National Geographic Image Collection).

nutrients in soils of the tropical and equatorial zones are generally low. Where conditions are cooler, decay proceeds more slowly, and organic matter is more abundant in the soil. Of course, if the climate is very dry or desert-like, then vegetation growth is slow or absent. No matter what desert temperatures are like, organic matter will be low.

Time is also an important factor. The characteristics and properties of soils require time for development. For example, a fresh deposit of mineral matter, like the clean, sorted sand of a dune, may require hundreds to thousands of years to acquire the structure and properties of a sandy soil.

Lastly, soil development is dependent on the **parent material**—the mineral matter that is available to make up the soil. Because different minerals weather at different rates to form different products, the starting material can be quite important.

Geographers are keenly interested in the differences in soils from place to place over the globe. The ability of the soils and climate of a region to produce food largely determines the size of the population it will support. In spite of the growth of cities, most of the world's inhabitants still live close to the soil that furnishes their food. And many of those same inhabitants die prematurely when the soil does not furnish enough food for all.



10.3 A cross section through the land surface

Vegetation and forest litter lie atop the soil. Below is regolith, produced by the breakup of the underlying bedrock.

INTRODUCING THE SOIL

Soil includes matter in all three states—solid, liquid, and gas. Because the matter in these states is constantly changing and interacting through chemical and physical processes, soil is a very dynamic layer.

Soil includes *mineral matter* from rock material and *organic matter* from both live and dead plants and microorganisms. Soil scientists use the term *humus* to describe finely divided, partially decomposed organic matter in soils. Some humus rests on the soil surface, and some is mixed through the soil, having been carried down through lower soil layers by rainfall. Humus particles can make soil look brown or black.

We also find air and water in soil. Water contains high levels of dissolved substances, such as nutrients. Air in soils can have high levels of carbon dioxide or methane and low levels of oxygen.

Soil is a complex mixture of solids, liquids, and gases. Solid matter includes both mineral and organic matter. Watery solutions and atmospheric gases are also found in soils.

Soil characteristics develop over a long period of time through a combination of many processes acting together. Physical processes break down rock fragments of regolith into smaller and smaller pieces. Chemical processes alter the mineral composition of the original rock, producing new minerals. Taken together, these physical and chemical processes are referred to as *weathering*.

In most soils, the inorganic material is made of fine particles of mineral matter that are derived from the parent material (Figure 10.3). Over time, weathering processes soften, disintegrate, and break bedrock apart, forming a layer of *regolith*. Other kinds of regolith are mineral particles transported by streams, glaciers, waves, and water currents, or winds. For example, dunes formed of sand transported by wind are a type of regolith on which soil can form.

Although we may think that soil is found all over the world, large expanses of continents don't possess soil. For example, dunes of moving sand, bare rock surfaces of deserts and high mountains, and surfaces of fresh lava near active volcanoes do not have a soil layer.

SOIL COLOR AND TEXTURE

Color is the most obvious feature of a soil (Figure 10.4). Some color relationships are quite simple. For example, Midwest prairie soils are black or dark brown in color because they contain many humus particles. And the red or yellow soils of the Southeast are created by the presence of iron-containing oxides.

In some areas, soil color is inherited from the mineral parent material, but, more generally, the color is generated during soil formation. For example, dry climates often have soils with a white surface layer of mineral salts that have been brought upward by evaporation. In the cold, moist climate of the boreal forest, a pale, ash-gray layer near the top of the soil is created

10.4 Soil color

▼ **Humus-rich soil** Dark soil colors normally indicate the abundance of organic matter in the form of humus. In this photo, we see a Iowa prairie Mollisol being plowed by hand and horse in a reenactment of 1900s technology.

▼ **Red soils of the Southeast** The red-brown color of this soil, near Cedar Mountain, Culpeper County, Virginia, is caused by iron oxides. The ancient soils of this region are highly productive with proper treatment (National Geographic Image Collection).

◀ **Calcium carbonate in soils** This dry desert soil in the Mojave Desert of California has a white surface deposit of calcium carbonate, also known as caliche, which accumulates when carbonate-containing ground water is drawn to the surface and evaporated.

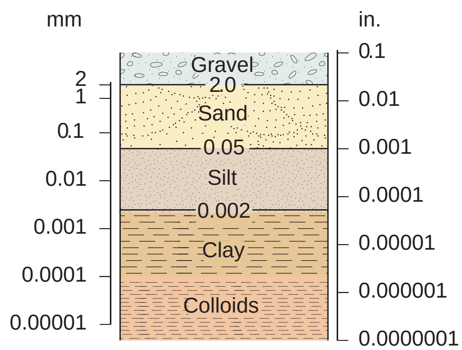
when organic matter and colored minerals are washed downward, leaving only pure, light-colored mineral matter behind.

The mineral matter of the soil consists of individual mineral particles that vary widely in size. The term **soil texture** refers to the proportion of particles that fall into each of three size grades—*sand*, *silt*, and *clay* (Figure 10.5). The finest soil particles, which are included in the clay size grade, are called *colloids*. The coarsest particles—*gravel*—are ignored in discussing soil texture because they don't play an important role in soil processes.

Soil texture refers to the proportions of sand, silt, and clay found in a soil. Soil color is usually determined by soil-forming processes and varies widely.

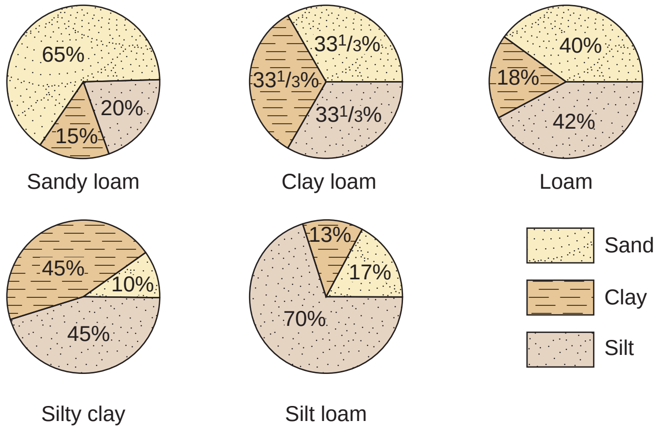
A *loam* is a soil mixture containing a substantial proportion of each of the three grades. Loams are classified as sandy, silty, or clay-rich, depending on which grade is dominant (Figure 10.6).

Why is soil texture important? Soil texture determines the ability of the soil to hold water. Coarse-textured (sandy) soils have many small passages between touching mineral grains that quickly conduct water through



10.5 Mineral particle sizes

Size grades are named sand, silt, and clay (which includes colloids). They are defined using the metric system, and each unit on the scale represents a power of ten.



10.6 Soil textures

These diagrams show the proportion of sand, silt, and clay in five different soil texture classes. In describing soil texture, clay includes colloids.

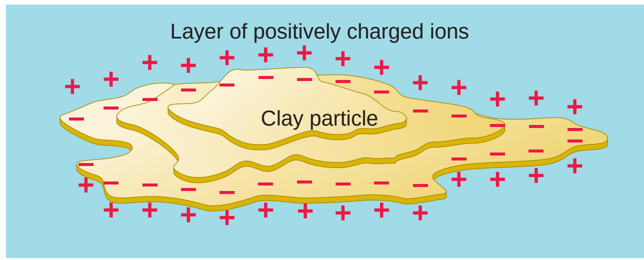
to deeper layers. But soils of fine particles have far smaller passages and spaces, so water will penetrate down more slowly and will tend to be held in the upper layers. We will return to the water-holding ability of soils later.

SOIL COLLOIDS

Soil colloids are particles smaller than one ten-thousandth of a millimeter (0.0001 mm, 0.000,004 in.). Like other soil particles, some colloids are mineral, whereas others are organic. Mineral colloids are usually very fine clay particles. They have a thin, plate-like shape that reflect their layered chemical crystal structure. When these particles are well mixed in water, they remain suspended indefinitely, turning the water murky. Organic colloids are tiny bits of organic matter that are resistant to decay.

Soil colloids are important because their surfaces attract soil nutrients, dissolved in soil water. The nutrients are in the form of ions, and Figure 10.7 shows how they interact with a colloidal particle. Among the many ions in soil water, one important group consists of **bases**, which are ions of four elements: calcium (Ca^{++}), magnesium (Mg^{++}), potassium (K^{+}), and sodium (Na^{+}). Bases are needed for plant growth. Colloids hold these ions, but also give them up to plants when they are in close contact with root membranes. Without soil colloids, most vital nutrients would be carried out of the soil by percolating water and taken away in streams, eventually reaching the sea.

Colloids are the finest particles in the soil. The surfaces of colloids attract base ions, which plants use as nutrients.



10.7 A colloid particle

Colloid surfaces tend to be negatively charged because of their molecular structure. They attract and hold positively charged ions, which often include nutrient bases such as calcium and magnesium.

SOIL ACIDITY AND ALKALINITY

Soil solution also contains the acid ions hydrogen (H^{+}) and aluminum (Al^{+++}). Unlike the bases, they are not plant nutrients, and they tend to make soil solutions acidic overall. Acid ions have the power to replace the nutrient bases clinging to the surfaces of the soil colloids. As the acid ions displace the bases and build up, the bases are released to the soil solution. The bases are then gradually washed downward below rooting level, reducing soil fertility. When this happens, the soil acidity is increased.

Soils in cold, humid climates typically have high acidities, while in arid climates, soils are typically alkaline. Acidity can be corrected by applying lime, a compound of calcium, carbon, and oxygen ($CaCO_3$), which removes acid ions and replaces them with the base calcium.

Soil acidity varies widely. Soils of cool, moist regions are generally acid, while soils of arid climates are alkaline. Acid soils are often low in base ions.

SOIL STRUCTURE

Soil structure refers to the way in which soil grains are clumped together into larger masses, called *peds*. The particles are bound together by soil colloids to create peds ranging from small grains to large blocks. Peds form when colloid-rich clays shrink as they dry out. Cracks form in the soil, which define the surfaces of the peds. Small peds, roughly shaped like spheres, give the soil a granular or crumb structure (see Figure 10.8). Larger peds provide an angular, blocky structure.

Soils with a well-developed granular or blocky structure are easy to cultivate—a factor that's especially important for farmers using primitive plows that are drawn by animals. Soils with a high clay content can lack peds. They are sticky and heavy when wet and are

10.8 Soil structure

This soil shows a granular structure. The grains are called peds. They form when the soil dries and clay minerals shrink and crack.

difficult to cultivate. When dry, they become too hard to be worked.

SOIL MINERALS

There are two classes of soil minerals: primary and secondary. *Primary minerals* are compounds found in unaltered rock. These are mostly silicon- and oxygen-containing minerals with varying proportions of aluminum, calcium, sodium, iron, and magnesium. Primary minerals make up a large fraction of the solid matter of many kinds of soils, but they don't play an important role in sustaining plant or animal life.

When primary minerals are exposed to air and water at or near the Earth's surface, their chemical composition is slowly altered. *Mineral alteration* is a chemical weathering process that is explained in more detail in Chapter 8. The primary minerals are altered into **secondary minerals**, which are essential to soil development and to soil fertility.

The most important secondary minerals for soils are *clay minerals*, which hold base ions. They make up the majority of fine mineral particles. Some clay minerals hold bases tightly, and others loosely.

Primary minerals in soils are minerals that remain from unaltered rock. Secondary minerals are formed by mineral alteration. Clay minerals and sesquioxides are important secondary minerals.

The clay minerals in a soil determine the soil's *base status*. If the clay minerals can hold abundant base ions, the soil is of *high base status* and will be highly fertile. If the clay minerals hold a smaller supply of bases, the soil is of low base status and is less fertile. Humus colloids have a high capacity to hold bases so they are associated with high soil fertility.

Mineral oxides are also significant secondary minerals. We find them in many kinds of soils, particularly those that have developed in warm, moist climates over very long periods of time (hundreds of thousands of years). Under these conditions, minerals are chemically broken down into simple oxides—compounds in which a single element is combined with oxygen.

Oxides of aluminum and iron are the most important oxides in soils. Two atoms of aluminum are combined with three atoms of oxygen to form the *sesquioxide* of aluminum (Al_2O_3). (The prefix *sesqui* means "one and a half" and refers to the chemical composition of one and one-half atoms of oxygen for every atom of aluminum.) In soils, aluminum sesquioxide and water molecules bind together to make the mineral bauxite. Where bauxite layers are thick and uniform, they are sometimes strip-mined as aluminum ore (Figure 10.9).

10.9 Bauxite mine

At this location on the island of Jamaica, ancient soils have weathered to provide a deep layer of aluminum oxide. Stained red by iron oxide, the layer is strip mined by power shovels to provide aluminum ore (National Geographic Image Collection).

Iron sesquioxide (Fe_2O_3) combines with water molecules to produce *limonite*, a yellowish to reddish mineral that makes soils and rocks reddish to chocolate-brown. At one time, shallow accumulations of limonite were mined for iron.

SOIL MOISTURE

The soil layer is also a reservoir of moisture for plants. Soil moisture is a key factor in determining how the soils of a region support vegetation and crops.

The soil receives water from rain and from melting snow. Where does this water go? Some of the water simply runs off, flowing into brooks, streams, and rivers, and eventually reaching the sea. But some sinks into the soil. Of that, a portion is returned to the atmosphere as water vapor when soil water evaporates and when plant transpiration lifts soil water from roots to leaves, where it evaporates. These two processes are together called *evapotranspiration*. Some water can also flow completely through the soil layer to recharge supplies of ground water at depths below the reach of plant roots.

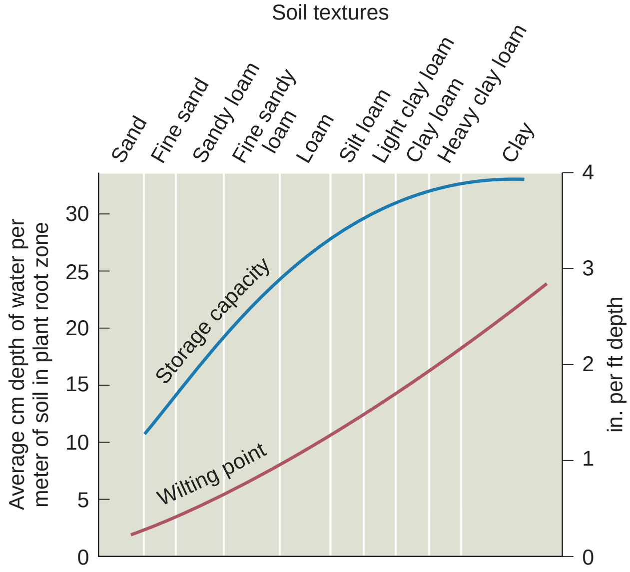
Suppose now that no further water enters the soil for a time. Excess soil water continues to drain downward, but some water clings to the soil particles. This water resists the pull of gravity because of the force of *capillary tension*. To understand this force, think about a droplet of condensation that has formed on the cold surface of a glass of ice water. The water droplet seems to be enclosed in a "skin" of surface molecules, drawing the droplet together into a rounded shape. That "skin" is produced by capillary tension, which keeps the drop clinging to the side of the glass indefinitely, defying the force of gravity. Similarly, tiny films of water stick to soil grains, particularly at the points of grain contacts. They remain until they evaporate or are absorbed by plant rootlets.

When a soil has first been saturated by water and then allowed to drain under gravity until no more water moves downward, the soil is said to be holding its *storage capacity* of water. For most soils, drainage takes no more than two or three days. Most excess water is drained out within one day.

Storage capacity is measured in units of depth, usually centimeters or inches, and depends largely on the texture of the soil (Figure 10.10). Finer textures hold more water than coarser textures because fine particles have a much larger surface area in a unit of volume than coarse particles. So, a sandy soil has a small storage capacity, while a clay soil has a large storage capacity.

Soil moisture clings to soil particles by capillary action. Soil storage capacity, which depends on soil texture, measures the ability of a soil to hold moisture after excess water has drained away.

Figure 10.10 also shows the *wilting point*—the water storage level below which



10.10 Soil texture, storage capacity, and wilting point

Finer-textured soils hold more water. They also hold water more tightly, raising the wilting point.

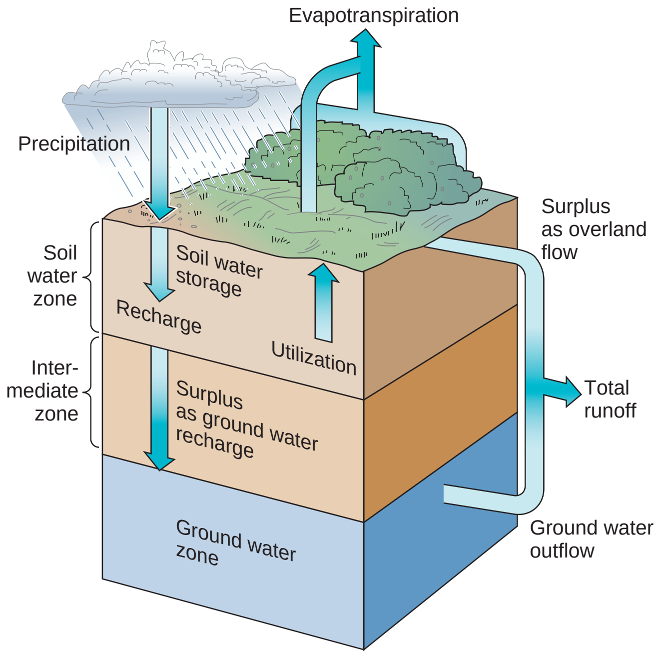
plants will wilt. It also depends on soil texture. Because fine particles hold water more tightly, it is more difficult for plants to extract moisture from fine soils. So plants can wilt in fine-textured soils even though they hold more soil water than coarse-textured soils. The difference between the storage capacity of a soil and its wilting point is the *available water capacity*—that is, the maximum amount of water available to plants when the soil is at storage capacity. The available water capacity is greatest in loamy soils.

SOIL-WATER BALANCE

It's clear that soil water is a critical resource needed for plant growth. The amount of water available at any given time is determined by the *soil-water balance*, which includes the gain and loss of water stored in the soil. Figure 10.11 is a diagram that illustrates the components of the soil-water balance.

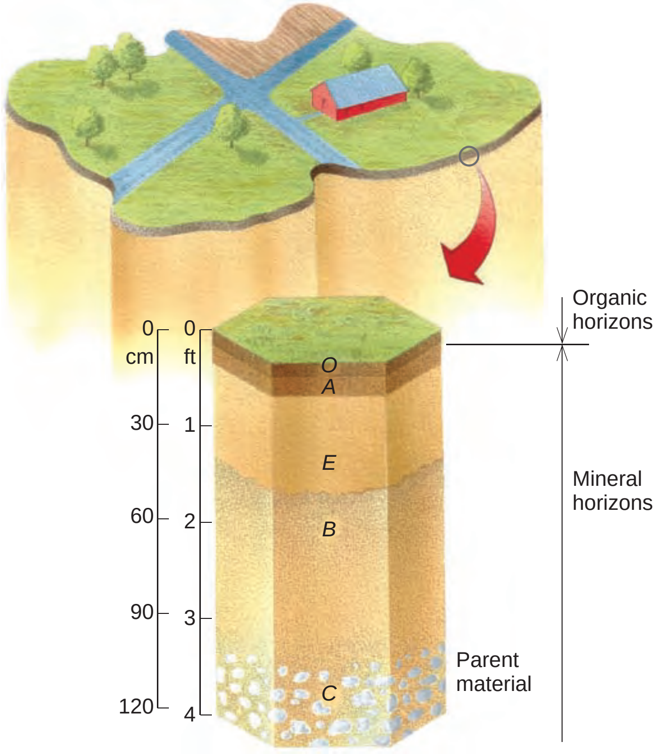
Precipitation reaching the surface of the soil has two paths. One part enters the soil and recharges the reservoir of soil-water storage, while another part runs off the surface as overland flow into streams and rivers. Water leaves the soil-water storage reservoir through evapotranspiration, which depends on the air temperature and the amount of vegetation cover. Gravity also pulls water from the soil layer into ground water below. As we will see in a later chapter, the extra ground water eventually emerges from the bottoms of streambeds and lakes, joining overland flow to constitute total runoff.

During warm weather, evapotranspiration increases, and water flows out of the soil-water reservoir. If precipitation does not increase as well, soil water decreases. Eventually, soil-water storage can be drawn down below



10.11 The soil-water balance

The soil-water storage reservoir loses water through evapotranspiration and by drainage to ground water. The soil-water storage reservoir gains water from precipitation.



10.12 Soil Horizons

A column of soil will normally show a series of horizons, which are horizontal layers with different properties.

the wilting point, and plants and crops suffer. When precipitation increases or temperatures fall, reducing transpiration, the soil-water reservoir is recharged.

The soil-water balance controls the availability of soil water for agriculture or natural vegetation. Depending on the balance, soil moisture may be lowered or recharged.

The soil-water balance is an important determiner of agricultural productivity, and it depends largely on climate—the variation in temperature and precipitation through the year. In a climate with a dry summer growing season, like the Mediterranean climate ⑦, irrigation is required for crops. In a climate with a wet summer or abundant year-round precipitation, such as the moist subtropical climate ⑥, soil water can maintain lush vegetation or crops through the growing season.

Soil Development

How do soils develop their distinctive characteristics? Let's turn to the processes that form soils and soil layers.

SOIL HORIZONS

Most soils have distinctive horizontal layers that differ in physical composition, chemical composition, organic content, or structure (Figure 10.12). We call these layers **soil horizons**. They develop through interactions between climate, living organisms, and the land surface, over time. Horizons usually develop by either selective removal or accumulation of certain ions, colloids, and chemical compounds. This removal or accumulation is normally produced by water seeping through the soil profile from the surface to deeper layers. Horizons often have different soil textures and colors.

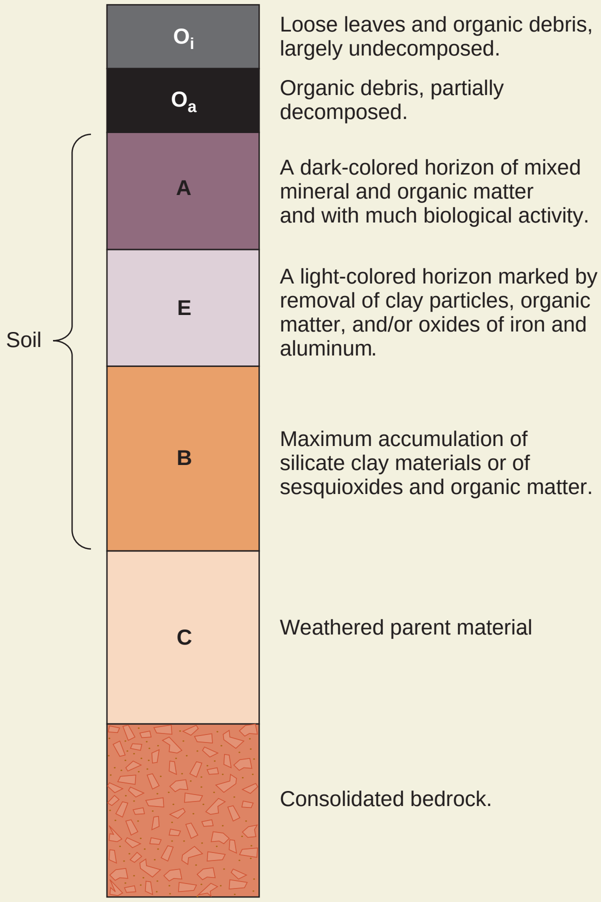
To simplify our discussion of soil horizons, let's look at the example of soils found in moist forest climates. A **soil profile**, as shown in Figure 10.13, displays the horizons on a cross section through the soil.

There are two types of soil horizons: organic and mineral. *Organic horizons*, marked with the capital letter *O*, lie over mineral horizons and are formed from plant and animal matter. The upper *O_i horizon* contains decomposing organic matter that you can easily recognize by eye, such as leaves or twigs. The lower *O_a horizon* contains humus, which has broken down beyond recognition.

Soil horizons are distinctive layers found in soils that differ in physical or chemical composition, organic content, or structure. The soil profile refers to the display of horizons on a cross section through the soil.

10.13 Forest soil profile

▼ A sequence of horizons that might appear in a forest soil developed under a cool, moist climate.



▼ An actual forest soil profile on outer Cape Cod. The pale grayish *E* horizon in the photograph overlies a reddish *B* horizon. A thin layer of wind-deposited silt and dune sand (pale brown layer) has been deposited on top.

There are four main mineral horizons. The *A horizon* is rich in organic matter, washed downward from the organic horizons. Next is the *E horizon*. Clay particles and oxides of aluminum and iron are removed from the *E* horizon by downward-percolating water, leaving behind pure grains of sand or coarse silt.

The *B horizon* receives the clay particles, aluminum, and iron oxides, as well as organic matter washed down from the *A* and *E* horizons. It's dense and tough because its natural spaces are filled with clays and oxides.

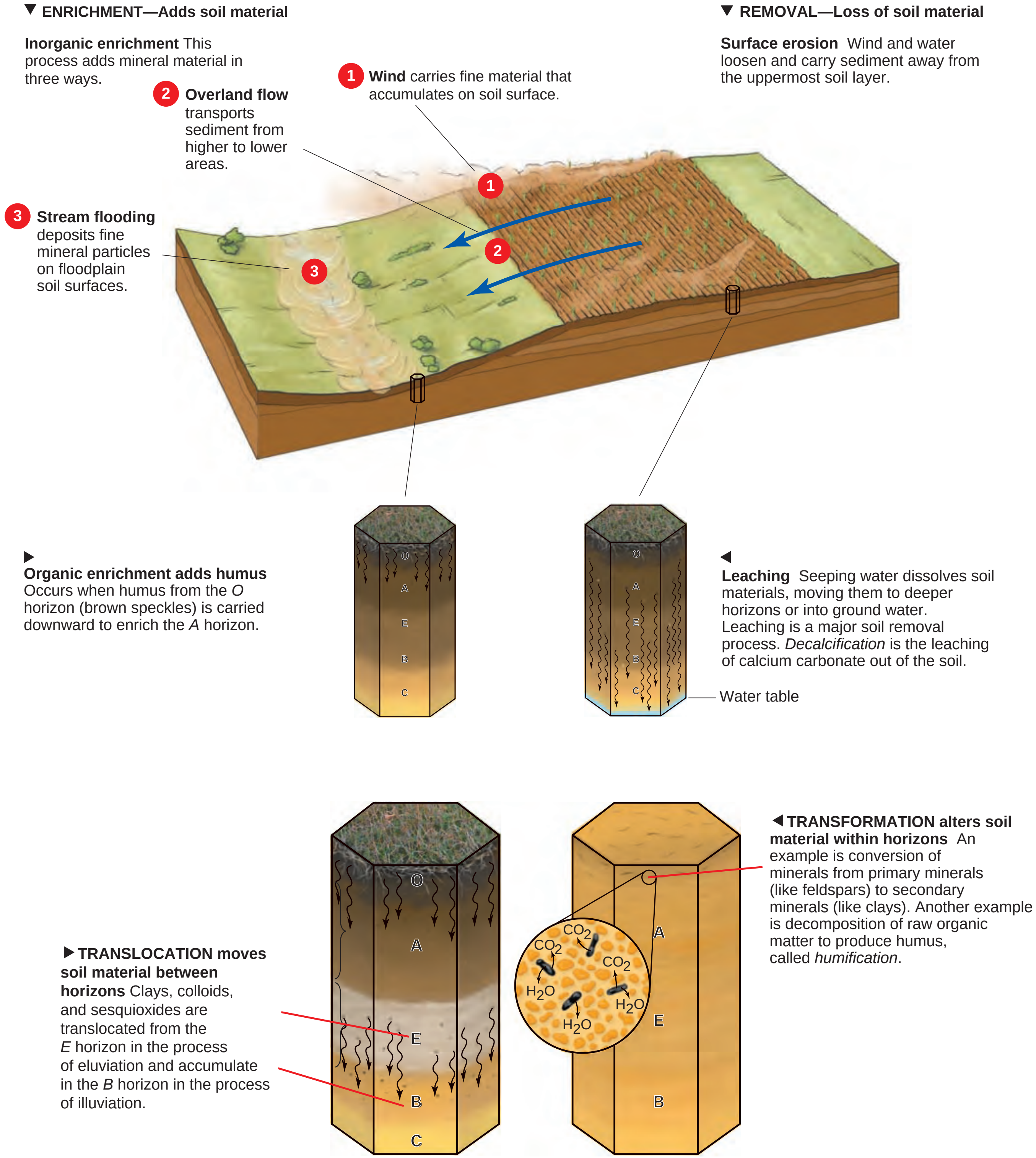
Beneath the *B* horizon is the *C horizon*. It consists of the parent mineral matter of the soil. Below this regolith lies bedrock or sediments of much older age than the soil. Soil scientists limit the term *soil* to the *A*, *E*, and *B* horizons, which plant roots can readily penetrate.

SOIL-FORMING PROCESSES

There are four classes of soil-forming processes: soil enrichment, removal, translocation, and transformation. Figure 10.14 diagrams these processes and shows how they work together on the landscape.

In *soil enrichment*, matter—organic or inorganic—is added to the soil. Mineral enrichment of silt by river floods or as wind-blown dust is an example. Organic enrichment occurs as water carries humus from the *O* horizon into the *A* horizon below.

In *removal* processes, material is removed from the soil body. This occurs when erosion carries soil particles into streams and rivers. *Leaching*—the loss of soil compounds and minerals by solution in water flowing to lower levels—is another important removal process.



10.14 Soil formation mechanisms—enrichment, removal, translocation, and transformation

Translocation describes the movement of materials upward or downward within the soil. Fine particles—particularly clays and colloids—are translocated downward, a process called **eluviation**. This leaves grains of sand or coarse silt to remain, forming the *E* horizon. Material brought downward from the *E* horizon—clay particles, humus, or sesquioxides of iron and aluminum—accumulates in the *B* horizon, a process called **illuviation**.

The soil profile shown in Figure 10.13 for a cool, humid forest climate displays the effects of both soil enrichment and translocation. The topmost layer of the soil is a thin deposit of wind-blown silt and dune sand, which has enriched the soil profile. Eluviation has removed colloids and sesquioxides from the whitened *E* horizon and illuviation has added them to the *B* horizon, which displays the orange-red colors of iron sesquioxide.

The four classes of soil-forming processes are enrichment, removal, translocation, and transformation. In translocation, fine particles are transported downward by eluviation and accumulate in lower horizons by illuviation.

The translocation of calcium carbonate is another important process. In moist climates, a large amount of surplus soil water moves downward to the groundwater zone. This water movement leaches calcium carbonate from the entire soil in a process called *decalcification*. Soils that have lost most of their calcium are also usually acidic, and so they are low in bases. Adding lime or pulverized limestone will not only correct the acid condition, but will also restore the missing calcium, which is used as a plant nutrient.

In dry climates, annual precipitation is not sufficient to leach the carbonate out of the soil and into the ground water below. Instead, it is carried down to the *B* horizon, where it is deposited as white grains, plates, or nodules, in a process called *calcification*.

Upward translocation can also occur in desert climates. In some low areas, a layer of ground water lies close to the surface, producing a flat, poorly drained area. As water at or near the soil surface evaporates, ground water is drawn to replace it by capillary tension, much like a cotton wick draws oil upward in an oil lamp. This ground water is often rich in dissolved salts. When the salt-rich water evaporates, the salts are deposited and build up. This process is called *salinization*. Large amounts of these salts are toxic to many kinds of plants. When salinization occurs in irrigated lands in a desert climate, the soil can be ruined with little hope of revival.

The last class of soil-forming processes involves the *transformation* of material within the soil body. An example is the conversion of minerals from primary to secondary types, which we have already described. Another example is decomposition of organic matter to produce humus, a process termed *humification*. Microorganisms break down the raw organic matter, producing CO_2 and water and leaving behind resistant organic compounds—humus—to decay more slowly.

GEODISCOVERIES **Soil Horizons**

Watch an animation demonstrating eluvation and illuviation through the soil profile.

SOIL TEMPERATURE AND OTHER FACTORS

Soil temperature also helps to determine the chemical development of soils and the formation of horizons. Below 10°C (50°F), biological activity is slowed, and at or below the freezing point (0°C, 32°F), biological activity stops and chemical processes affecting minerals are inactive. The root growth of most plants and germination of their seeds require soil temperatures above 5°C (41°F). Plants in the warm, wet low-latitude climates may need temperatures of at least 24°C (75°F) for their seeds to germinate.

The temperature of the uppermost soil layer and the soil surface also strongly affects the rate at which organic matter is decomposed by microorganisms. In cold climates, decomposition is slow, and so organic matter accumulates to form a thick *O* horizon. This material becomes humus, which is carried downward to enrich the *A* horizon. But in warm, moist climates of low latitudes, bacteria rapidly decompose plant material, so you won't find an *O* horizon layer, and the entire soil profile will contain very little organic matter.

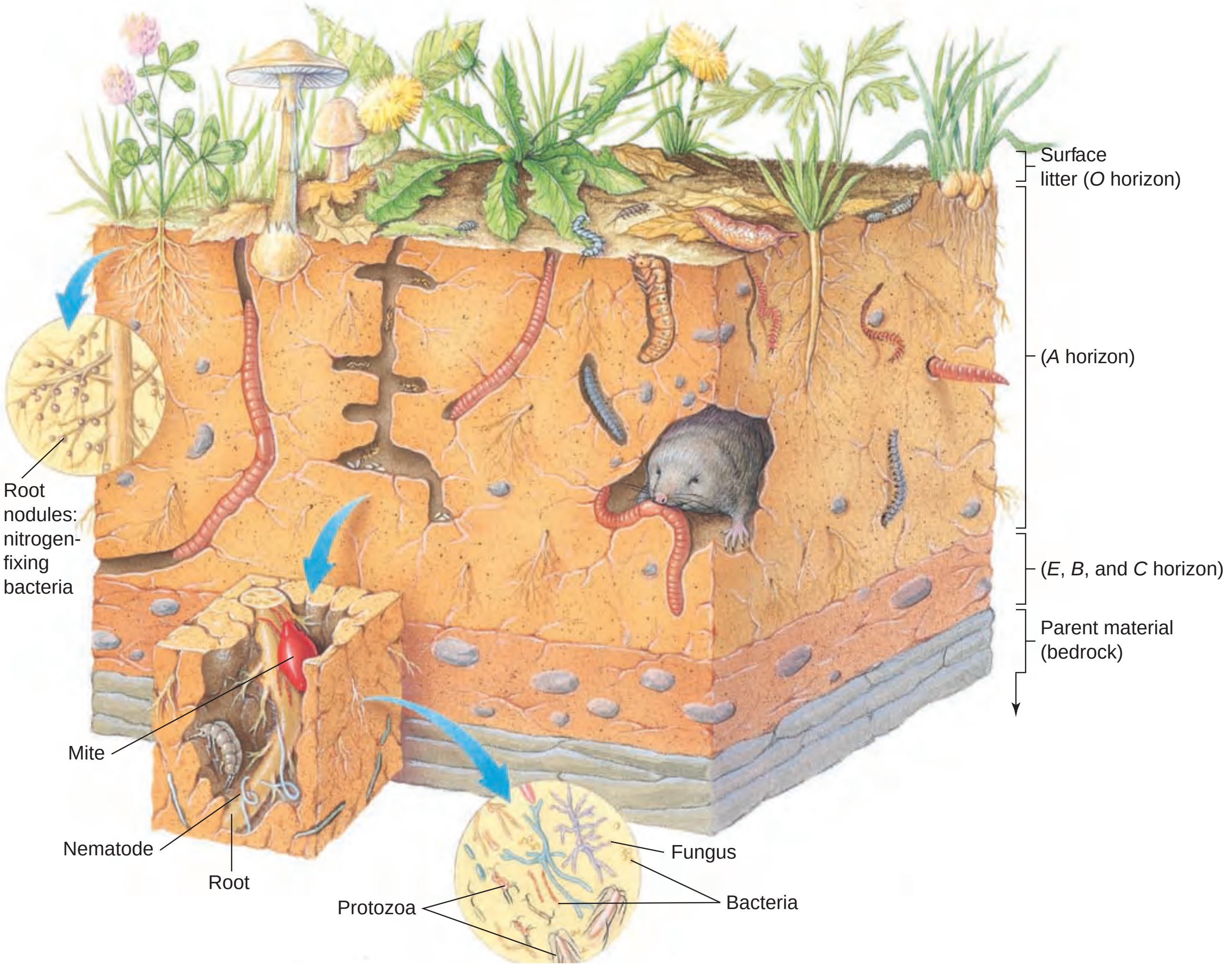
The configuration, or shape, of the ground surface also influences soil formation. Generally speaking, soil horizons are thick on gentle slopes but thin on steep slopes. This is because the soil is more rapidly removed by erosion on the steeper slopes. In addition, slopes facing away from the Sun are sheltered from direct insolation and tend to have cooler, moister soils. Slopes facing toward the Sun are exposed to direct solar rays, raising soil temperatures and increasing evapotranspiration.

Living plants and animals, as well as their nonliving organic products, have an important effect on soil. We have already noted the role that organic matter as humus plays in soil fertility. Humus holds bases, which are needed for plant growth. It also helps bind the soil into crumbs and clumps, which allows water and air to penetrate the soil freely. Plant roots, by their growth, mix and disturb the soil and provide organic material directly to upper soil horizons.

Organisms living in the soil include many species—from bacteria to burrowing mammals (Figure 10.15). Earthworms continually rework the soil not only by burrowing, but also by passing soil through their intestinal tracts. They ingest large amounts of decaying leaf matter, carry it down from the surface, and incorporate it into the mineral soil horizons. Many forms of insect larvae perform a similar function. And moles, gophers, rabbits, badgers, prairie dogs, and other burrowing animals make larger, tube-like openings.

Temperature has an important influence on soil development. In cold climates, decomposition of organic matter is slow and organic matter accumulates. In warm climates, organic matter decomposes rapidly and soil organic matter is scarce.

Human activity also influences the physical and chemical nature of the soil. Large areas of agricultural



10.15 Soil organisms

The diversity of life in fertile soil includes plants, algae, fungi, earthworms, flatworms, roundworms, insects, spiders and mites, bacteria, and burrowing animals such as moles and groundhogs. Soil horizons are not drawn to scale.

soils have been cultivated for centuries. As a result, both the structure and composition of these agricultural soils have undergone great changes. These altered soils are often recognized as distinct soil classes that are just as important as natural soils.

The Global Scope of Soils

How soils are distributed around the world helps to determine the quality of environments of the globe. That's because soil fertility, along with the availability of fresh water, is a basic measure of the ability of an environmental region to produce food for human consumption.

We classify soils according to a system developed by scientists of the U.S. Natural Resources Conservation Service, in cooperation with soil scientists of many other nations. In this book, we'll discuss the two highest levels of this classification system. The top level contains 12 **soil orders** summarized in Table 10.1. We'll also mention a few important *suborders* that make up the second classification level.

There are three groups of soil orders, as shown in the table. The largest group includes seven orders with well-developed horizons or fully weathered minerals. A second group includes a single soil order that is very rich in organic matter. The last group includes four soil orders with poorly developed horizons or no horizons. Figure 10.16 is a map of world soil orders. Let's look at the soil orders in more detail.

Soils are classified by soil order and suborder. These divisions are largely distinguished by the presence of diagnostic horizons with unique physical or chemical properties.

Table 10.1 Soil Orders

Group I	
Soils with well-developed horizons or with fully weathered minerals, resulting from long-continued adjustment to prevailing soil temperature and soil-water conditions.	
Oxisols	Very old, highly weathered soils of low latitudes, with a subsurface horizon of accumulation of mineral oxides and very low base status.
Ultisols	Soils of equatorial, tropical, and subtropical latitude zones, with a subsurface horizon of clay accumulation and low base status.
Vertisols	Soils of subtropical and tropical zones with high clay content and high base status. Vertisols develop deep, wide cracks when dry, and the soil blocks formed by cracking move with respect to each other.
Alfisols	Soils of humid and subhumid climates with a subsurface horizon of clay accumulation and high base status. Alfisols range from equatorial to subarctic latitude zones.
Spodosols	Soils of cold, moist climates, with a well-developed *B* horizon of illuviation and low base status.
Mollisols	Soils of semiarid and subhumid midlatitude grasslands, with a dark, humus-rich epipedon and very high base status.
Aridisols	Soils of dry climates, low in organic matter, and often having subsurface horizons of accumulation of carbonate minerals or soluble salts.
Group II	
Soils with a large proportion of organic matter.	
Histosols	Soils with a thick upper layer very rich in organic matter.
Group III	
Soils with poorly developed horizons or no horizons, and capable of further mineral alteration.	
Entisols	Soils lacking horizons, usually because their parent material has accumulated only recently.
Inceptisols	Soils with weakly developed horizons, having minerals capable of further alteration by weathering processes.
Gelisols	Soils underlain by permafrost, with organic and mineral materials churned by forest action.
Andisols	Soils with weakly developed horizons, having a high proportion of glassy volcanic parent material produced by erupting volcanoes.

GEODISCOVERIES Soils of the World

Take a second look at the world map of soils and click on a soil type to see a photo of the soil profile. An animation.

OXISOLS, ULTISOLS, AND VERTISOLS

The low latitudes are dominated by three soil orders: Oxisols, Ultisols, and Vertisols. These soils have developed over long time spans in an environment with warm soil temperatures and plentiful soil water either in a wet season or throughout the year.

Oxisols have developed in the moist climates of the equatorial, tropical, and subtropical zones on land surfaces that have been stable over long periods of time. We find these soils over vast areas of South America and Africa in the wet equatorial climate ①, where the native vegetation is rainforest. The wet-dry tropical climate ③ in South America and Africa, with its large seasonal water surplus, is also associated with Oxisols. Figure 10.17 shows a soil profile for an Oxisol in Hawaii.

Ultisols are similar to the Oxisols, but have a subsurface clay horizon (Figure 10.18). They originate in closely related environments. In a few areas, the Ultisol profile contains a subsurface horizon of sesquioxides called *laterite* (Figure 10.19). This horizon can harden into brick-like blocks when it is exposed to the air.

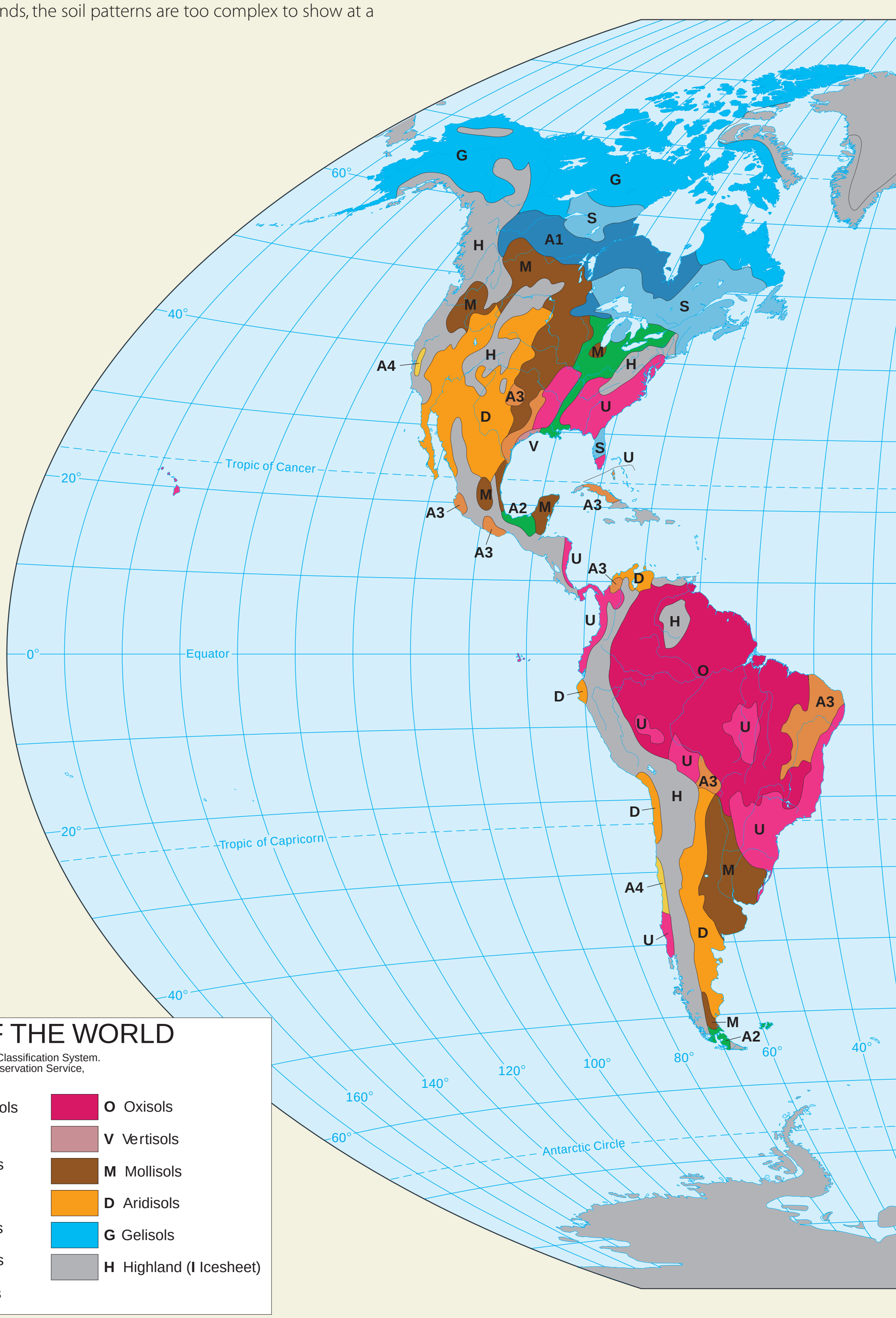
We find Ultisols throughout Southeast Asia and the East Indies. Other important areas are in eastern Australia, Central America, South America, and the southeastern United States. Ultisols extend into the lower midlatitude zone in the United States, where they correspond quite closely with areas of moist subtropical climate ⑥. In lower latitudes, Ultisols are identified with the wet-dry tropical climate ③ and the monsoon and trade-wind coastal climate ②. Note that all these climates have a dry season, even though it may be short.

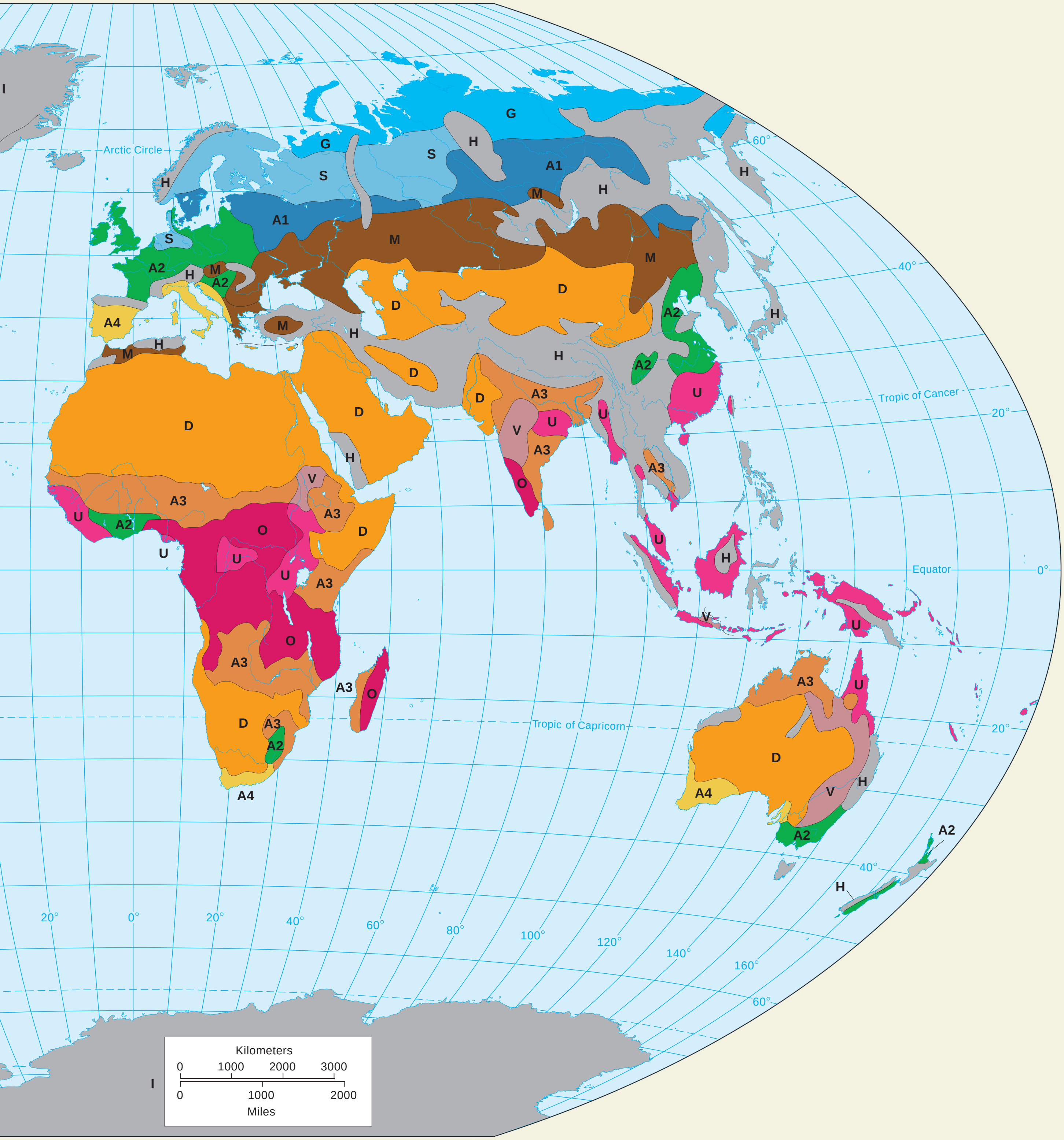
Before the advent of modern agricultural technology, both Oxisols and Ultisols of low latitudes were cultivated for centuries using a primitive slash-and-burn agriculture. Without fertilizers, these soils can sustain crops on freshly cleared areas for only two or three years at most, before the nutrient bases are exhausted and the garden plot must be abandoned. For sustained high-crop yields, substantial amounts of lime and fertilizers are required. Ultisols are also vulnerable to devastating soil erosion, particularly on steep hill slopes.

Oxisols and Ultisols develop over long time periods in warm, moist climates. Oxisols have substantial accumulations of iron and aluminum sesquioxides. Ultisols have a horizon of clay accumulation.

10.16 Soils of the world

The map shows the general distribution of 11 soil types, including seven soil orders and four suborders of Alfisols that correspond well to four basic climate zones. Soils found on floodplains, glacial landforms, sand dunes, marshlands, bogs, and volcanic ash deposits are not represented because they are of local occurrence. In highlands, the soil patterns are too complex to show at a global scale.

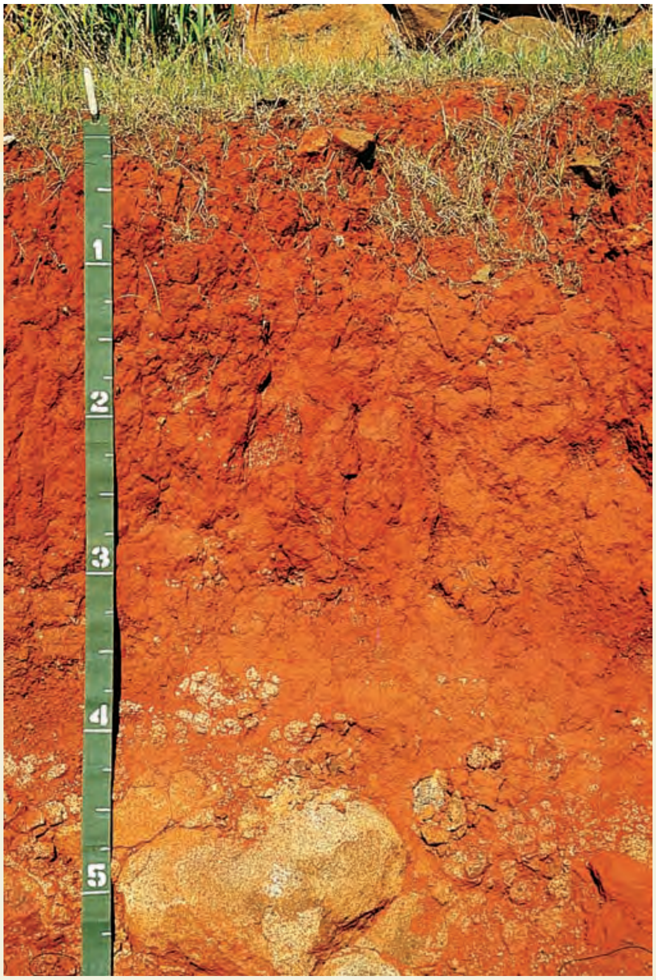



Arctic Circle
Tropic of Cancer
Equator
Tropic of Capricorn
60°
40°
20°
0°
20°
20°
0°
20°
40°
60°
80°
100°
120°
140°
160°
60°
G
S
H
A1
M
A2
A4
D
A3
V
U
O
I
Kilometers
0 1000 2000 3000
0 1000 2000
Miles

10.17 Oxisols

Oxisols usually lack distinct horizons, except for darkened surface layers. Soil minerals are weathered to an extreme degree and are dominated by stable sesquioxides of aluminum and iron, giving them red, yellow, and yellowish-brown colors. The soil has a very low base status because nearly all the bases have been removed. There's a small store of nutrient bases very close to the soil surface. The soil is quite easily broken apart, so rainwater and plant roots can easily penetrate.

▼ **An Oxisol in Hawaii** Sugarcane is being cultivated here on the island of Oahu.



▲ **Soil profile for an Oxisol** The intense red color is produced by iron sesquioxides. This profile shows an Oxisol of the suborder Torrox in Hawaii.

Vertisols have a unique set of properties that stand in sharp contrast to the Oxisols and Ultisols. They are black in color and have a high clay content (Figure 10.20). The clay minerals are of a particular type that swells and shrinks with wetting and drying, producing deep cracks in the soil. Vertisols typically form under grass and savanna vegetation in subtropical and tropical climates with a pronounced dry season. These climates include the semiarid subtype of the dry tropical steppe climate ④ and the wet-dry tropical climate ③.

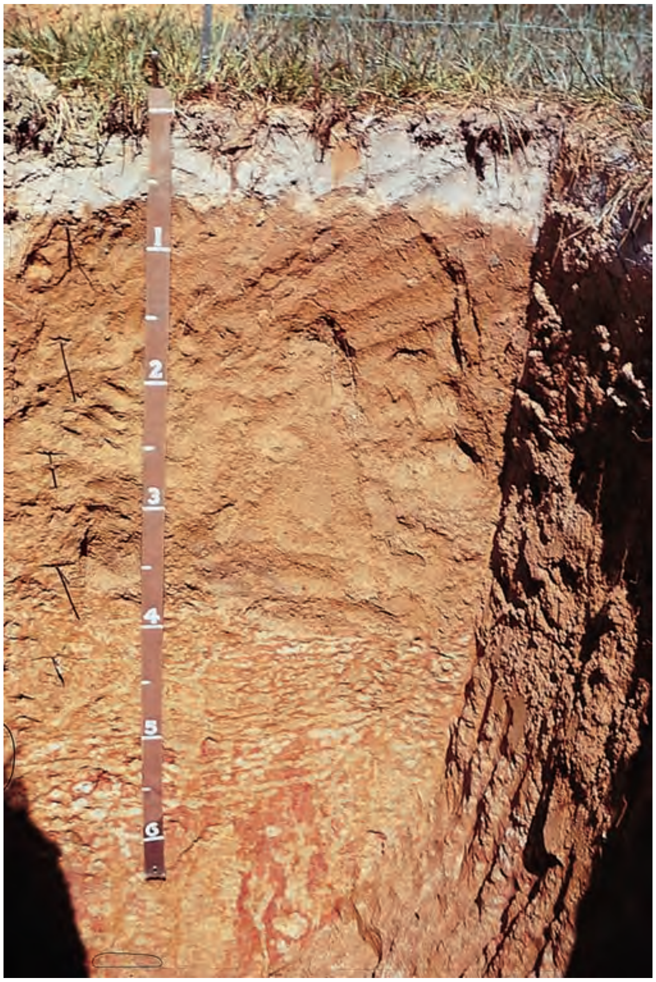
Vertisols develop on certain rock types in wet-dry climates under grassland and savanna vegetation. They expand and contract strongly on wetting and drying, creating deep cracks in the soil.

Because Vertisols require a particular type of silicate mineral as a parent material, regions of this soil are scattered and show no distinctive pattern on the world map. An important region of Vertisols is the Deccan Plateau of western India, where basalt, a dark variety of igneous rock, supplies the silicate minerals that are altered into the necessary clay minerals.

ALFISOLS AND SPODOSOLS

The **Alfisols** are soils characterized by a clay-rich horizon produced by illuviation (Figure 10.21).

The world distribution of Alfisols is extremely wide in latitude. Alfisols range from latitudes as high as 60° N in North America and Eurasia to the equatorial zone in South America and Africa. Obviously, the Alfisols span an enormous range in climate types. For this reason, we need to recognize four of the important suborders of Alfisols, each with its own climate affiliation.



10.18 Soil profile for an Ultisol

Ultisols are reddish to yellowish in color. They have a subsurface horizon of clay, which is not found in the Oxisols. It is a *B* horizon and has developed by illuviation. Although the characteristic native vegetation is forest, Ultisols have a low base status. As in the Oxisols, most of the bases are found in a shallow surface layer where they are released by the decay of plant matter. They are quickly taken up and recycled by the shallow roots of trees and shrubs. This profile is for an Ultisol from North Carolina. The pale layer is the *E* horizon, and the thin, dark top layer is all that remains of the *A* horizon after erosion.

Boralfs are Alfisols of cold (boreal) forest lands of North America and Eurasia. They have a gray surface horizon and a brownish subsoil. *Udalfs* are brownish Alfisols of the midlatitude zone. *Ustalfs* are brownish to reddish Alfisols of the warmer climates. *Xeralfs* are Alfisols of the Mediterranean climate ⑦, with its cool moist winter and dry summer. The Xeralfs are typically brownish or reddish in color.

Alfisols have horizons of eluviation and illuviation of clays. They have a high base status and can be very productive.

Poleward of the Alfisols in North America and Eurasia lies a great belt of soils of the order **Spodosols**, formed in the cold boreal forest climate ⑪ beneath a needleleaf forest. They are distinguished by a *spodic horizon*—a dense accumulation of iron and aluminum oxides and organic matter—and a gray or white *albic E horizon* that lies above the spodic horizon (Figure 10.22).

10.19 Laterite

Soil erosion began when this slope in Borneo was stripped of vegetation. Natural accumulations of laterite, formed below the soil surface, were soon exposed. They now form tough, solid caps on columns of weaker soil (National Geographic Image Collection).

Spodosols are closely associated with regions recently covered by the great ice sheets of the Pleistocene Epoch. These soils are therefore very young. Typically, the parent material is coarse sand consisting largely of the mineral quartz. This mineral cannot weather to form clay minerals, so Spodosols are naturally poor soils in terms of agricultural productivity. Because they are acid, lime application is essential. They also need heavy applications of fertilizers. With proper management, Spodosols can be highly productive, if the soil texture is favorable—they give high yields of potatoes in Maine and New Brunswick.

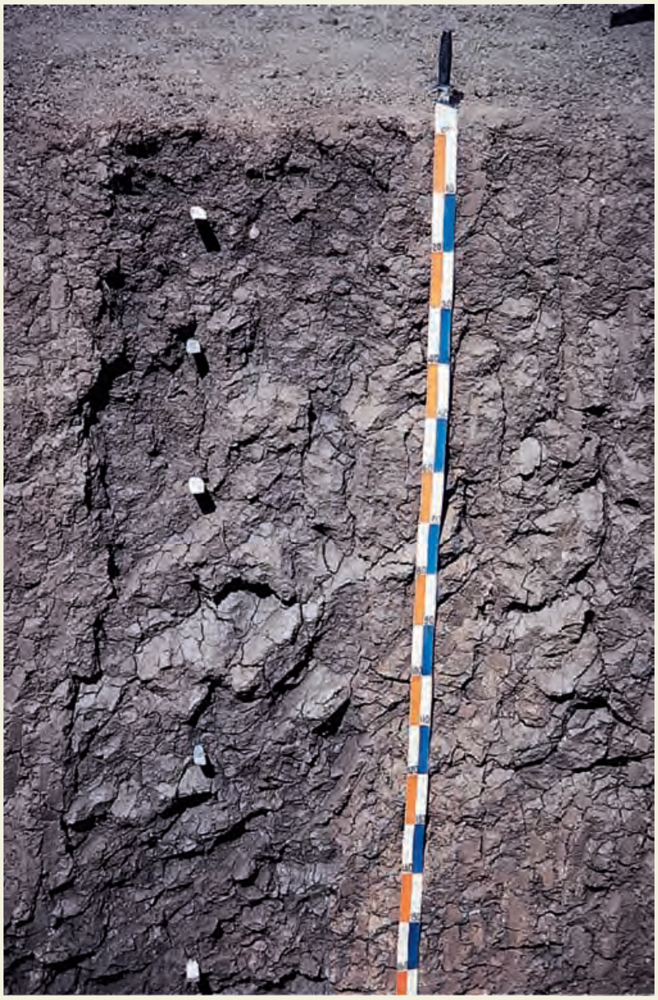
Spodisols have a light-colored albic horizon of eluviation and a dense spodic horizon of illuvation. They develop under cold needleleaf forests and are quite acid.

HISTOSOLS

Throughout the northern regions of Spodosols are countless patches of **Histosols**. This unique soil order has a very high content of organic matter in a thick, dark upper layer (Figure 10.23). Most Histosols go by

10.20 Vertisols

Vertisols have a high base status and are particularly rich in calcium and magnesium nutrients with a moderate content of organic matter. The soil retains large amounts of water because of its fine texture, but much of this water is held tightly by the clay particles and is not available to plants. The clay minerals that are abundant in Vertisols shrink when they dry out, producing deep cracks in the soil surface. As the dry soil blocks are wetted and softened by rain, some fragments of surface soil drop into the cracks before they close, so that the soil "swallows itself" and is constantly being mixed.



▲ **Soil profile for a Vertisol in India** The very dark color and shiny surfaces of the clay particles are typical of Vertisols. This profile is for a Vertisol of suborder Ustert in India.

▲ **Vertisol in Texas** On drying, Vertisols develop deep vertical cracks.

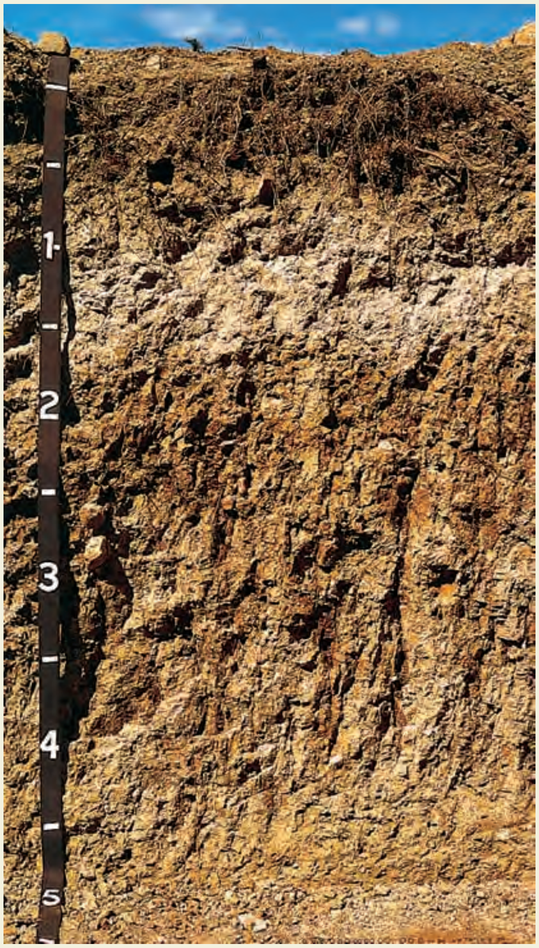
common names such as peats or mucks. They have formed in shallow lakes and ponds by accumulation of partially decayed plant matter. In time, the water is replaced by a layer of organic matter, or *peat*, and becomes a *bog*. Peat from bogs is dried and baled for sale as a mulch for use on suburban lawns and shrubbery beds. For centuries, Europe has used dried peat from bogs of glacial origin as a low-grade fuel.

Histosols are organic soils, often termed peats or mucks. They are typically formed in cool or cold climates in areas of poor drainage.

Some Histosols are *mucks*—organic soils composed of fine black materials of sticky consistency. These are agriculturally valuable in midlatitudes, where they occur as beds of former lakes in glaciated regions. After appropriate drainage and application of lime and fertilizers, these mucks are remarkably productive for garden vegetables.

10.21 Alfisols

Alfisols have a gray, brownish, or reddish surface horizon. Unlike the clay-rich horizon of the Ultisols, the *B* horizon of Alfisols is enriched by silicate clay minerals that can hold bases such as calcium and magnesium, giving Alfisols a high base status. Below the *A* horizon is a pale *E* horizon, which has lost some of the original bases, clay minerals, and sesquioxides by eluviation. These materials have become concentrated in the *B* horizon.



▲ **Udalf from Michigan** Udalfs are a suborder of Alfisols closely associated with the moist continental climate in North America, Europe, and eastern Asia. The *E* horizon is the lighter layer below the top darker plow layer.

▲ **Ustalf from Texas** Ustalfs are a suborder of Alfisols that range from the subtropical zone to the Equator and are often associated with the wet-dry tropical climate ③ in Southeast Asia, Africa, Australia, and South America. This Ustalf, however, is from Texas.

Histosols are also found in low latitudes where poor drainage has favored thick accumulations of plant matter.

ENTISOLS, INCEPTISOLS, GELISOLS, AND ANDISOLS

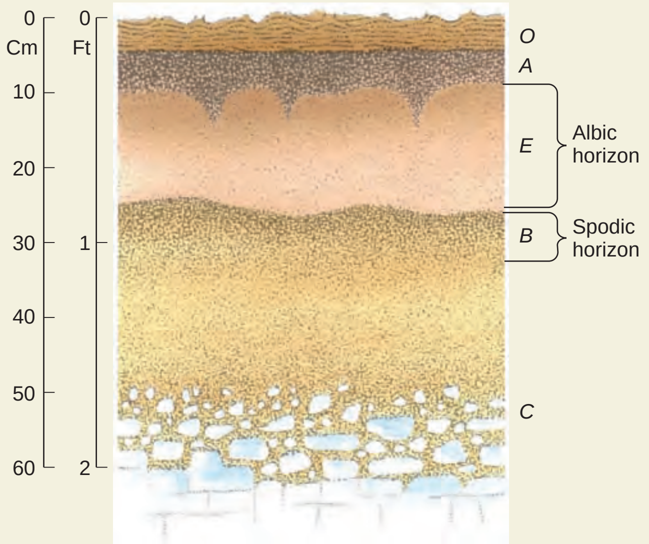
Entisols are mineral soils without distinct horizons. They are soils in the sense that they support plants, but they may be found in any climate and under any vegetation. They don't have distinct horizons for two reasons: either the parent material, for example, quartz sand, is not appropriate for horizon formation; or not enough time has passed for horizons to form in recent deposits of alluvium or on actively eroding slopes. **Inceptisols** are soils with weakly developed horizons, usually because the soil is quite young. Entisols and Inceptisols can be found anywhere from equatorial to arctic latitude zones. Often they occur as patches too small to show on the global soils map (Figure 10.16).

Entisols lack horizons, often because they are only recently deposited. They may occur in any climate or region.

Entisols and Inceptisols of floodplains and delta plains in warm and moist climates are among the most highly

10.22 Spodosol profile

▼ The spodosol profile is marked by a light gray or white albic horizon—an *E* horizon that is bleached by organic acids percolating downward from a slowly decomposing *O* horizon. Also diagnostic is the spodic horizon, a dense mixture of organic matter and compounds of aluminum and iron, all brought downward by eluviation from the overlying *E* horizon. Spodosols are strongly acid and are low in plant nutrients such as calcium and magnesium. They are also low in humus. Although the base status of the Spodosols is low, forests of pine and spruce are supported through the process of recycling of the bases.



◀ This Spodosol from France, of suborder Orthod, clearly shows the albic *E* horizon above the yellowish spodic *B* horizon. The *O* and *A* horizons have been removed by erosion.

productive agricultural soils in the world because of their favorable texture, ample nutrient content, and large soil-water storage. In Southeast Asia, Inceptisols support dense populations of rice farmers (Figure 10.24). Annual river floods cover low-lying plains and deposit layers of fine silt. This sediment is rich in primary minerals that yield bases as they weather chemically over time. The constant enrichment of the soil explains the high soil fertility in a region where uplands develop Ultisols with low fertility.

Inceptisols have only weakly developed horizons. Inceptisols of river floodplains and deltas are often very productive.

Gelisols are soils of cold regions that are underlain by permanently frozen ground, or *permafrost*. They usually consist of very recent parent material, left behind by glacial activity during the Ice Age, along with organic matter that decays only slowly at low temperatures. They are subjected to frequent freezing and thawing, which causes ice lenses and wedges to grow and melt in the soil. This action churns the soil, mixing parent material and organic matter irregularly and inhibiting development of a soil profile.

Gelisols are soils of permafrost regions that are churned by freeze-thaw ice action.

Andisols are soils in which more than half of the parent mineral matter is volcanic ash, spewed high into the air from the craters of active volcanoes and coming to rest in layers over the surrounding landscape. The fine ash particles are glass-like shards. Andisols have a high proportion of carbon, formed from decaying plant matter, so the soil is very dark. They form over a wide range of latitudes and climates and are generally fertile soils. In moist climates they support a dense natural vegetation cover.

Andisols aren't shown on our world map because they are found in small patches associated with individual volcanoes that are located mostly in the "Ring of Fire"—the chain of volcanic

Andisols are unique soils that form on volcanic ash of relatively recent origin. They are dark in color and typically fertile.

10.23 Histosols

▼ **A Histosol from Minnesota** This soil consists almost entirely of a deep layer of weathered peat.

▲ **Peat bog** This peat bog in Galway, Ireland, has been trenched to reveal a Histosol profile. Peat blocks, seen to the sides of the trench, are drying for use as fuel.

EYE ON THE LANDSCAPE **What else would the geographer see?** Peat bogs are a type of glacial terrain. The hummocky terrain (A) at the edge of this bog may be part of a moraine, a landform that occurs at the melting edge of an ice sheet as wasting ice leaves piles of sentiment behind in a chaotic and disorganized fashion. The isolated angular boulders (B) may be *erratics*—large rocks that are carried in the ice and moved long distances from their sources. Landforms of glacial ice sheets are described in Chapter 17.

10.24 Fertile Inceptisols

Broad river floodplains are often the sites of fertile Inceptisols, given their abundant water and a frequent flooding cycle that adds nutrients to the soil. Shown here are rice paddies in Vietnam (National Geographic Image Collection).

mountains and islands that surrounds the great Pacific Ocean. Andisols are also found on the island of Hawaii, where volcanoes are presently active.

MOLLISOLS

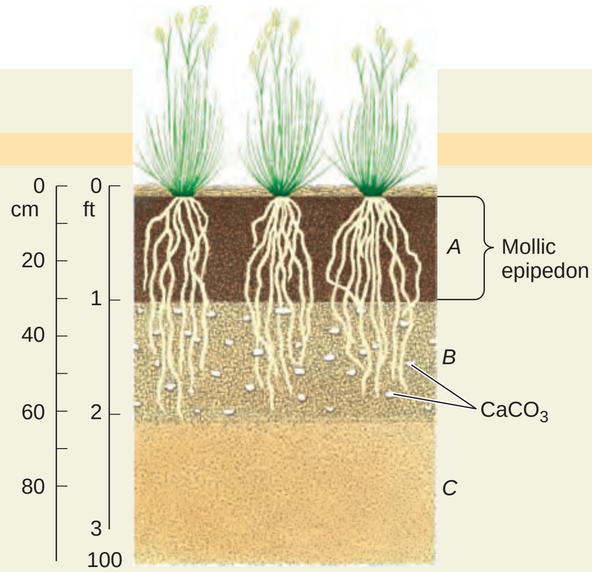
Mollisols are grassland soils that occupy vast areas of semiarid and subhumid climates in midlatitudes. They are unique in having a very thick, dark brown to black surface horizon called a *mollic epipedon* (Figure 10.25).

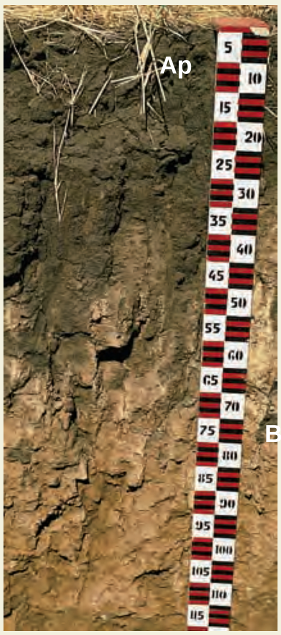
Most areas of Mollisols are closely associated with the semiarid subtype of the dry midlatitude climate ⑨ and the adjacent portion of the moist continental climate ⑩. In North America, Mollisols dominate the Great Plains region, the Columbia Plateau, and the northern Great Basin. In South America, a large area of Mollisols covers the Pampa region of Argentina and Uruguay. In Eurasia, a great belt of Mollisols stretches from Romania eastward across the steppes of Russia, Siberia, and Mongolia.

Because of their loose texture and very high base status, Mollisols are among the most naturally fertile soils in the world. They now produce most of the world's commercial grain crop. Most of these soils have been used for crop production only in the last century. Before that, they were used mainly for grazing by nomadic herds. The Mollisols have favorable properties for

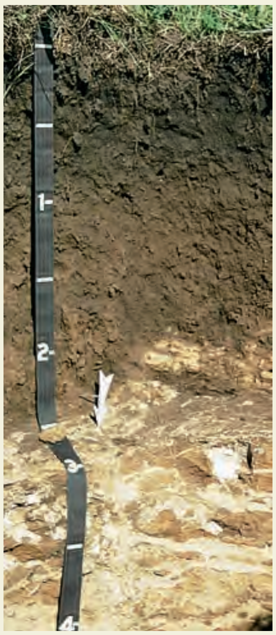
10.25 Mollisols

▶ **A schematic diagram of a Mollisol profile** Mollisols have a very dark brown to black surface horizon lying within the A horizon. It is always more than 25 cm (9.8 in.) thick. The soil has a loose, granular structure or a soft consistency when dry. Mollisols are dominated by calcium among the bases of the *A* and *B* horizons, giving them a very high base status.





▲ **Boroll** A Mollisol of cold-climate regions. This example is from Russia.



▲ **Udoll** A Mollisol of moist midlatitude climates. This example is from Argentina.

▲ **Ustoll** A Mollisol from a midlatitude semiarid climate. This example is developed on loess.

growing cereals in large-scale mechanized farming and are relatively easy to manage. Production of grain varies considerably from one year to the next because seasonal rainfall is highly variable.

A brief mention of four suborders of the Mollisols commonly found in the United States and Canada will help you to understand important regional soil differences related to climate (Figure 10.25). *Borolls*, the cold-climate suborder of the Mollisols, are found in a large area extending on both sides of the U.S.-Canadian border east of the Rocky Mountains as well as in Russia. *Udolls* are Mollisols of a relatively moist climate. They used to support tall-grass prairie, but today they are closely identified with the corn belt in the American Midwest, as well as the Pampa region of Argentina. *Ustolls* are Mollisols of the semiarid subtype of the dry midlatitude climate ⑨, with a substantial soil-water shortage in the summer months. They underlie much of the short-grass prairie region east of the Rockies. *Xerolls* are Mollisols of the Mediterranean climate ⑦, with its tendency to cool, moist winters and rainless summers.

Mollisols are soils of grasslands in subhumid to semiarid climates. They have a thick, dark brown surface layer termed a mollic epipedon. Because of their loose texture and high base status, they are highly productive.

ARIDISOLS

Aridisols, soils of the desert climate, are dry for long periods of time. Because the climate supports only very sparse vegetation, the soils are low in organic matter. They are pale-colored, ranging from gray to red (Figure 10.26). They may have horizons with significant accumulations of calcium carbonate or soluble

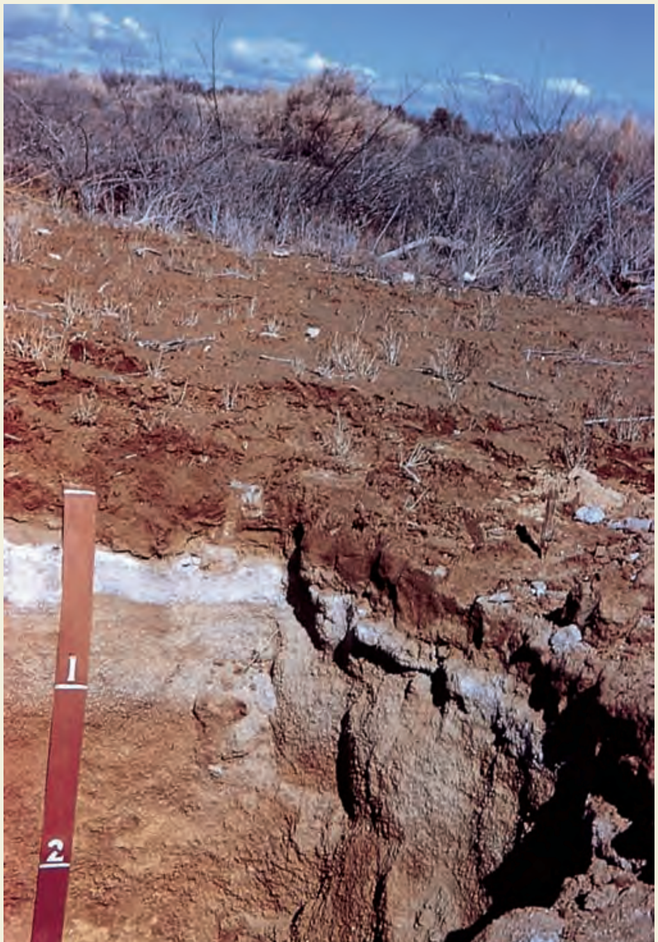
Aridisols are desert soils with weakly developed horizons. They often exhibit subsurface layers of accumulation of calcium carbonate or soluble salts. With irrigation and proper management, they are quite fertile.

10.26 Aridisols

The soil horizons of Aridisols are often weakly developed, but there may be important subsurface horizons of calcium carbonate or soluble salts.

▼ **Aridisol from Colorado** Carbonate accumulations are visible as white blotches and patches in this Aridisol, subclass Argid, from Colorado.

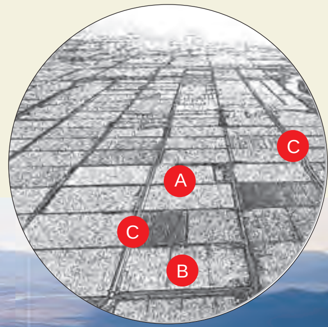
▼ **Salic horizon** The white layer close to the surface in this Aridisol profile in the Nevada desert is a salic horizon.



10.27 Irrigated Aridisols

Cotton farming along the Colorado river, near Parker, Arizona, is shown in this oblique air photo.

EYE ON THE LANDSCAPE **What else would the geographer see?** The broad floodplain of the Colorado River (right) shows how productive Aridisols can be when properly managed and irrigated. A consistent climate with abundant sunlight, coupled with abundant river water, makes for high productivity and crop yields. Fallow fields (A) show typical Aridisol colors of gray to brown, while cotton fields are vibrant green (B). Note the network of canals (C) serving the fields.



salts. The salts, mostly containing sodium, make the soil very alkaline. The Aridisols are closely correlated with the arid subtypes of the dry tropical ④a, dry subtropical ⑤a, and dry midlatitude ⑨a climates.

Most Aridisols are still used for nomadic grazing, just as they have been through the ages. With low and sporadic rainfall, it's difficult to cultivate crops. But with irrigation, Aridisols can be highly productive (Figure 10.27).

A Look Ahead

An important message of these last three chapters is that climate, vegetation, and soils are closely interrelated. The nature of the vegetation cover depends largely on the climate, varying from desert to tundra biomes. Soils depend on both climate and vegetation to develop their unique characteristics. But soils can also influence vegetation development. Similarly, the climate at a location can be influenced by its vegetation cover.

The next two chapters also comprise a set of topics that are strongly related. They deal with the lithosphere—the realm of the solid Earth. Our survey of the lithosphere will begin with the nature of Earth materials and then move to a discussion of how continents and ocean basins are formed and how they are continually changing, even today. Finally, we will discuss landforms occurring within continents that are produced by such lithospheric processes as volcanic activity and earthquake faulting.

GEODISCOVERIES Interaction of Climate, Vegetation, and Soil
Return to the animations for Chapter 7 to view climate, vegetation, and soils maps superimposed to see common patterns. One animation for each of five global regions.

GEODISCOVERIES Web Quiz
Take a quick quiz on the key concepts of this chapter.

IN REVIEW GLOBAL SOILS

- At first, global climate change will increase crop yields as temperatures increase, but eventually crop yields will fall with increasing stress on crop plants. Food prices will probably rise, but adjustments in farming practices may compensate.
- **Soil** is the uppermost layer of the land surface. The major factors influencing soil and soil development are **parent material**, climate, vegetation, and time.
- Soil colors range from white to red or yellow to brown and black. Color is usually generated in the soil formation process.
- The soil layer is a complex mixture of solid, liquid, and gaseous components. It is derived from *regolith* that is produced from parent material by *weathering*.
- **Soil texture** refers to the proportions of *sand*, *silt*, and *clay* that are present. A loam is a mixture of sizes. Soil texture determines water-holding characteristics.
- **Soil colloids** are the finest particles in soils and are important because they help retain nutrient ions, or **bases**, that are used by plants.
- Soils range from acid to alkaline. Acid ions tend to displace bases, making acid soils generally less fertile. Soils of cool and cold climates are usually acid, while arid climates often have alkaline soils.
- *Peds* are soil grains ranging from small grains to large blocks. Soils with granular or blocky structures are most easily cultivated.
- In soils, *primary minerals* are chemically altered to **secondary minerals**, which include *mineral oxides* and *clay minerals*. The nature of the clay minerals determines the soil's base status. If *base status* is *high*, the soil retains nutrients. Mineral oxides are products of long-continued weathering.
- The soil receives water from precipitation. It loses water by evapotranspiration and by percolation of water down to ground water below.
- When a soil is fully wetted by heavy rainfall or snowmelt and allowed to drain, it reaches its *storage capacity*. If soil water is lost by evapotranspiration without recharge, the *wilting point* is eventually reached.
- The *soil-water balance* describes the gain and loss of soil-water storage. The balance depends on precipitation, evapotranspiration, and runoff.
- Most soils possess distinctive horizontal layers called **soil horizons** that are produced by soil processes acting through time. The **soil profile** describes the layered structure of a particular soil.
- *Organic horizons* (*O horizons*) lie at the top of the soil profile and consist of organic matter in various stages of decay.
- *Mineral horizons* include the *A horizon*, rich in organic matter; *E horizon*, from which clay particles and oxides are removed; *B horizon* in which clays and oxides accumulate; and *C horizon* of unaltered regolith.
- These layers are developed by processes of enrichment, removal, translocation, and transformation. In *enrichment*, organic or mineral matter is added to the soil. In *removal*, matter is lost, for example, by erosion.
- In downward *translocation*, *humus*, clay particles, mineral oxides, and calcium carbonate are removed by **eluviation** from an upper horizon and accumulate by **illuviation** in a lower one. In *salinization*, salts are translocated upward by evaporating irrigation water to accumulate near the surface and reduce crop yields.
- In *transformation*, primary minerals are altered to secondary minerals. *Humification* is a transformation process in which organic matter is broken down by bacterial decay.
- Factors influencing soil development include soil temperature, the ground surface configuration, animal activity, and human activity.
- Global soils are classified into 11 **soil orders**, often by the presence of one of more diagnostic horizons.
- **Oxisols** are old, highly weathered soils of low latitudes. They have a horizon of mineral oxide accumulation and a low base status.
- **Ultisols** are also found in low latitudes. They have a horizon of clay accumulation and are also of low base status.
- **Vertisols** are rich in a type of clay mineral that expands and contracts with wetting and drying, and has a high base status.
- **Alfisols** have a horizon of clay accumulation like **Ultisols**, but they are of high base status. They are found in moist climates from equatorial to subarctic zones.
- **Spodosols**, found in cold, moist climates, exhibit an *albic horizon* of eluviation and a *spodic horizon* of illuviation. The base status of Spodosols is low.

- **Histosols** have a thick upper layer formed almost entirely of organic matter.
- **Entisols**, **Inceptisols**, **Gelisols**, and **Andisols** are soil orders with poorly developed horizons or no horizons. Entisols are composed of fresh parent material and have no horizons. The horizons of Inceptisols are only weakly developed. Gelisols are soils of premafrost regions that are churned by frost action. Andisols are weakly developed soils occurring on young volcanic deposits.
- **Mollisols** have a thick upper layer rich in humus. They are soils of midlatitude grasslands.
- **Aridisols** are soils of arid regions, marked by horizons of accumulation of carbonate minerals or salts.

KEY TERMS

soil, p. 000
parent material, p. 000
soil texture, p. 000
soil colloids, p. 000
bases, p. 000
secondary minerals, p. 000
soil horizons, p. 000
soil profile, p. 000
eluviation, p. 000
illuviation, p. 000
soil orders, p. 000
Oxisols, p. 000
Ultisols, p. 000
Vertisols, p. 000
Alfisols, p. 000
Spodosols, p. 000
Histosols, p. 000
Entisols, p. 000
Inceptisols, p. 000
Gelisols, p. 000
Andisols, p. 000
Mollisols, p. 000
Aridisols, p. 000

REVIEW QUESTIONS

1. How will increasing temperature affect agricultural crop yields? What will be the effect of increasing atmospheric CO_2 concentrations?
2. What actions can farmers and farm managers take to mitigate the effects of climate change?
3. What is the predicted impact of global climate change on food prices? Who will be most affected?
4. Which important factors condition the nature and development of the soil?
5. Identify important soil materials and components. What is *weathering?* What is *regolith?*
6. Soil color and soil texture are used to describe soils and soil horizons. Identify these terms, showing how they are applied.
7. What are *soil colloids?* Why are they important? How is the ability of colloids to hold bases affected by soil acidity?
8. How does soil structure affect cultivation? What are *peds?* Which soils lack peds?
9. Identify two important classes of secondary minerals in soils and provide examples of each class.
10. How does the ability of soils to hold water vary, and how does this ability relate to soil texture? In your answer, define *storage capacity* and *wilting point*.
11. What processes determine the soil-water balance? How are they related to climate?
12. What is a soil horizon? Distinguish between organic and mineral horizons. Generally describe *A, E, B,* and *C* horizons.
13. Identify four classes of soil-forming processes and describe each.
14. What are translocation processes? Explain using the terms *eluviation* and *illuviation*. How is calcium carbonate translocated in soils?
15. Briefly describe the effect of the following factors on soil development: soil temperature, ground surface configuration, living organisms in the soil, human activity.
16. How many soil orders are there? Try to name them all.
17. Identify three soil orders that are especially associated with low latitudes. For each order, provide at least one distinguishing characteristic and explain it.
18. Compare Alfisols and Spodosols. What features do they share? What features separate them? Where are they found?
19. Which soil orders lack distinct horizons? How are they distinguished from each other?
20. Describe a Mollisol profile. How are the properties of Mollisols related to climate and vegetation cover? Name four suborders within the Mollisols.
21. What are the key features of Aridisols? Where are they found?

VISUALIZING EXERCISES

1. Sketch the profile of a Spodosol, labeling *O*, *A*, *E*, *B*, and *C* horizons. Diagram the movement of materials from the zone of eluviation to the zone of illuviation.
2. Examine the world soils map (Figure 10.19) and identify three soil types that are found near your location. Develop a short list of characteristics that would help you tell them apart.

ESSAY QUESTIONS

1. Document the important role of clay particles and clay mineral colloids in soils. What is meant by the term *clay*? What are *colloids*? What are their properties? How does the type of clay mineral influence soil fertility? How does the amount of clay influence the water-holding capacity of the soil? What is the role of clay minerals in horizon development?
2. Using the world maps of global soils and global climate, compare the pattern of soils on a transect along the 20° E longitude meridian with the patterns of climate encountered along the same meridian. What conclusions can you draw about the relationship between soils and climate? Be specific.

Chapter 11
Earth Materials and Plate Tectonics

Many types of rocks are produced by volcanic activity. In addition to lava, volcanoes can eject huge volumes of volcanic ash, burying the local landscape. These ash deposits, eventually carried downslope as watery mudflows in heavy rainstorms, buried the village of Bacalor, Luzon, Philippines in volcanic mud several meters deep. Although the town was abandoned at first, new dwellings were eventually built on top of the deposits, sometimes next to the buried homes they replaced.

The eruption of Mount Pinatubo in June 1991 was the second largest terrestrial eruption of the twentieth century. The volcano ejected about 10 km³ (2.4 mi³) of material—about 10 times more than the 1980 eruption of Mount Saint Helens. The most violent eruptions, on June 12–13, produced plumes as high as 21 km (69,000 ft) that lofted millions of tons of dust and sulfur dioxide gas into the stratosphere. These aerosols reduced the amount of sunlight reaching the Earth's surface by about 10 percent, dropping global temperatures by about half a degree C (about 1°F) for a year.

Fortunately, there was plenty of warning before the eruption, and evacuation was largely successful. Only about 875 persons died, although many more were injured.

The village of Bacalor, Luzon, Philippines, after the eruption of Mount Pinatubo

Earth Materials and Plate Tectonics

The geography of the Earth—its continents, oceans, mountains, and plains—is determined by geologic processes acting over millions of years. How do these geologic processes work? How are Earth materials formed and transformed? Today's continents are in motion. What happens when they split apart? When they collide? These are some of the questions we will answer in this chapter.

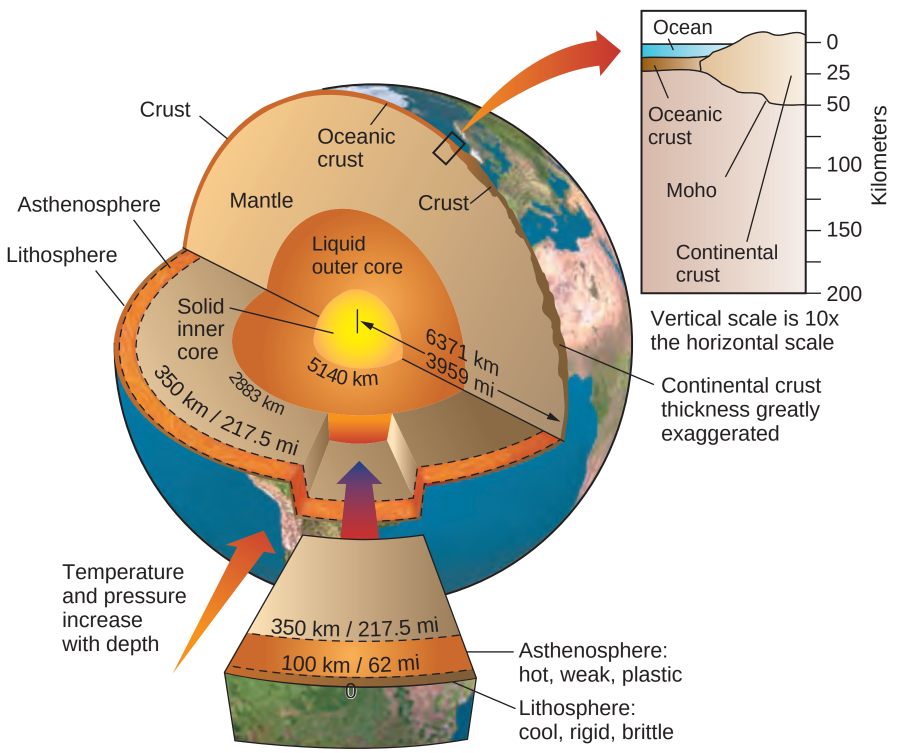
Minerals and Rocks of the Earth's Crust

What lies deep within the Earth? Our planet has a central core with several layers, or shells, surrounding it. The densest matter is at the center, and each layer above it is increasingly less dense.

THE EARTH'S INTERIOR

Our planet is almost spherical, with a radius of approximately 6400 km (about 4000 mi). Its central **core** is about 3500 km (about 2200 mi) in radius (Figure 11.1). We know that the outer core is liquid from measurements of earthquake waves passing through the Earth, which suddenly change behavior when they reach the core. But the innermost part of the core is solid and made mostly of iron, with some nickel. The core is very hot—somewhere between 3000°C and 5000°C (about 5400°F to 9000°F).

The core is surrounded by the **mantle**—a shell about 2900 km (about 1800 mi) thick. Mantle temperatures range from about 2800°C (about 5100°F) near the core to about 1800°C (about 3300°F) near the crust. The mantle is composed of *ultramafic rock*, which is made



11.1 The structure of the Earth

The upper part of this cutaway shows compositional layers, and the lower part shows layers with differing rock properties. Note that the boundaries between compositional layers and properties do not always coincide. For example, the rigid lithosphere includes both the crust and a small upper layer of the mantle.

up of the densest forms of iron and magnesium combined with silicon and oxygen.

The thin, outermost layer of our planet is the Earth's **crust**. This skin of varied rocks and minerals ranges from about 8 to 40 km (about 5 to 25 mi) thick and contains the continents and ocean basins. It is the source of soil on the lands, salts in the sea, gases in the atmosphere, and of all the water of the oceans, atmosphere, and lands.

The layers of the Earth's interior include the crust, mantle, liquid outer core, and solid inner core. Continental crust has both felsic and mafic rock zones, while oceanic crust has only mafic rock.

The base of the crust is sharply defined where it contacts the mantle. This contact is detected by the way in which earthquake waves abruptly change velocity at that level. The boundary surface between crust and mantle is called the *Moho*, a simplification of the name of the scientist, Andrija Mohorovicic, who discovered it in 1909.

The crust that lies below ocean floors—*oceanic crust*—consists almost entirely of silicates of magnesium and iron—*mafic rocks*. But the *continental crust* consists of two continuous zones—an upper zone of rocks that are less dense and are composed of silicates of aluminum, sodium, potassium, and calcium—*felsic rocks*—and a lower zone of denser, mafic rock. Another key distinction between continental and oceanic crust is that the crust beneath the continents is much thicker—35 km (22 mi) on average—than it is beneath the ocean floors, where it is typically 7 km (4 mi).

MINERALS AND ROCKS

Minerals are naturally occurring inorganic substances, often with a crystalline structure (Figure 11.2). They are composed largely of the most abundant elements in the Earth's crust, silicon and oxygen, coupled with metals or the metallic elements of iron, calcium, sodium, potassium, and magnesium.

Rocks are usually composed of two or more minerals. Often, many different minerals are present, but a few rock varieties are made almost entirely of one mineral. Most rock in the Earth's crust is extremely old, dating back many millions of years, but rock is also being formed at this very hour as active volcanoes emit lava that solidifies on contact with the atmosphere or ocean.

Rocks fall into three major classes: (1) igneous, (2) sedimentary, and (3) metamorphic rocks. The three classes of rocks are constantly being transformed from one to another in a continuous process through which the crustal minerals have been recycled during many millions of years of geologic time. Figure 11.3 diagrams these transformations.

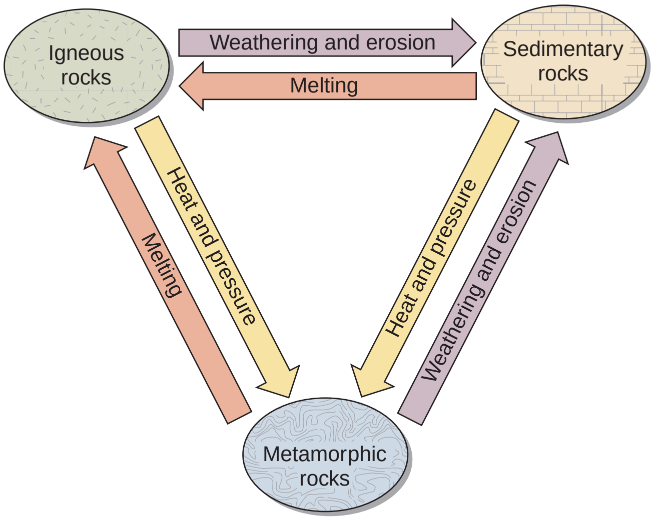
Rocks are composed of minerals—naturally occurring inorganic substances. The three classes of rocks are igneous, sedimentary, and metamorphic. Earth processes transform rocks from one class to another.

In the process of *melting*, preexisting rock of any class is melted and then later cools to form igneous rock. In *weathering and erosion*, preexisting rock is broken down and

11.2 Examples of minerals

▼ **Salt crystals** Minerals are naturally occurring crystalline chemical compounds. Salt, sodium chloride, is an example. These clear salt crystals were deposited near the vent of an underwater volcano. In many rocks, mineral crystals are too small to be seen without magnification (National Geographic Image Collection).

▼ **Quartz crystals** Quartz, or silicon dioxide, is a very common mineral. Under unusual circumstances, quartz is found as regular six-sided crystals, shown here in this sample from Venezuela. Usually, it is found as a clear or light-colored mineral, and it is often present in sediments such as beach sand or river gravel (National Geographic Image Collection).



11.3 Rock transformation

The three classes of rock are transformed into one another by weathering and erosion, melting, and exposure to heat and pressure.

accumulated in layers that become sedimentary rock. *Heat and pressure* convert igneous and sedimentary rocks to metamorphic rock. We will return to this cycle later in the chapter, after we have taken a more detailed look at rocks, minerals, and their formation processes.

GEODISCOVERIES **Virtual Rock Lab Interactivity**
How are minerals and rocks identified? Learn the characteristics of common minerals and rocks and test the knowledge you've gained in the chapter with this interactivity.

IGNEOUS ROCKS

Igneous rocks are formed when molten material, or **magma**, solidifies. The magma moves upward from pockets a few kilometers below the Earth's surface, through fractures in older solid rock. There the magma cools, forming rocks of mineral crystals.

Most igneous rock consists of *silicate minerals*—chemical compounds that contain silicon and oxygen atoms. These rocks also contain mostly metallic elements. The mineral grains in igneous rocks are very tightly interlocked, and so the rock is normally very strong. *Quartz*, which is made of silicon dioxide (SiO_2), is the most common mineral of all rock classes (Figure 11.2). It is quite hard and resists chemical breakdown.

Figure 11.4 shows some other common silicate minerals and the intrusive and extrusive rocks that are made from them. As noted earlier, silicate minerals in igneous rocks are classed as *felsic*, which are light-colored and less dense, and *mafic*, which are dark-colored and more dense. *Felsic rock* contains mostly felsic minerals, and *mafic rock* contains mostly mafic minerals. *Ultramafic rock* is dominated by two heavy mafic minerals and is the densest of the three rock types. Three common igneous rocks shown in the figure are *granite* (felsic, intrusive); *andesite* (felsic, extrusive); and *basalt* (mafic, intrusive).

> **Igneous rocks form when molten rock cools, forming silicate mineral crystals. Felsic minerals are light colored and less dense, and mafic minerals are dark colored and more dense.**

Magma that solidifies below the Earth's surface and remains surrounded by older, preexisting rock is called *intrusive igneous* rock. Because intrusive rocks cool slowly, they develop mineral crystals visible to the eye. If the magma reaches the surface and emerges as *lava*, it forms *extrusive* igneous rock. Extrusive igneous rocks cool very rapidly on the land surface or ocean bottom and thus show crystals of only microscopic size. You can see formation of extrusive igneous rock today where volcanic processes are active (Figure 11.5).

A body of intrusive igneous rock is called a **pluton**. Granite typically accumulates in enormous plutons, called *batholiths*. Figure 11.6 shows the relationship of a batholith to the overlying rock. As the hot fluid magma rises, it melts and incorporates the older rock lying above it. A single batholith extends down several kilometers and may occupy an area of several thousand square kilometers.

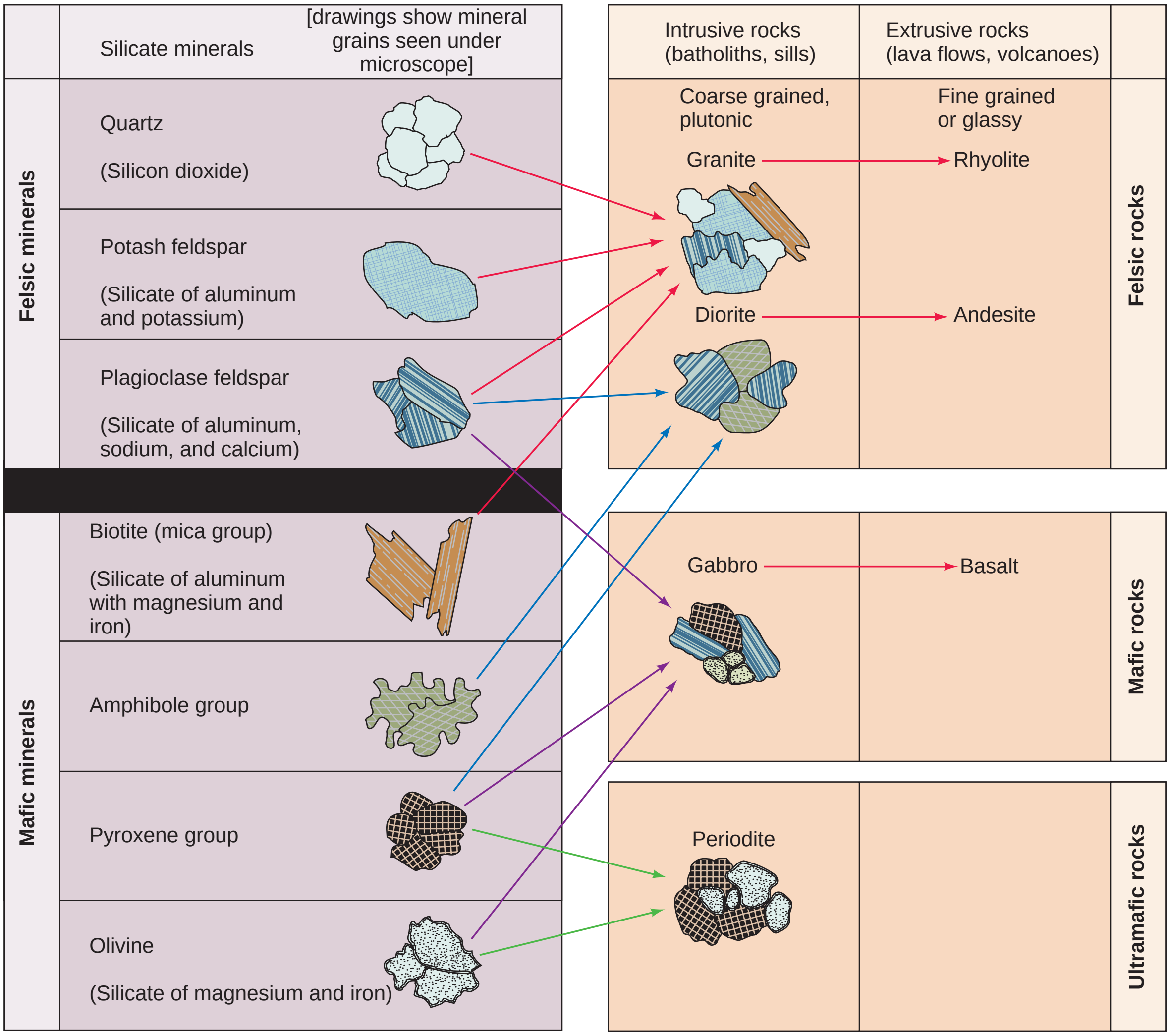
Figure 11.6 shows other common forms of plutons. One is a *sill*, a plate-like layer formed when magma forces its way between two preexisting rock layers. In the example shown, the sill has lifted the overlying rock layers to make room. A second kind of pluton is the *dike*, a wall-like body formed when a vertical rock fracture is forced open by magma (Figure 11.7). These vertical fractures conduct magma to the land surface in the process of *extrusion*. The dike rock is fine-textured because of its rapid cooling. Magma entering small, irregular, branching fractures in the surrounding rock solidifies in a branching network of thin veins.

> **Intrusive igneous rocks cool slowly below the Earth's surface and develop visible mineral crystals. Extrusive igneous rocks cool rapidly on the land surface or ocean bottom and show microscopic crystals.**

GEODISCOVERIES **Igneous Rock Animation**
Take another look at our diagram of silicate minerals and igneous rocks. Click on the diagram to see photos of the minerals and rocks and learn more about their characteristics.

SEDIMENTS AND SEDIMENTARY ROCKS

Now let's turn to the second rock class, the **sedimentary rocks**. Sedimentary rocks are made from layers, or *strata*, of mineral particles found in other rocks that have been weathered and from newly formed organic matter. Most inorganic minerals in sedimentary rocks are from igneous rocks.

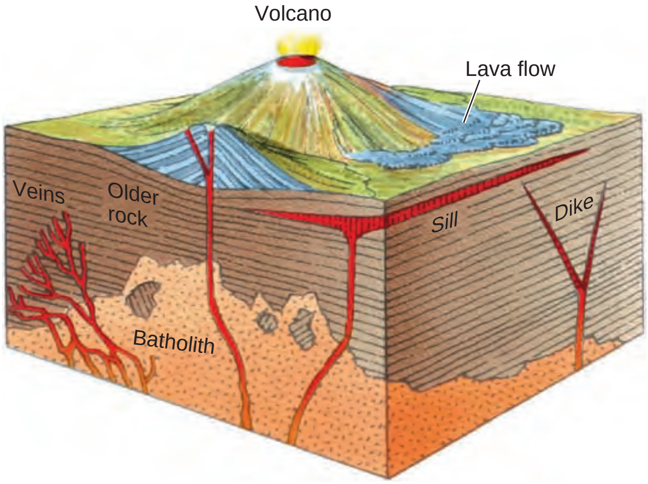


11.4 Silicate minerals and igneous rocks

Only the most important silicate mineral groups are listed, along with four common igneous rocks.

11.5 A lava flow on Kilauea volcano

As shown by its red-hot interior, this recent tongue of lava is still cooling. The cooled lava forms the igneous extrusive *rock basalt* (National Geographic Image Collection). Hawaii Volcanoes National Park.



11.6 Volcanic rock formations

This block diagram illustrates various forms of intrusive igneous rock plutons as well as an extrusive lava flow.

11.7 Exposure of a dike

A dike of mafic igneous rock with nearly vertical parallel sides, cutting across flat-lying sedimentary rock layers. Arrows mark the contact between igneous rock and sedimentary rock. Spanish Peaks region, Colorado.

When rock minerals are weathered, their chemical composition is changed, weakening the solid rock. The rock breaks up into particles of many sizes. When these particles are transported in a fluid—air, water, or glacial ice—we call them *sediment*. Streams and rivers carry sediment to lower land levels, where it builds up. Most sediments accumulate on shallow seafloors bordering continents, but they also collect in inland valleys, lakes, and marshes. Wind and glacial ice are two other agents of transportation that can move sediment. Over long spans of time, the sediments become compacted and harden to form sedimentary rock, with distinctive visible characteristics.

Sedimentary rocks are composed of sediment, which may be clastic, chemically precipitated, or organic. Layers of sediment are termed strata.

There are three major classes of sediment: clastic sediment, chemically precipitated sediment, and organic sediment (Figure 11.8). *Clastic sediment* is made up of inorganic rock and mineral fragments, called *clasts*. These can come from igneous, sedimentary, or metamorphic rocks, and so they can include a very wide range of minerals. Quartz and feldspar usually dominate clastic sediment.

The size of the clastic sediment particles determines how easily and how far they are transported by water currents. Fine particles are easily suspended in fluids, while coarse particles tend to settle to the bottom. In this way, particles of different sizes are sorted in the fluid.

Clastic sedimentary rocks are formed when sediments are compressed and cemented. Sandstone and shale are common examples. Limestone is formed by chemical precipitation in a marine environment.

When layers of clastic sediment build up, the lower strata are pushed down by the weight of the sediments above them. This pressure compacts the sediments, squeezing out excess water. Dissolved minerals recrystallize in the spaces between mineral particles in a process called *cementation*. Figure 11.9 shows some important varieties of clastic sedimentary rocks. *Sandstone*, a rock made of sand, and *shale*, a rock made of clay particles, are typical examples.

Chemically precipitated sediment is made of solid inorganic mineral compounds that precipitate from water solutions or are formed by organisms living in water. One of the most common sedimentary rocks formed by chemical precipitation is *limestone* (Figure 11.10).

The third class of sediment is *organic sediment*. This is made up of the tissues of plants and animals. *Peat* is an example of an organic sediment. This soft, fibrous, brown or black substance accumulates in bogs and marshes where the water stops the plant or animal remains from decaying.

Peat is a compound of hydrogen, carbon, and oxygen. Hydrocarbon compounds such as this are the most important type of organic sediment—one that we increasingly depend on for fuel. They formed from plant remains that built up over millions of years and were compacted under thick layers of inorganic clastic sediment. Hydrocarbons can be solid (peat and coal), liquid (petroleum), or gas (natural gas). Coal is the only hydrocarbon that is a rock (Figure 11.11). We often find natural gas and petroleum in open interconnected pores in a thick sedimentary rock layer, such as in a porous sandstone (Figure 11.11).

These **fossil fuels**, as they are known, took millions of years to build up. But our industrial society is consuming them rapidly. They are *nonrenewable resources*—once they are gone, there will be no more. Even if we wait another thousand years for more fossil fuels to be created, the amount we gain will scarcely be measurable in comparison to the stores produced in the geologic past.

Hydrocarbons in sedimentary rocks include coal, petroleum, natural gas, and peat. These mineral fuels power modern industrial society.

GEODISCOVERIES **Clastic Rocks Animation**
Learn the terms used for clasts of different sizes and examine several different types of clastic rocks.

GEODISCOVERIES **Hydrocarbons in Sedimentary Rocks**
Watch this animation to see how ocean floor sediment accumulates and ultimately provides deposits of oil and gas.

11.8 Common sedimentary rock types

Subclass	Rock Type	Composition
Clastic (composed of rock and/or mineral fragments)	Sandstone 	Cemented sand grains
	Siltstone	Cemented silt particles
	Conglomerate	Sandstone containing pebbles of hard rock
	Mudstone	Silt and clay, with some sand
	Claystone	Clay
	Shale 	Clay, breaking easily into flat flakes and plates
Chemically precipitated (formed by chemical precipitation from sea water or salty inland lakes)	Limestone 	Calcium carbonate, formed by precipitation on sea or lake floors
	Dolomite	Magnesium and calcium carbonates, similar to limestone
	Chert	Silica, a microcrystalline form of quartz
	Evaporites	Minerals formed by evaporation of salty solutions in shallow inland lakes or coastal lagoons
Organic (formed from organic material)	Coal 	Rock formed from peat or other organic deposits; may be burned as a mineral fuel
	Petroleum (mineral fuel)	Liquid hydrocarbon found in sedimentary deposits; not a true rock but a mineral fuel
	Natural gas (mineral fuel)	Gaseous hydrocarbon found in sedimentary deposits; not a true rock but a mineral fuel

METAMORPHIC ROCKS

The mountain-building processes of the Earth's crust involve tremendous pressures and high temperatures. These extreme conditions alter igneous or sedimentary rocks, transforming them into **metamorphic rock** (see the accompanying table below). In many cases, the mineral components of the parent rock are

Metamorphic rocks are formed from preexisting rocks by intense heat and pressure, which alter rock structure and chemical composition. Shale is transformed to slate or schist, sandstone to quartzite, and limestone to marble.

Rock Type	*Description*
Slate	Shale exposed to heat and pressure that splits into hard flat plates
Schist	Shale exposed to intense heat and pressure that shows evidence of shearing
Quartzite	Sandstone that is "welded" by a silica cement into a very hard rock of solid quartz
Marble	Limestone exposed to heat and pressure, resulting in larger, more uniform crystals
Gneiss	Rock resulting from the exposure of elastic sedimentary or intrusive igneous rocks to heat and pressure

11.9 Important varieties of clastic sedimentary rocks

▲ **Conglomerate** Conglomerate is a sedimentary rock of coarse particles of many different sizes. These climbers are working their way through some beds of conglomerate on their way to the top of Shipton's Arch, Xinjiang, China. On the left, the softer sediment between hard cobbles has eroded away, leaving the rounded rocks sticking out (National Geographic Image Collection).

▲ **Sandstone** Sandstone is composed of sand particles, normally grains of eroded quartz, that are cemented together in the process of rock formation. This example is the Navajo sandstone, which is found on the Colorado Plateau in Utah and Arizona.

EYE ON THE LANDSCAPE **What else would the geographer see?** Note how these fine sedimentary beds (A) are crossed at angles by other beds. This cross-bedding is characteristic of dune sands. As the sand dune moves forward, sand layers accumulate on its sloping forward surface. Later, the wind erodes the dune, forming a new surface across the beds that cuts them at an angle. That surface is then covered by more sand layers. Sand dune formation and movement is covered in Chapter 16.

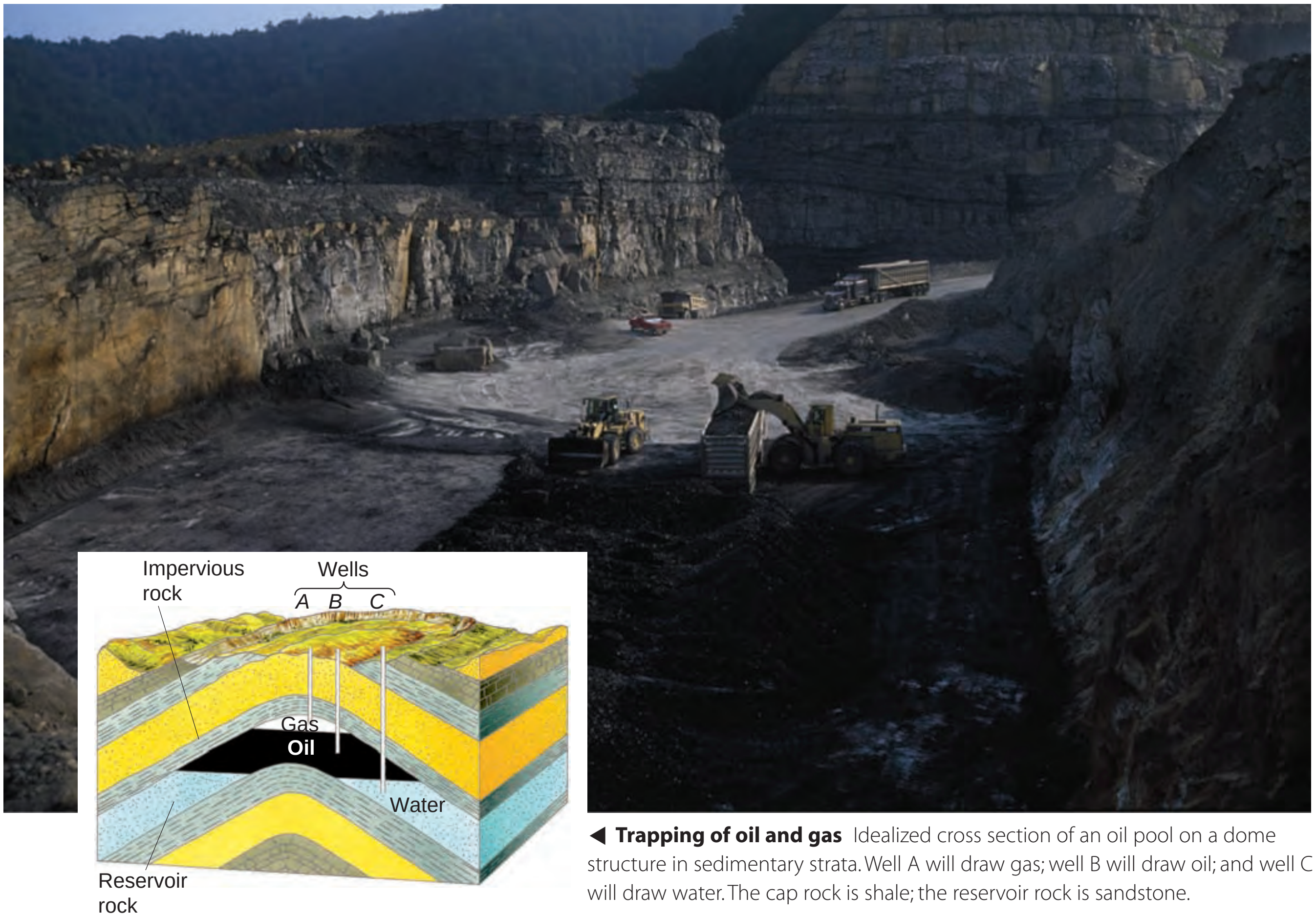
▼ **Shale** Shale is a rock formed mostly from silt and clay. It is typically gray or black in color and breaks into flat plates, as shown here. Some shale deposits contain fossils, like these ancient trilobites, marine animals of Cambrian age. Near Antelope Springs, Utah (National Geographic Image Collection).

11.10 Chalk cliffs

Chalk, composed of calcium carbonate, is a light and spongy form of limestone. Where it outcrops along a coast, it forms cliffs that are constantly eroded by waves. Rugen Island, Jasmund National Park, Germany (National Geographic Image Collection).

11.11 Fossil fuels

▼ **Strip mine** In strip mining, layers of coal are mined by removing overlying rock, allowing direct access to the coal deposit. Man, West Virginia.



◀ **Trapping of oil and gas** Idealized cross section of an oil pool on a dome structure in sedimentary strata. Well A will draw gas; well B will draw oil; and well C will draw water. The cap rock is shale; the reservoir rock is sandstone.

11.12 Two common metamorphic rock types

▲ **Quartzite** Under heat and pressure, sandstone recrystallizes to form a very strong rock of connected quartz grains called quartzite. Seneca Rocks, West Virginia (National Geographic Image Collection).

▶ **Schist** Metamorphic heat and pressure bakes shales and mudstones into schist, a rock with a wavy structure inherited from the original bedding planes. Crystals of garnet and other diagnostic minerals are formed in the baking process. Susquehanna River, Pennsylvania.

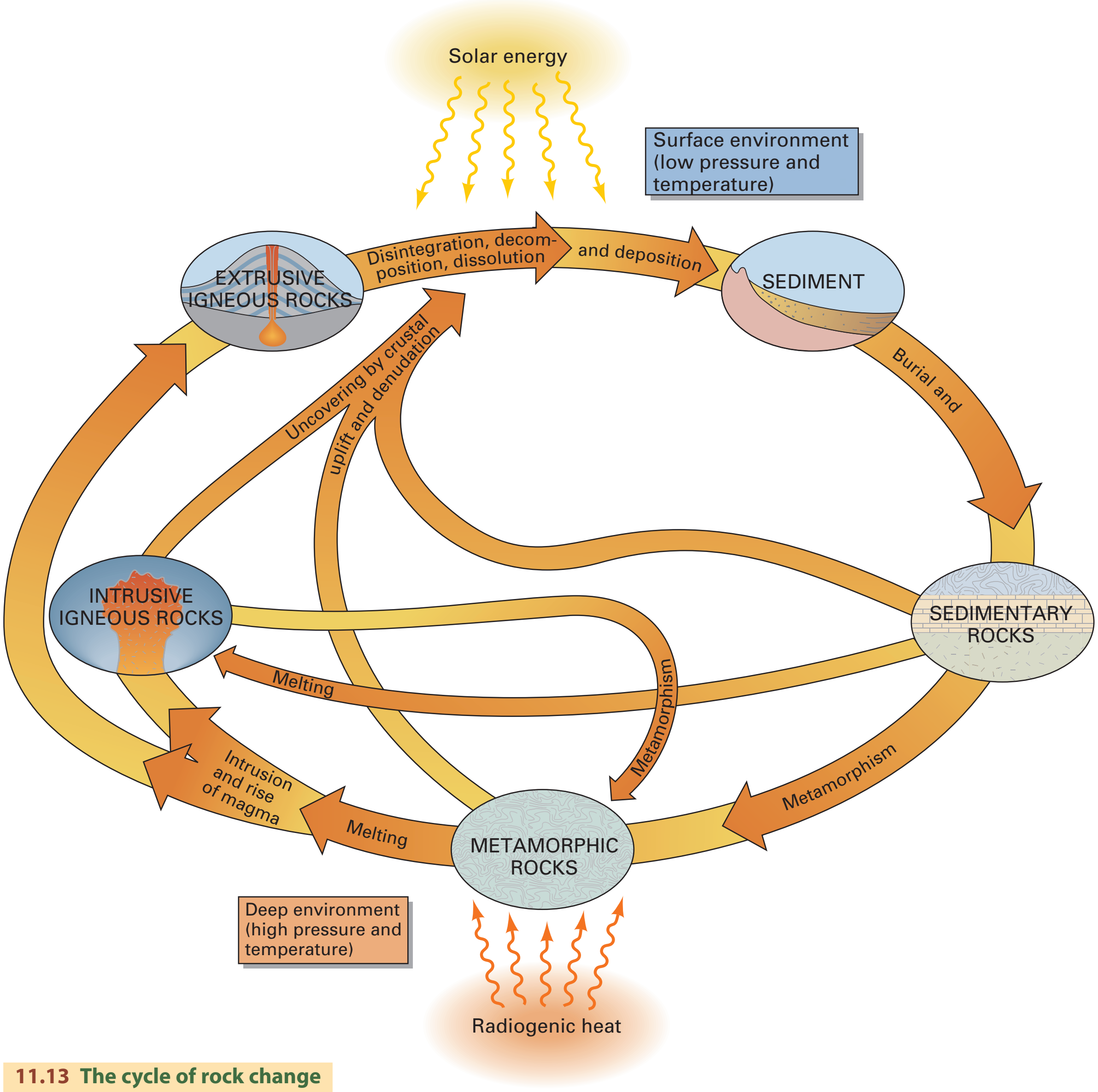
changed into different mineral varieties. In some cases, the original minerals may recrystallize.

Extreme heat and pressure transform shale into *slate* or *schist*, sandstone into *quartzite*, and limestone into *marble* (Figure 11.12). *Gneiss* forms when an intrusive magma cools next to igneous or sedimentary rocks.

THE CYCLE OF ROCK CHANGE

The processes that form rocks, when taken together, constitute a single system that cycles and recycles Earth materials over geologic time from one form to another. The **cycle of rock change**, shown in Figure 11.13, describes this system.

There are two environments—a surface environment of low pressures and temperatures and a deep environment of high pressures and temperatures. The surface environment is the site of rock alteration and sediment deposition. Here, igneous, sedimentary, and metamorphic rocks are uplifted and exposed to air and water. Their minerals are altered chemically and broken free from the parent rock, yielding sediment. The sediment accumulates in basins, where deeply buried sediment layers are compressed and cemented into sedimentary rock.



11.13 The cycle of rock change

This cycle links sediment with sedimentary, metamorphic, intrusive igneous, and extrusive igneous rocks in processes of rock formation and destruction.

Sedimentary rock, entering the deep environment, is heated and comes into a zone of high confining pressure. Here, it is transformed into metamorphic rock. Pockets of magma are formed in the deep environment and move upward, melting and incorporating surrounding rock as they rise. Upon reaching a higher level, magma cools and solidifies, becoming intrusive igneous rock, which reaches the surface environment when it is uncovered by erosion. Or it may emerge at the surface to form extrusive igneous rock. Either way, the cycle is completed.

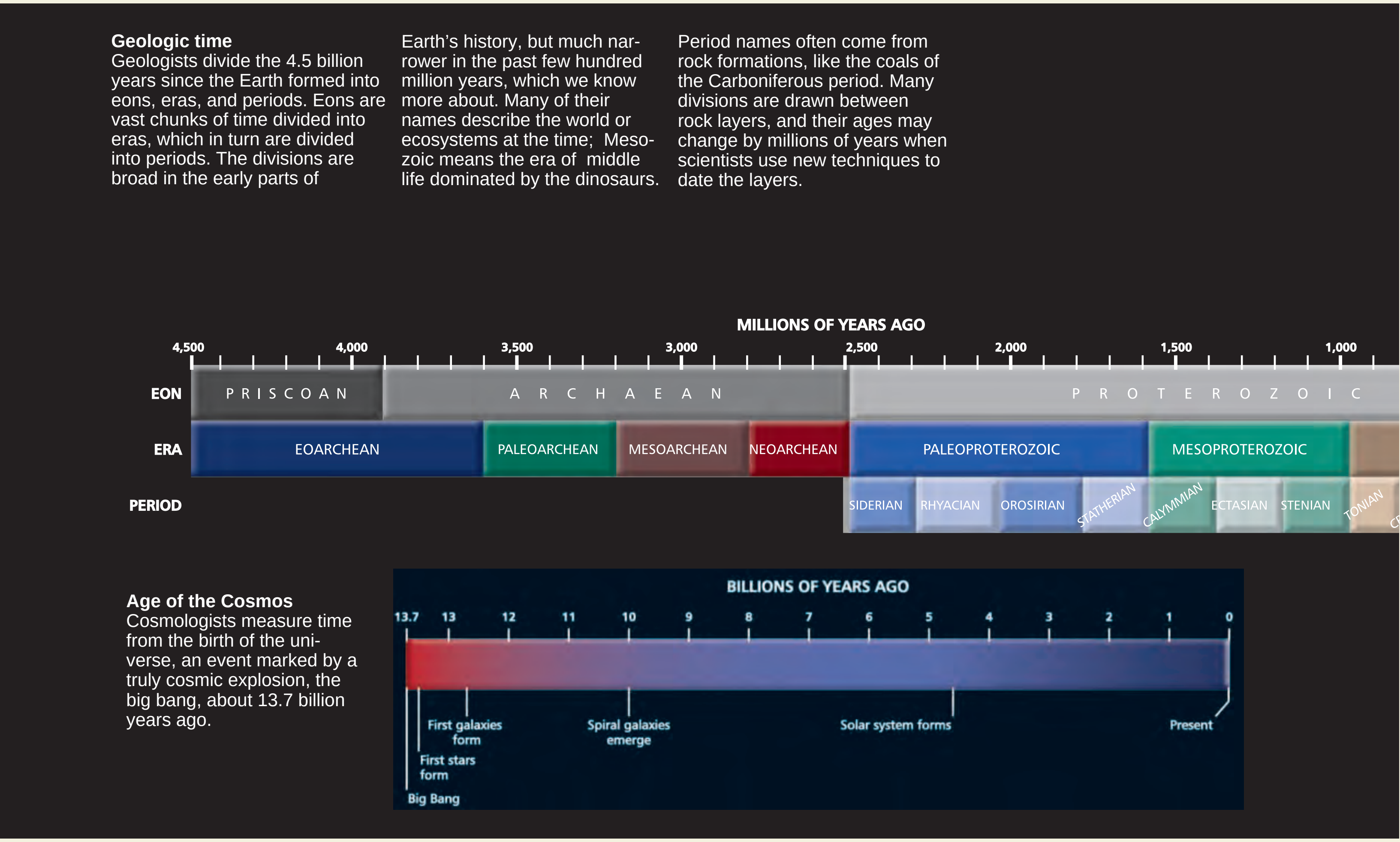
In the surface environment, rocks weather into sediment. In the deep environment, heat and pressure transform sediment into rock that is eventually exposed at the surface.

The cycle of rock change has been active since our planet became solid and internally stable, continuously forming and re-forming rocks of all three major classes. Not even the oldest igneous and metamorphic rocks found so far are the "original" rocks of the Earth's crust. These were recycled eons ago.

THE GEOLOGIC TIME SCALE

So far we've talked about how rocks are formed. Soon we will look at how many of the features on the Earth's surface developed—including mountains, oceans basins, and the continents themselves. All of

11.14 Geologic time



(National Geographic Image Collection)

these formation processes took place over millions of years, and in our discussion we will need to refer to some major units of the *geologic time scale*. Figure 11.14 maps out the major divisions of geologic time. The longest unit is the *eon*. Next is the *era*, followed by the *period* and the *epoch*.

A very important benchmark in the geologic time scale is the *Cambrian period*, when life on Earth began to flourish. In *Precambrian* time, life had early beginnings but is generally absent from the geologic record. Nearly all the landscape features visible today have been formed within the *Cenozoic era*, which is the most recent era.

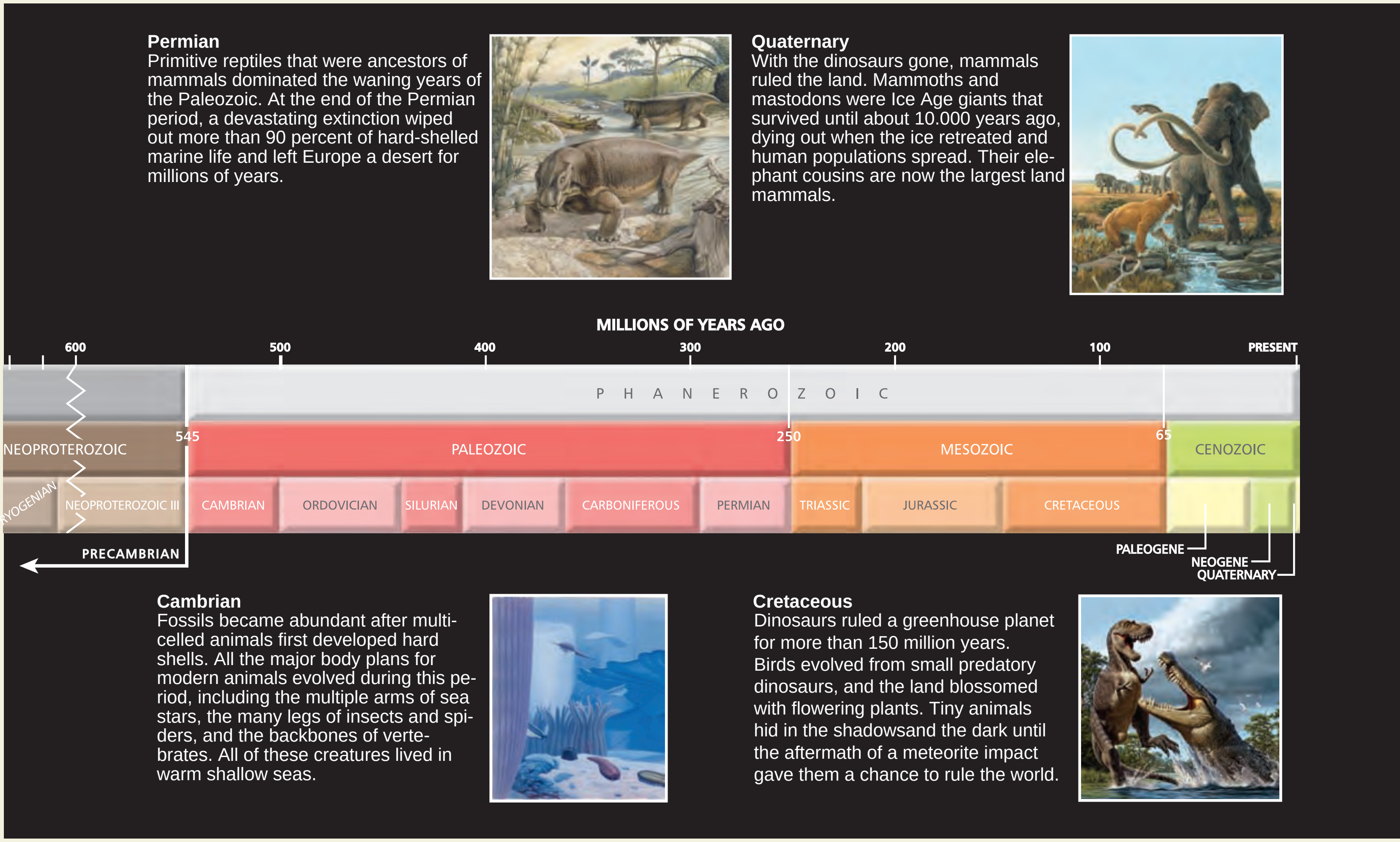
> **Life on Earth became abundant in the Cambrian period. The Cenozoic era is most recent, and nearly all the landscape features visible today have been formed within that era.**

If you think of the history of the Earth since its formation as spanning a single 24-hour day, you can place the age of each geologic time division on a 24-hour time scale. Precambrian time ends at about 21:10. That means that life only proliferated on Earth during the last 2 hours and 50 minutes of this day. The human genus itself arises at about 30 seconds before midnight, and the last 5000 years of human civilization would occupy about half a second—truly a fleeting moment in our planet's vast history.

Major Relief Features of the Earth's Surface

THE LITHOSPHERE AND ASTHENOSPHERE

The major relief features of the Earth—its continents and ocean basins—were created by the movements of plates on the surface of the Earth.



Geologists use the term *lithosphere* to describe an outer Earth shell of rigid, brittle rock, including the crust and also the cooler, upper part of the mantle (Figure 11.15). The lithosphere ranges in thickness from 60 to 150 km (40 to 95 mi). It is thickest under the continents and thinnest under the ocean basins.

Some tens of kilometers deep in the Earth, the brittle lithospheric rock gives way gradually to a plastic, or "soft," layer named the *asthenosphere*. But at still greater depth in the mantle, the strength of the rock material increases again. You can think of the lithosphere on top of the asthenosphere as a hard, brittle shell resting on a soft, plastic underlayer. Because the asthenosphere is soft and plastic, the rigid lithosphere can easily move over it.

The lithosphere is the solid, brittle outermost layer of the Earth. It includes the crust and the cooler, brittle upper part of the mantle. The asthenosphere, which lies below the lithosphere, is plastic.

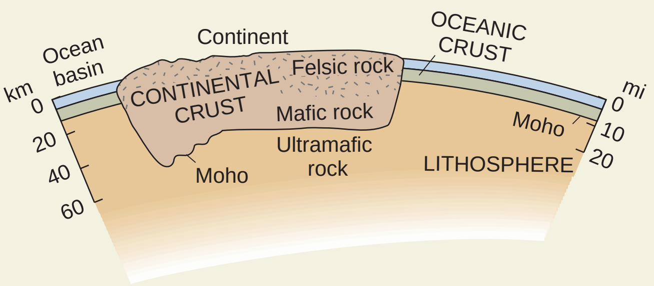
The lithospheric shell is divided into large pieces called **lithospheric plates**. A single plate can be as large as a continent and can move independently of the plates that surround it—like a great slab of ice floating on the polar sea. Lithospheric plates can separate from one another at one location, while elsewhere they may collide in crushing impacts that raise great ridges.

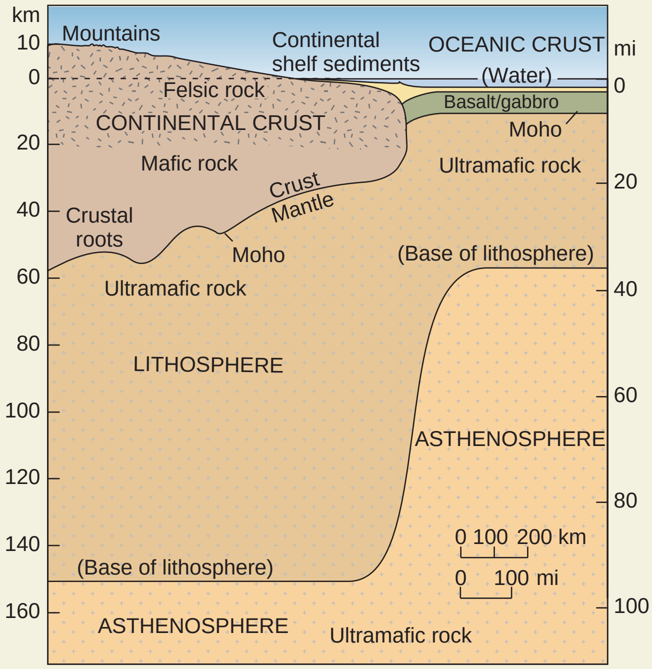
RELIEF FEATURES OF THE CONTINENTS

We divide continents into two types of region: active mountain-making belts (Figure 11.16) and inactive regions of old, stable rock. The mountain ranges in the active belts grow through one of two very different geologic processes. First is *volcanism*, in which massive accumulations of volcanic rock are formed by extrusion

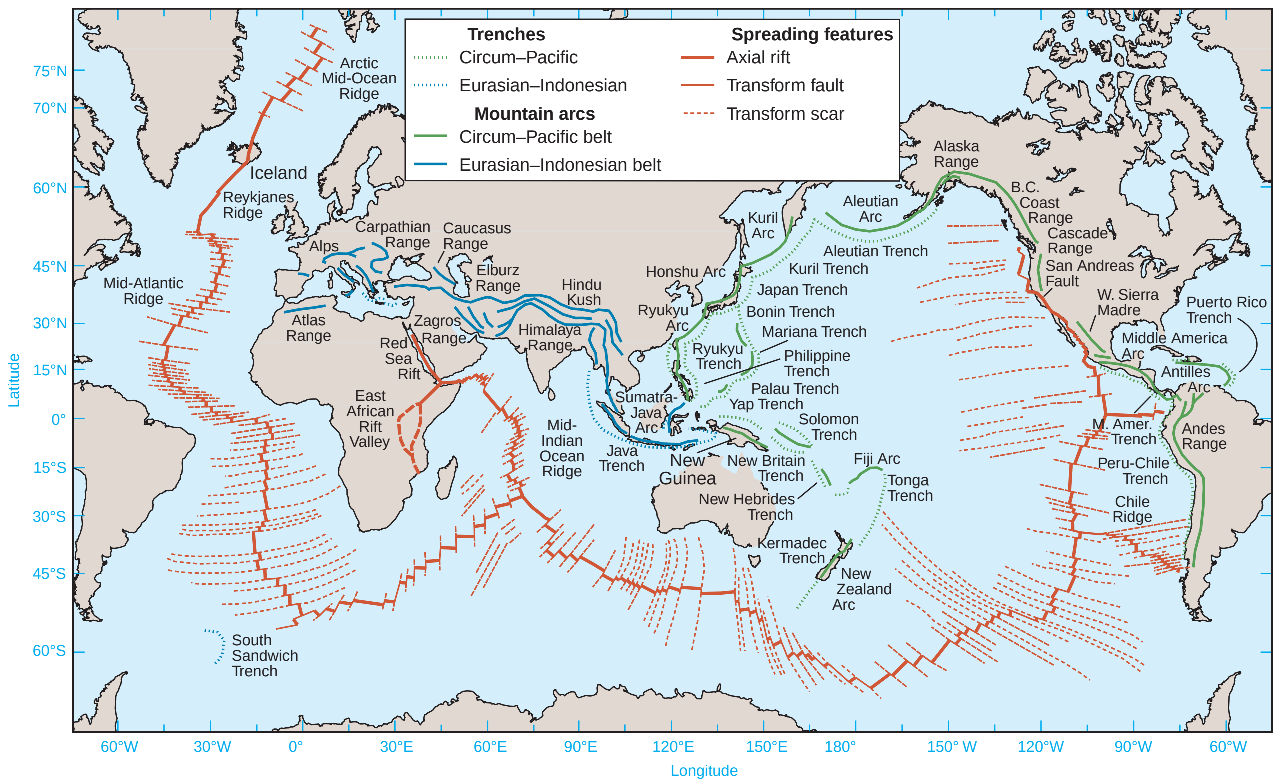
11.15 Outer layers of the Earth

▼ Idealized cross section of the Earth's crust and upper mantle.





▶ Details of the crust and mantle at the edge of a continent.



11.16 Tectonic features of the world

Tectonic features include the Earth's mountain arcs, island arcs, trenches, and the midoceanic ridge.

of magma. Many lofty mountain ranges consist of chains of volcanoes built of extrusive igneous rocks.

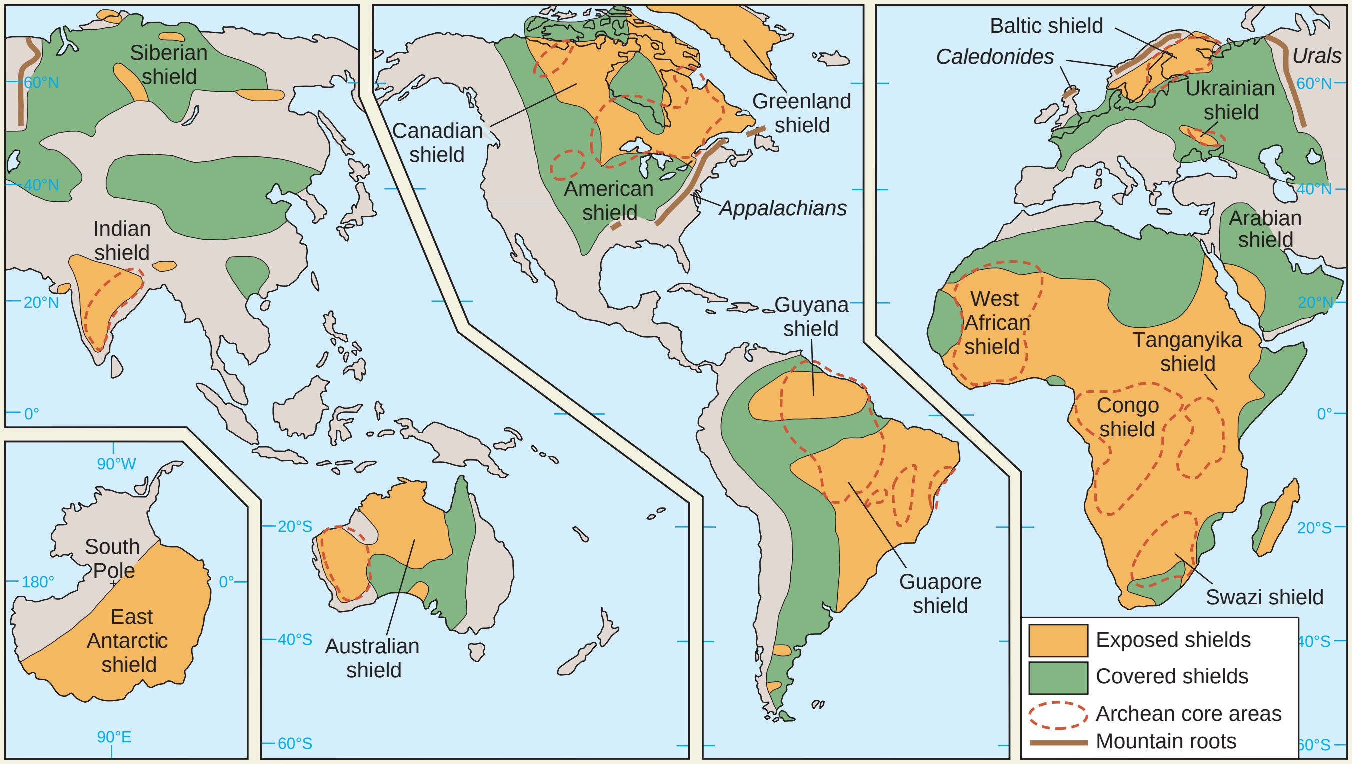
The second mountain-building process is *tectonic activity*—the breaking and bending of the Earth's crust under internal Earth forces. This tectonic activity usually occurs when great lithospheric plates come together in titanic collisions, as we will see in more detail later in this chapter. Crustal masses that are raised by tectonic activity create mountains and plateaus. In some instances, volcanism and tectonic activity combine to produce a mountain range. Tectonic activity can also lower crustal masses to form depressions.

Active mountain-making belts are narrow zones that are usually found along the margins of lithospheric plates. We call these belts *alpine chains* because they are characterized by high, rugged mountains, such as the Alps of central Europe or the Himalayas of Asia. Even today, alpine mountain-building continues in many places.

Belts of recent and active mountain-building account for only a small portion of the continental crust. The rest is much older, comparatively inactive rock. There are two types of stable structures—*continental shields* and *mountain roots*. Continental shields are regions of low-lying igneous and metamorphic rocks (Figure 11.17). Shields may be exposed or

The two basic subdivisions of continental masses are active belts of mountain-making and inactive regions of old, stable rock. Mountains are built by volcanism and tectonic activity.

11.17 Continental shields



▲ **Map of continental shields** Continental centers of early Precambrian age lie within the areas encircled by a broken red line. Heavy brown lines show mountain roots of later orogenies.

▶ **Canadian shield** Shields are areas of ancient rocks that have been eroded to levels of low relief. Continental glaciers stripped the Canadian shield of its sediments during the Ice Age, leaving a landscape of low hills, rock outcrops, and many lakes. Sudbury Basin, near Sudbury, Ontario, Canada.

covered by layers of sedimentary rock. The core areas of some shields are made of rock dating back to the Archean eon, 2.5 to 3.5 billion years ago.

Inactive continental regions of stable rocks include continental shields and ancient mountain roots. Continental shields are low-lying areas of old igneous and metamorphic rock.

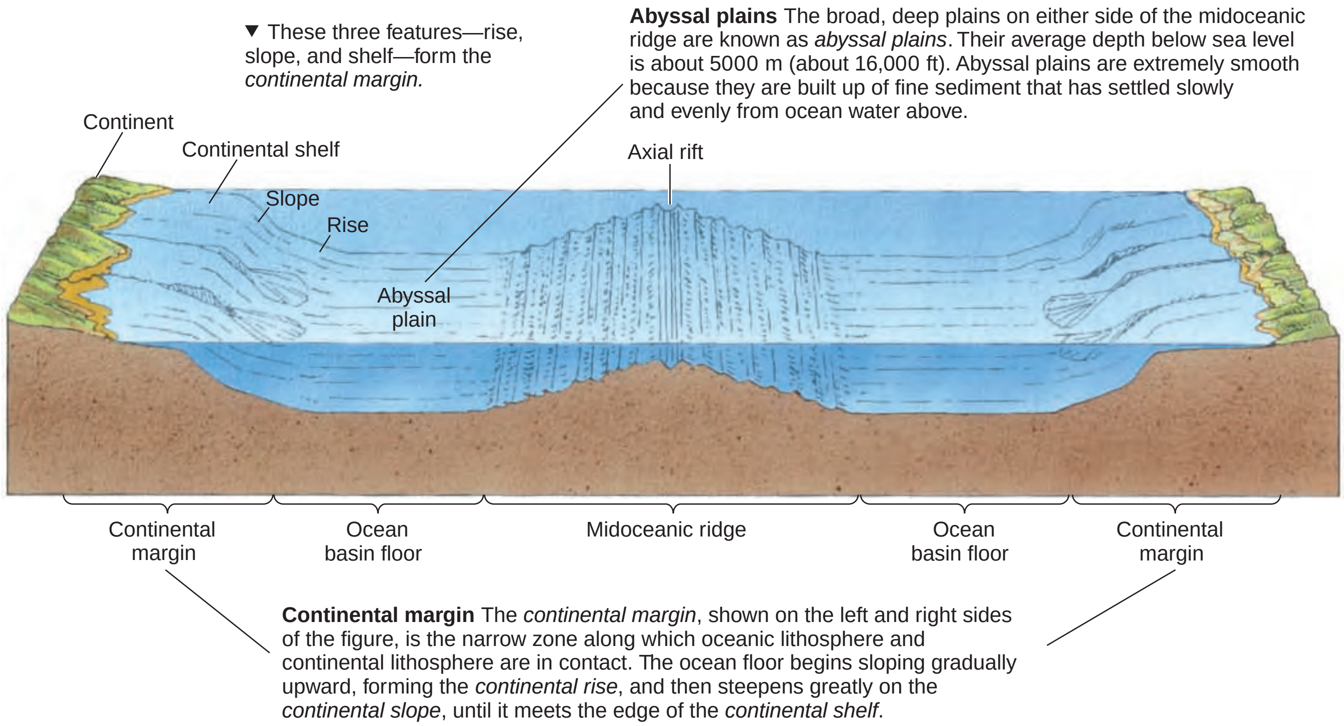
Remains of older mountain belts lie within the shields in many places. These mountain roots are mostly formed of Paleozoic and early Mesozoic sedimentary rocks that have been intensely bent and folded, and in some locations changed into metamorphic rocks. Thousands of meters of overlying rocks have been removed from these old tectonic belts, so that only the lowermost structures remain. Roots appear as chains of long, narrow ridges, rarely rising over a thousand meters above sea level (Figure 11.18).

RELIEF FEATURES OF THE OCEAN BASINS

Oceans make up 71 percent of the Earth's surface. Relief features of oceans are quite different from those of the continents. Much of the oceanic crust is less than 60 million years old, while the great bulk of the

11.18 Mountain roots

The Appalachians of the eastern United States are a good example of ancient mountain roots. Shown here are the rounded ridges and knobs of the Blue Ridge Mountains near Floyd, Virginia, underlain by igneous and metamorphic rocks of Paleozoic age.



11.19 Ocean basins

This schematic block diagram shows the main features of ocean basins. It applies particularly well to the North and South Atlantic oceans.

continental crust is of Proterozoic age—mostly over 1 billion years old. The young age of the oceanic crust is quite remarkable. We will see later that plate tectonic theory explains this age difference.

Figure 11.19 shows the important relief features of ocean basins. A *midoceanic ridge* of submarine hills divides the basin in about half. Precisely in the center of the ridge, at its highest point, is a narrow trench-like feature called the *axial rift*. The location and form of this rift suggest that the crust is being pulled apart along the line of the rift.

Ocean basins include a midoceanic ridge with a central axial rift where crust is being pulled apart.

Figure 11.19 shows a symmetrical ocean-floor model. This model fits the undersea topography of the North and South Atlantic oceans nicely (Figure 11.20, right), as well as the Indian, and Arctic Ocean basins. These oceans have *passive continental margins*, which haven't been subjected to strong tectonic and volcanic activity during the last 50 million years. This is because the continental and oceanic lithospheres that join at a passive continental margin are part of the same lithospheric plate and move together, away from the axial rift.

Passive continental margins accumulate thick deposits of continental sediments. Active continental margins have oceanic trenches where oceanic crust is sliding beneath continental crust.

But unlike the symmetrical ocean-floor model of the North Atlantic, the margins of the Pacific Ocean Basin (Figure 11.20, left) have deep offshore oceanic trenches. We call these trenched ocean-basin edges *active continental margins*. Here, oceanic crust is being bent downward and forced under continental crust, creating trenches and inducing volcanic activity.

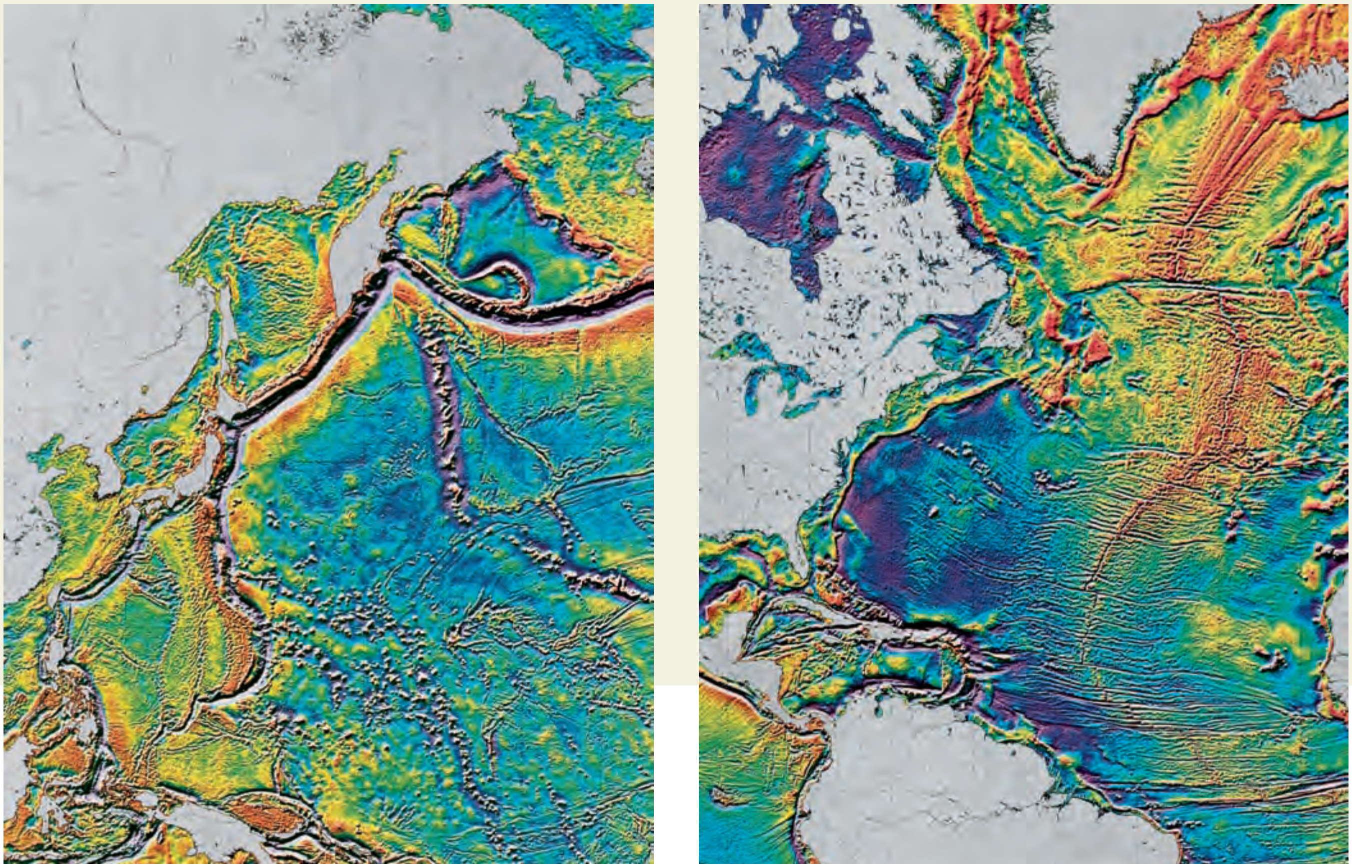
Plate Tectonics

On the globes and maps we've seen since childhood, the outline of each continent is so unique that we would never mistake one continent for another. But why are no two continents even closely alike? The answer lies in the long formation history of the Earth's surface features, which is driven by the movement of lithospheric plates. The science of lithospheric plate motions is called **plate tectonics.**

Prominent mountain masses and mountain chains (other than volcanic mountains) are created either by *extensional tectonic activity* or by *compressional tectonic activity* (Figure 11.21). Extensional tectonic activity occurs when oceanic plates are pulled apart or when a continental plate breaks up into fragments. As the crust thins, it is fractured and pushed upward, producing block mountains.

11.20 Undersea topography

Deeper regions of the ocean are shown in tones of purple, blue, and green, while shallower regions are in tones of yellow and reddish brown. On the left, the ring of subduction trenches of the western Pacific Basin is readily visible. On the right, the mid-Atlantic ridge and other features of seafloor spreading are prominent features. Data were acquired by the U.S. Navy Geosat satellite altimeter.



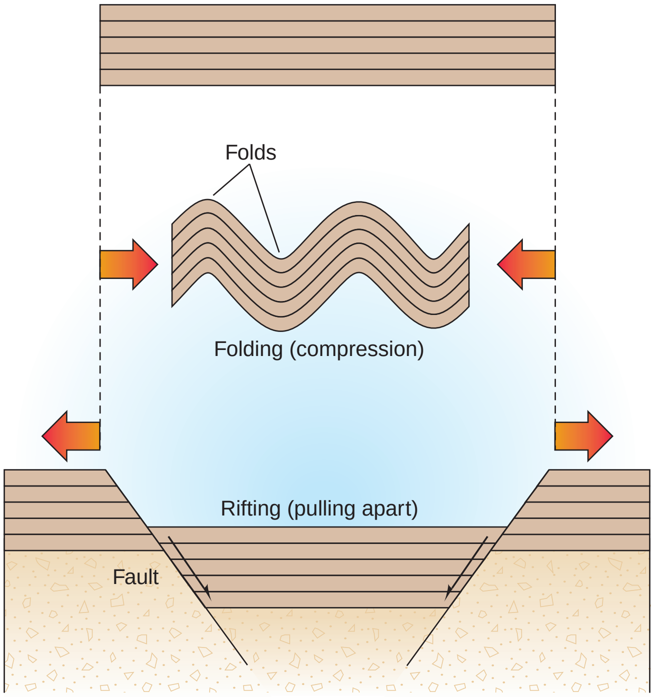
Compressional tectonic activity—squeezing together or crushing—acts at converging plate boundaries. The result is often an alpine mountain chain consisting of intensely deformed strata of marine origin. The strata are tightly compressed into wave-like structures called *folds*. Accompanying the folding is a form of faulting in which slices of rock move over the underlying rock on fault surfaces with gentle inclination angles (Figure 11.22). These are called *overthrust faults*. The individual rock slices, called *thrust sheets*, are carried many tens of kilometers over the underlying rock. In the European Alps, thrust sheets of this kind were named *nappes* (from the French word meaning "cover sheet" or "tablecloth").

Tectonic processes include extension and compression. Extension causes fracturing and faulting of the crust, while compression produces folds and overthrust faults.

PLATES AND BOUNDARIES

Figure 11.23 shows the major features of plate interactions. There are two types of lithosphere—oceanic and continental. *Oceanic lithosphere* is thinner and denser (about 50 km, or 30 mi thick), whereas *continental lithosphere* is thicker and lighter (about 150 km, or 95 mi thick). Think of these plates as "floating" on the plastic asthenosphere, similar to blocks of wood floating in water, where a thicker block rides higher above the water surface than a thinner block. For the same reason, the thicker continental surfaces rise higher above the ocean floors.

In the figure, plates X and Y are pulling apart along their common boundary, which lies along the axis of a midoceanic ridge. This pulling apart creates a gap in the crust that is filled by magma rising from the mantle beneath. The magma appears as basaltic lava in the floor of the rift and quickly congeals. At greater depth under the rift, magma solidifies into *gabbro*, an intrusive rock



11.21 Two basic forms of tectonic activity

Flat-lying rock layers may be compressed to form folds or pulled apart to form faults by rifting.

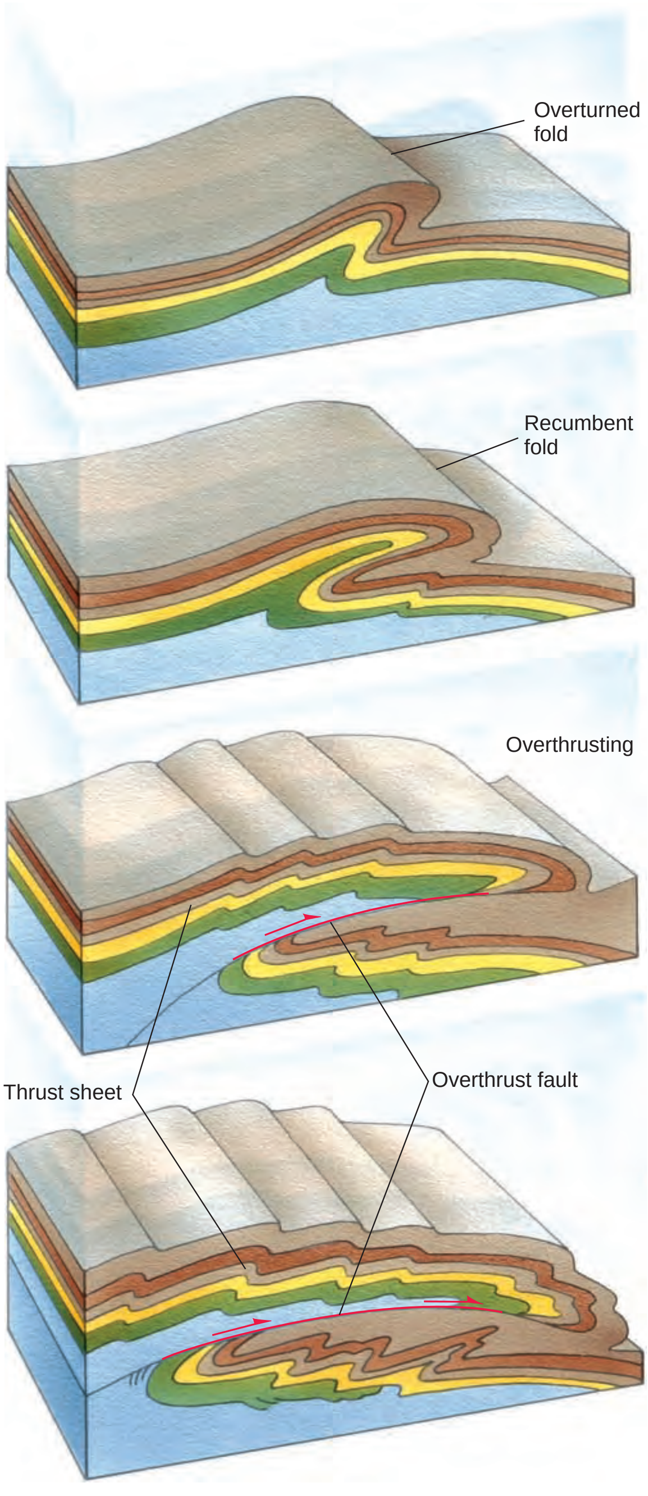
of the same composition as basalt. Together, the basalt and gabbro continually form new oceanic crust. This type of boundary between plates is termed a **spreading boundary**.

At the right, the oceanic lithosphere of plate Y is moving toward the continental lithosphere of plate Z. Where these two plates collide, they form a **converging boundary**. Because the oceanic plate is comparatively thin and dense, in contrast to the thick, buoyant continental plate, the oceanic lithosphere bends down and plunges into the asthenosphere. The process in which one plate is carried beneath another is called **subduction**.

The leading edge of the descending plate is cooler and therefore denser than the surrounding hot, soft asthenosphere. As a result, the slab sinks under its own weight, once subduction has begun. However, as the slab descends, it is heated and softened. The under portion, which is mantle rock in composition, simply reverts to mantle rock.

The descending plate is covered by a thin upper layer of less dense mineral matter derived from oceanic and continental sediments. This material can melt and become magma. The magma tends to rise because it is less dense than the surrounding material. The figure shows some magma pockets on the right, formed from the upper edge of the slab. They are pictured as rising like hot-air balloons through the overlying continental lithosphere. When

At a spreading boundary, crust is being pulled apart. At a converging boundary, one plate is subducted beneath another. At a transform boundary, two plates glide past each other.



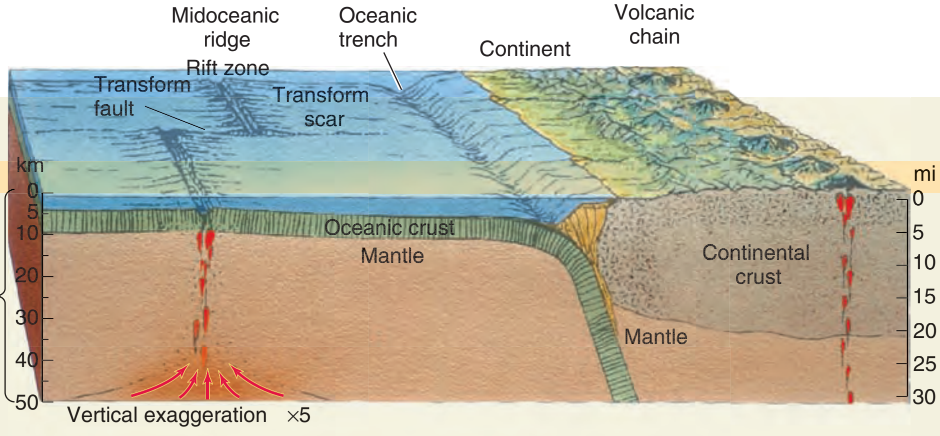
11.22 Formation of overthrust faults

These schematic diagrams show the development of a recumbent fold, broken by a low-angle overthrust fault to produce a thrust sheet, or nappe, in alpine structure.

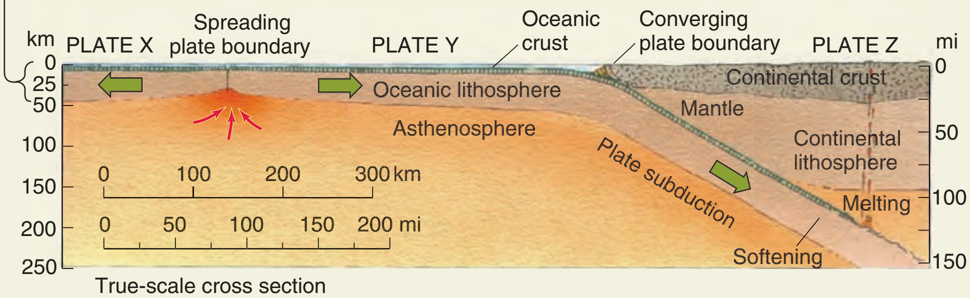
11.23 Plate motions and boundaries

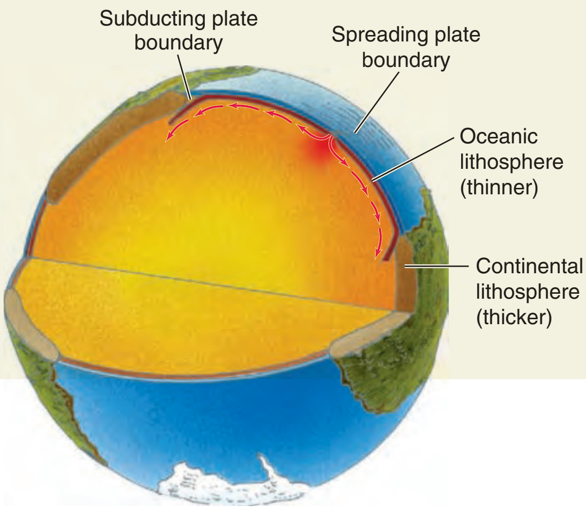
A plate of oceanic lithosphere is moving to the right, away from a spreading boundary at an axial rift at the left. At the converging boundary on the right, the plate is subducting under a plate of continental lithosphere.

▶ **Close-up** This diagram shows the important features of the two boundaries.



▶ **True scale** Here the plates are drawn to scale.





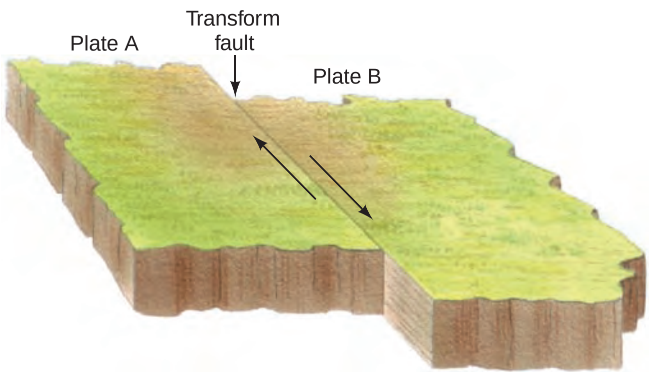
◀ **Global view** Spreading and converging boundaries are sketched on a globe cross section.

they reach the Earth's surface, they form a chain of volcanoes lying about parallel with the deep oceanic trench that marks the line of descent of the oceanic plate.

In addition to spreading and converging boundaries, there is also the *transform boundary*. Here, one lithospheric plate slides past the other without separating or converging. The two plates are in contact along a vertical fracture, called a *transform fault* (Figure 11.24).

GEODISCOVERIES **Tectonic Plate Boundary Relationships**

Play this movie to see the landscapes of spreading, converging, and transform boundaries between lithospheric plates. Iceland, the Cascades, Himalayas, Alps, and the San Andreas fault are featured.



11.24 Transform fault

A transform fault occurs when two adjacent lithospheric plates slide past each other.

GEODISCOVERIES **Plate Tectonics**

See the structure of active and passive plate margins in this animation. Watch as seafloor spreads, forming oceanic crust that collides with a continent and is subducted.

THE GLOBAL SYSTEM OF LITHOSPHERIC PLATES

The Earth's surface is composed of six major lithospheric plates—Pacific, American, Eurasian, African, Austral-Indian, and Antarctic. There are also several lesser plates and subplates. Figure 11.25 shows the major plates and describes their motions.

GEODISCOVERIES **Remote Sensing and Tectonic Landforms Interactivity**

Select "tectonics" to review the names and locations of tectonic plates as well as examine a famous transform fault—the San Andreas.

CONTINENTAL RUPTURE AND NEW OCEAN BASINS

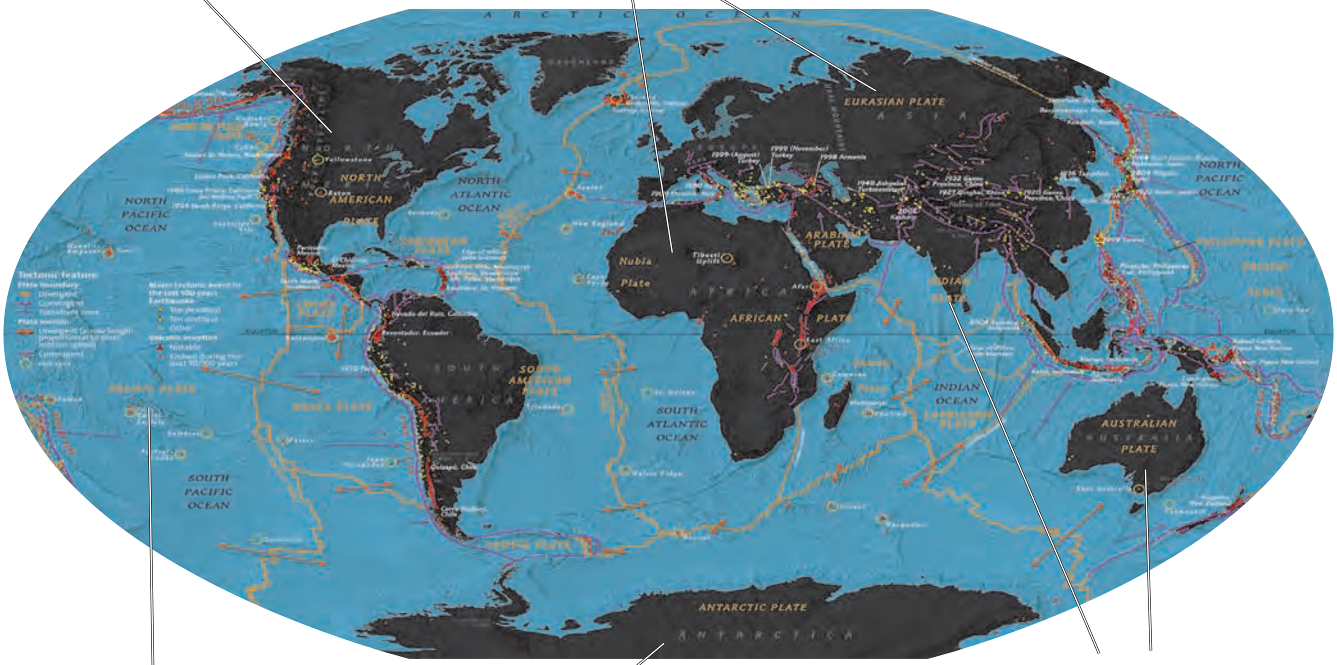
We have already noted that the Atlantic margins have no important tectonic activity, even though they mark the contact between oceanic lithosphere and continental lithosphere.

Passive margins such as these are created by a process called *continental rupture* (Figure 11.26). This occurs when tectonic forces uplift a plate of continental lithosphere and pull it apart. At first, a *rift valley* forms, and as the bottom of the rift valley sinks below sea level, sea water enters. Eventually, a wide ocean forms with an axial rift down its center.

Continental rupture begins with the formation of a rift valley and tilted block mountains. Ocean soon invades the rift. As the continental crust recedes, oceanic crust fills the gap.

The American plate includes most of the continental lithosphere of North and South America. The western edge of the American plate is mostly a subduction boundary, with oceanic lithosphere diving beneath the continental lithosphere. The eastern edge is a spreading boundary. Some scientists regard the North and South portions of the American plate as separate plates, providing a total of seven major plates.

The Eurasian plate is mostly continental lithosphere, but it is fringed on the west and north by a belt of oceanic lithosphere. The African plate (Nubia plate) has a central core of continental lithosphere nearly surrounded by oceanic lithosphere.

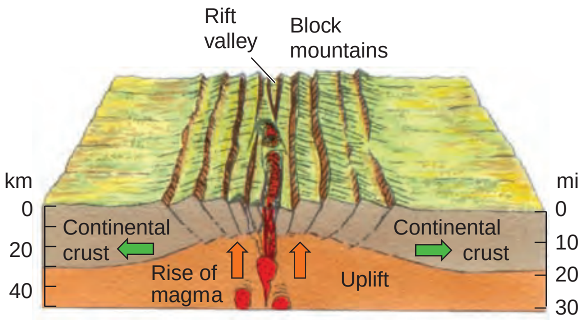


The great Pacific plate occupies much of the Pacific Ocean basin and consists almost entirely of oceanic lithosphere. It has a subduction boundary along most of the western and northern edge, and a spreading boundary at the eastern and southern edge. A sliver of continental lithosphere makes up the coastal portion of California. It is bounded by an active transform fault, the San Andreas fault.

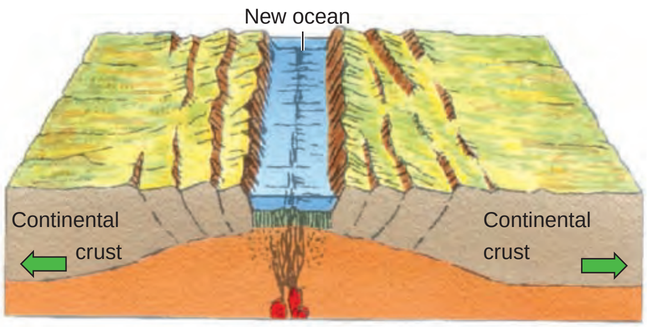
The Antarctic plate is almost completely enclosed by a spreading plate boundary. This means that the other plates are moving away from the pole. The continent of Antarctica forms a central core of continental lithosphere completely surrounded by oceanic lithosphere.

The Austral-Indian plate is mostly oceanic lithosphere but contains two cores of continental lithosphere–Australia and peninsular India. Recent evidence shows that these two continental masses are moving independently and may actually be considered to be parts of separate plates, as they are shown here.

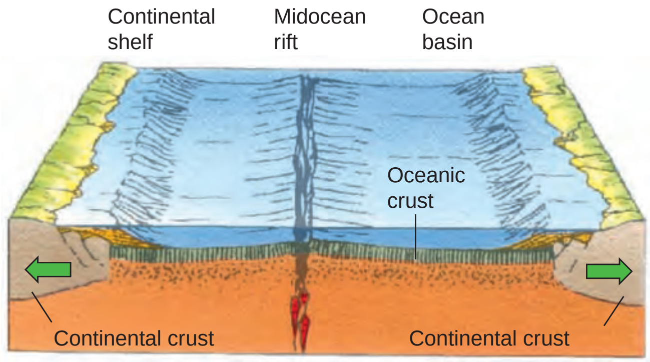
11.25 Global map of lithospheric plates



▲ The crust is uplifted and stretched apart, causing it to break into blocks that become tilted on faults. Eventually a long narrow *rift valley* appears. Magma rises up from the mantle to continually fill the widening crack at the center.



▲ The magma solidifies to form new crust in the rift valley floor. Crustal blocks on either side slip down along a succession of steep faults, creating mountains. A narrow ocean is formed, floored by new oceanic crust.



▲ The ocean basin can continue to widen until a large ocean has formed and the continents are widely separated. The ocean basin widens, while the passive continental margins subside and receive sediments from the continents. The vertical scale is greatly exaggerated to emphasize surface features.

11.26 Continental rupture and spreading

The Red Sea is a good example of a continental rupture in progress. Figure 11.27 shows an astronaut photo of the Red Sea where it joins the Gulf of Aden. As shown in the inset map, this is a triple junction of three spreading boundaries created by the motion of the Arabian plate pulling away from the African plate. It is easy to visualize how the two plates have split apart, allowing the ocean to enter.

ISLAND ARCS AND COLLISION OF OCEANIC LITHOSPHERE

When a continent ruptures to form an ocean basin with axial rift, the two new plates move apart and create a new ocean. But eventually the plate motions may reverse, and the ocean basin may start to close. For this to happen, a plate must fracture and produce a subduction boundary. If the fracture occurs at a passive continental margin, oceanic crust will be subducted below continental crust, as shown in Figure 11.23. But what happens if the fracture occurs in the middle of a plate of oceanic lithosphere? This situation is shown in Figure 11.28.

As the subducted oceanic lithosphere plunges downward, oceanic crust is carried into the mantle. Since it originally came from the mantle and is of the same composition, it simply melts and disappears into the mantle rock.

However, the descent of the plate also carries a thin layer of ocean-floor sediment into the mantle. The heat and pressure of the mantle melt this sediment, and because it is less dense than the mantle rock, it begins to rise. The result is the formation of an *island arc*—a chain of volcanoes paralleling the subduction trench. We saw this process earlier in the formation of a volcanic arc on land, near the margin of a continent, in the collision of lithospheric crust with oceanic crust in Figure 11.23.

At a subduction boundary where plates of oceanic lithosphere collide, subducted seafloor sediment melts, rises, and forms a volcanic island arc.

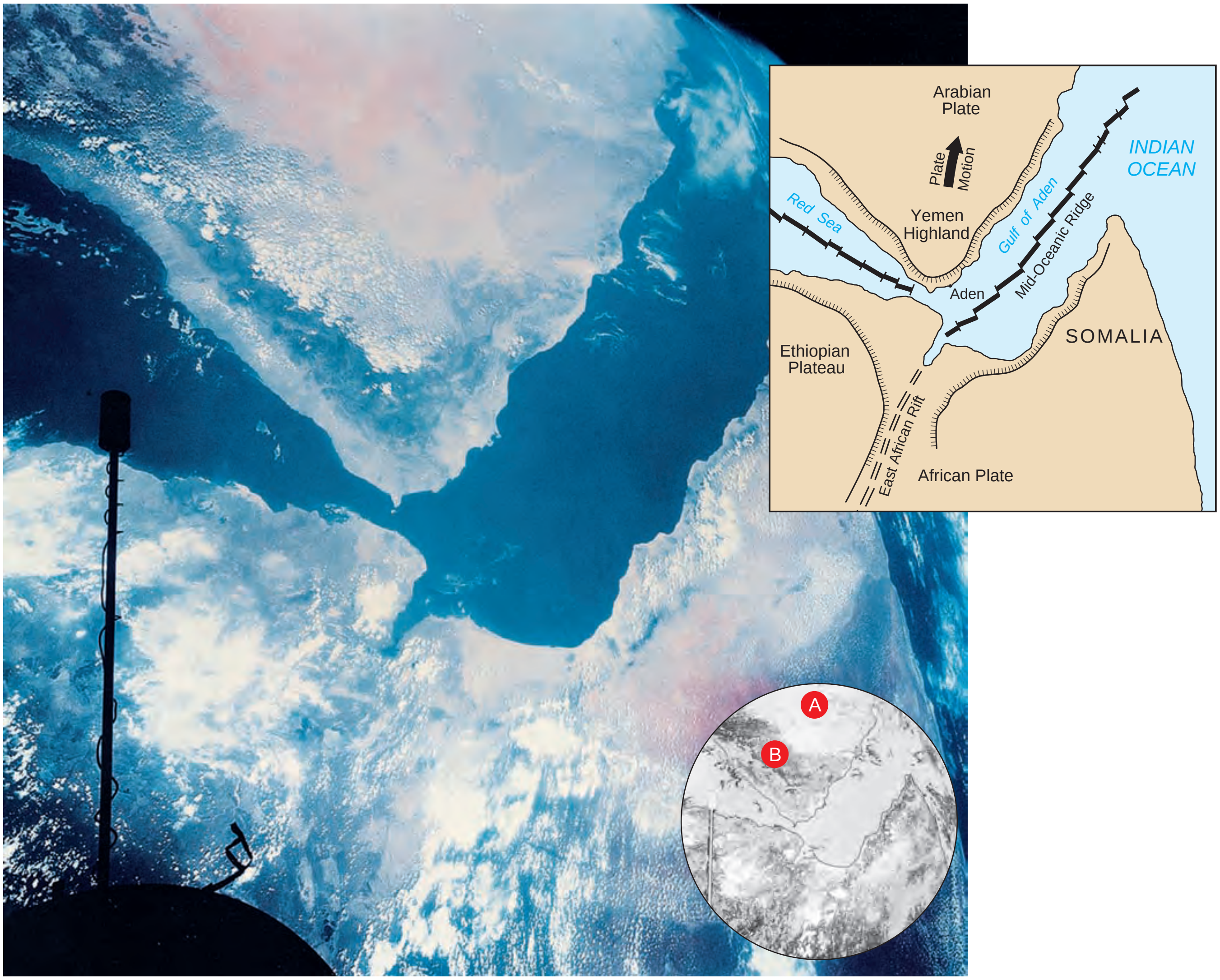
In the early stages, the island arc is an isolated chain of island volcanoes. The Aleutian Islands are a good example. They stretch from Alaska to Russia and are seen along the northernmost oceanic trench in the left part of Figure 11.20.

As the process continues, seafloor sediment piles up in the trench, forming an accretionary wedge of sediments. Meanwhile, the continuing rise of magma fortifies the island arc from below, increasing the height and width of the volcanic mass.

ARC-CONTINENT COLLISION

If ocean-basin closing continues, the island arc eventually collides with a passive continental margin. Since the island arc is thick and buoyant, it is not subducted but pushed up against the continent. The layers of sediment that have accumulated on the continental shelf and continental slope are crushed and deformed. The sediments are thrust far inland over the older

Eventually, the island arc can collide with a passive continental margin producing an arc-continent collision.



11.27 The Red Sea and Gulf of Aden from orbit

This spectacular photo, taken by astronauts on the Gemini XI mission, shows the southern end of the Red Sea and the southern tip of the Arabian Peninsula.

EYE ON THE LANDSCAPE **What else would the geographer see?** The pinkish tones of the interior Arabian desert (A) are caused by iron oxides in the desert rocks and soils; note the absence of any dark vegetation. The cumulus clouds at (B) are the result of the lifting of moist air over the coastal mountain ranges.

continental rocks, creating nappes and foreland folds. We call this process "telescoping" because it's similar to the way that a folding telescope collapses from a long tube into a short cylinder. The mass of collided rocks is called an *orogen*, and the process of its formation is described as an *orogeny*. If collision continues, another fracture develops and a new subduction boundary is formed.

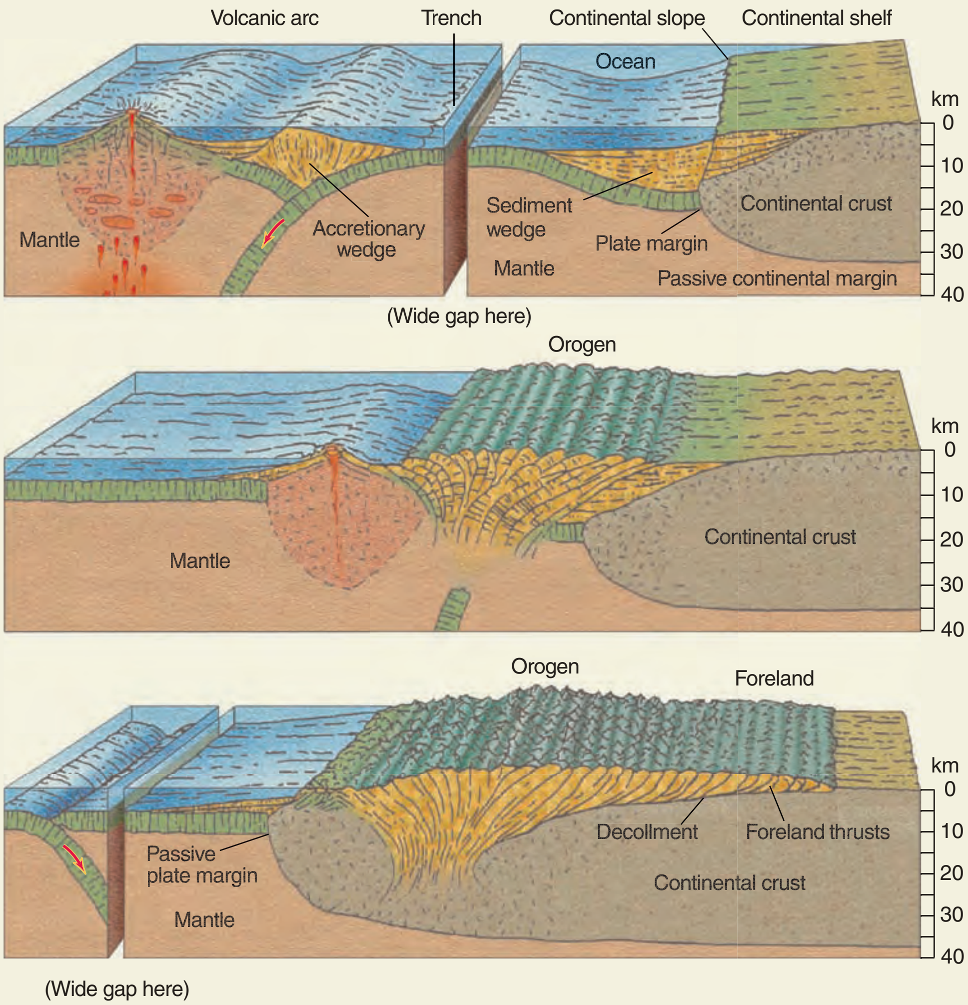
CONTINENT-CONTINENT COLLISION

Where the subduction boundary closing the ocean basin lies at the edge of a continent, continued closing results in a *continent-continent collision* (Figure 11.29). The collision permanently unites the two plates, so that there is no further tectonic activity along that collision zone. The collision zone is called a **continental suture**.

Continent-continent collisions occurred in the Cenozoic era along a great tectonic line that marks the southern boundary of the Eurasian plate. The line begins with the Atlas Mountains of North Africa and runs, with a few gaps, to the great Himalayan Range, where it is still active. Each segment of this collision zone represents the collision of a different north-moving plate against the single and relatively immobile Eurasian plate.

When two continental lithospheric plates collide in an orogeny, continental rocks are crumpled and overthrust. The plates become joined in a continental suture.

11.28 Formation of an island arc and arc-continent collision



◀ **Formation of an Island arc** As an ocean basin closes, oceanic lithosphere is subducted below oceanic lithosphere. Seafloor sediment piles up in an accretionary wedge. Subducted sediment melts and rises, forming the island arc.

◀ **Arc-continent collision** Eventually the island arc collides with the passive continental margin. The sediments of the continental shelf and continental slope are compressed, forming folds and thrust sheets.

◀ **Formation of a passive plate margin** The collision complete, a large orogen is formed, with ancient volcanoes on one side, metamorphic rocks in the middle, and foreland thrusts and folds on the other. A new fracture forms in oceanic lithosphere, and the orogen remains at the edge of a new passive plate margin.

Continent-continent collisions have occurred many times since the late Precambrian time, including many with island arcs sandwiched between the colliding land masses. Geologists have identified several ancient sutures in the continental shields. One example is the Ural Mountains, which divide Europe from Asia and were formed near the end of the Paleozoic era. Others are the Appalachian Mountains of eastern North America and the Caledonian Mountains of Scotland, Norway, Svalbord, and eastern Greenland, which date from mid-Paleozoic time.

THE WILSON CYCLE AND SUPERCONTINENTS

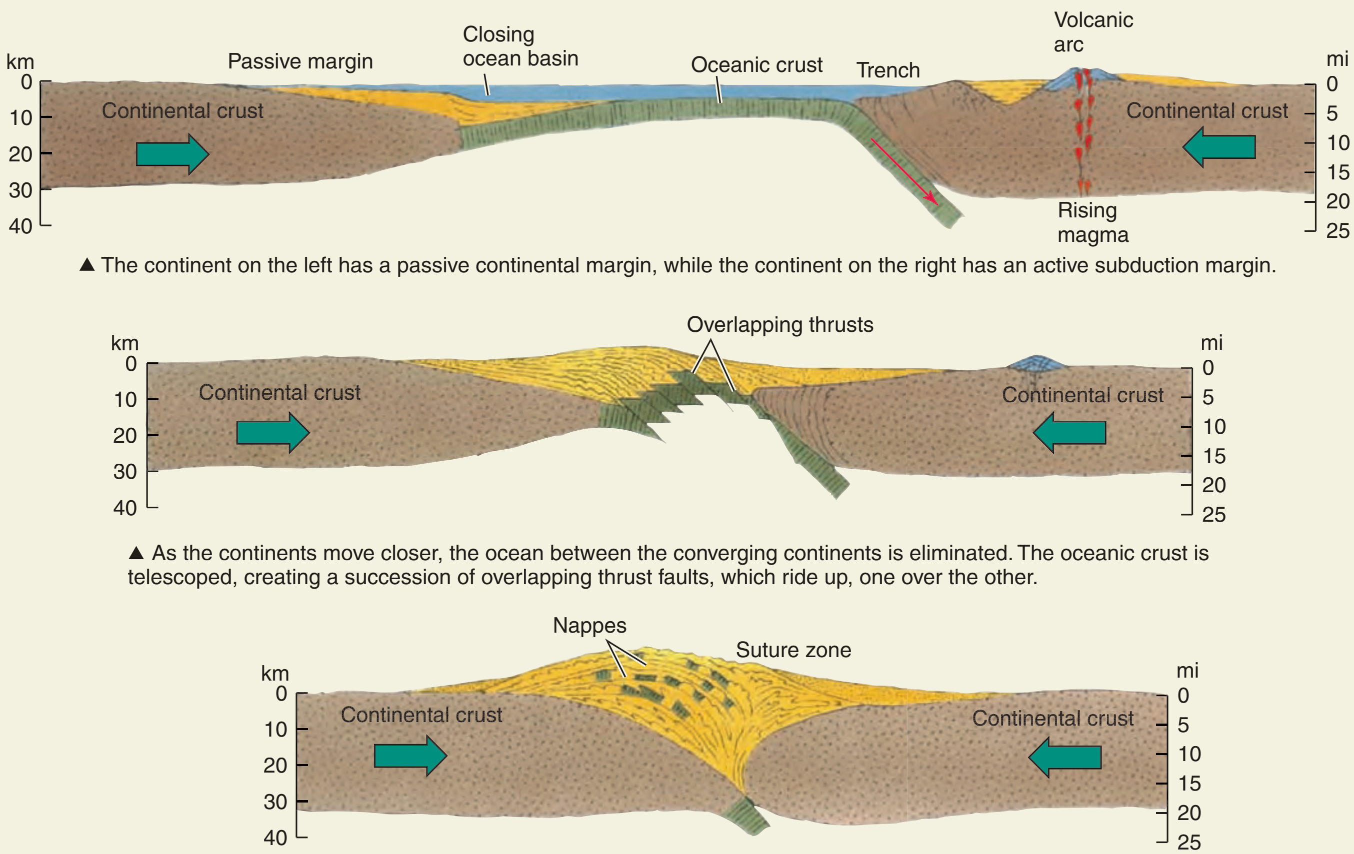
Geologic evidence has shown that ocean basins have opened and closed many times in the geologic past. The cycle of opening and closing is called the *Wilson cycle*, named for the Canadian geophysicist J. Tuzo Wilson (Figure 11.30).

The Wilson cycle begins with continental rupture and the formation of a wide ocean basin (stages 1–3). As the relative plate motions reverse, and the ocean basin begins to close, oceanic lithosphere fractures and new subduction boundaries are formed (stage 4a). Island arcs soon appear and continue to grow with time (stage 4b). Eventually, fractures occur at the continental margins, and the arcs collide with continents, producing arc-continent orogens (stage 5). In the final stage, the orogens collide, producing a continental suture (stage 6).

With the continents in motion, we might ask where they all go and when. There is strong evidence that all the continents were once joined in a single land mass that subsequently broke apart. Imagine that the world's ocean basins all close at once, following the Wilson cycle. The result would be a *supercontinent* containing most or all of the Earth's

Ocean basins open and close in the Wilson cycle, which describes how continents are split and reunited.

11.29 Continent-continent collision



▲ The continent on the left has a passive continental margin, while the continent on the right has an active subduction margin.

▲ As the continents move closer, the ocean between the converging continents is eliminated. The oceanic crust is telescoped, creating a succession of overlapping thrust faults, which ride up, one over the other.

▲ As the slices become more and more tightly squeezed, they are forced upward. The upper part of each thrust sheet turns horizontal, forming a nappe, which then glides forward under gravity. A mass of metamorphic rock forms between the joined continental plates, welding them together. This new rock mass is the continental suture.

continental crust. Many lines of evidence show that such a supercontinent, now called *Pangaea*, came into existence about 200 million years ago. It was actually preceded by an earlier supercontinent, dubbed Rodinia, that was fully formed about 700 million years ago.

Figure 11.31 shows this *supercontinent cycle*, in which a supercontinent is formed, then split apart by lithospheric fractures and multiple plate motions. The continents then converge again with new orogens along their margins, forming a new supercontinent. There may have been as many as 6 to 10 such cycles in the Earth's ancient history. The hypothesis of a time cycle of supercontinents now holds its place as the basic theme of the geologic evolution of our planet.

The Earth's history includes supercontinent cycles in which the continents unite in a single land mass and then break apart. Pangaea is the most recent supercontinent.

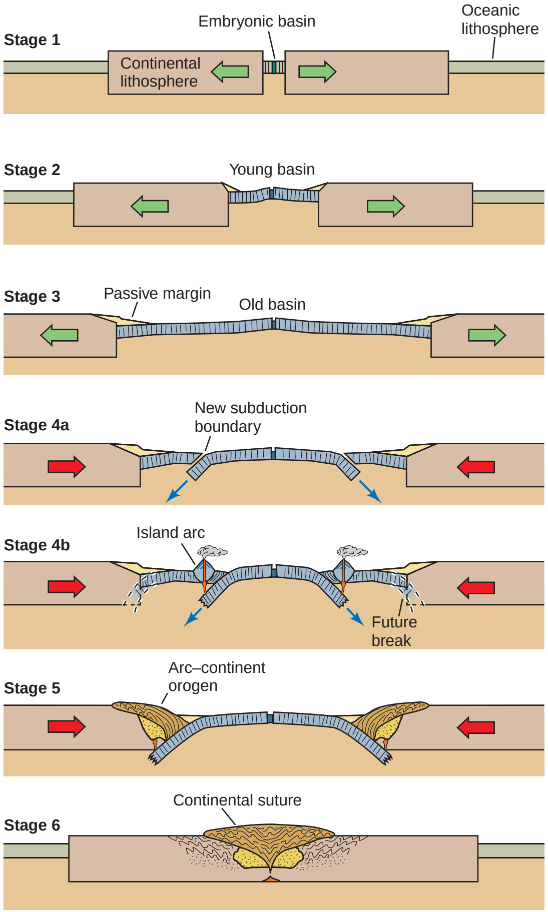
THE POWER SOURCE FOR PLATE MOVEMENTS

Lithospheric plates are huge, so it must take enormous power to drive their motion. Where does this power come from? The power source lies in the heat released by radioactivity.

You may know from basic chemistry that some elements have *unstable isotopes*—forms that spontaneously emit energy or matter in the process of *radioactive decay*. The energy is absorbed by the surrounding matter and is called *radiogenic heat*. Most of the Earth's radiogenic heat is released in the rock beneath the continents, within the uppermost 100 km or so (about 60 mi). This heat keeps Earth layers below the crust close to the melting point, providing the power source for the formation of magma.

Radiogenic heat is the power source for plate tectonic motions.

We don't know exactly how radiogenic heating



Stage 1 Embryonic ocean basin The Red Sea separating the Arabian Peninsula from Africa is an active example.

Stage 2 Young ocean basin The Labrador Basin, a branch of the North Atlantic lying between Labrador and Greenland, is an example of this stage.

Stage 3 Old ocean basin Includes all of the vast expanse of the North and South Atlantic oceans and the Antarctic Ocean. Passive margin sedimentary wedges have become wide and thick.

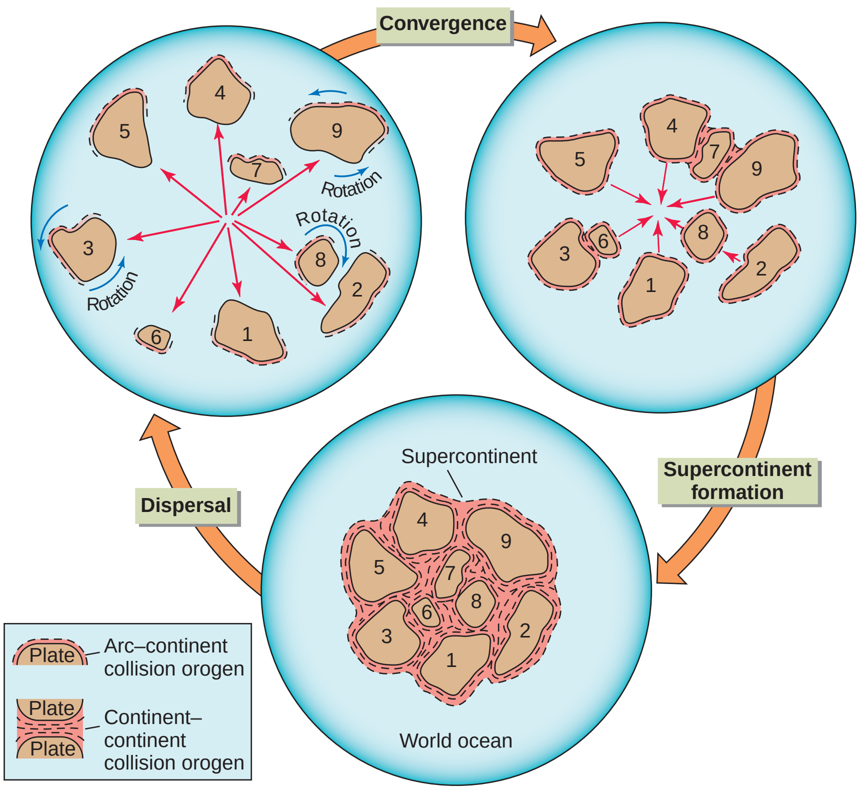
Stage 4a The ocean basin begins to close as continental plates collide with it. New subduction boundaries begin to form.

Stage 4b Island arcs have risen and grown into great volcanic island chains. These are found surrounding the Pacific plate, with the Aleutian arc as an example.

Stage 5 Closing continues Formation of new subduction margins close to the continents is followed by arc-continent collisions. The Japanese Islands represent this stage.

Stage 6 The ocean basin has finally closed with a collision orogen, forming a continental suture. The Himalayan orogen is a recent example, with activity continuing today.

11.30 The Wilson cycle



11.31 Supercontinent cycle

Over hundreds of millions of years, supercontinents are formed and re-formed in a cycle of formation, dispersal, and convergence. Wiggly dashes show collision orogens that accumulate around and between the continents.

produces plate motions. One theory is that plate motions are produced by *convection currents* in hot mantle rock. Since hotter rock is less dense than cooler rock, unequal heating could produce streams of upwelling mantle rock that rise steadily beneath spreading plate boundaries.

Some geologists hypothesize that the rising mantle lifts the lithospheric plate up and the plate then fractures and moves horizontally away from the spreading axis under the influence of gravity. This is called *gravity gliding.* Another theory is that once the plate begins to descend, the descending part pulls the rest of the plate along because it is cooler, and therefore more dense, than the mantle rock. Explaining the mechanisms that drive plate motions is a future research goal of many geophysicists.

CONTINENTS OF THE PAST

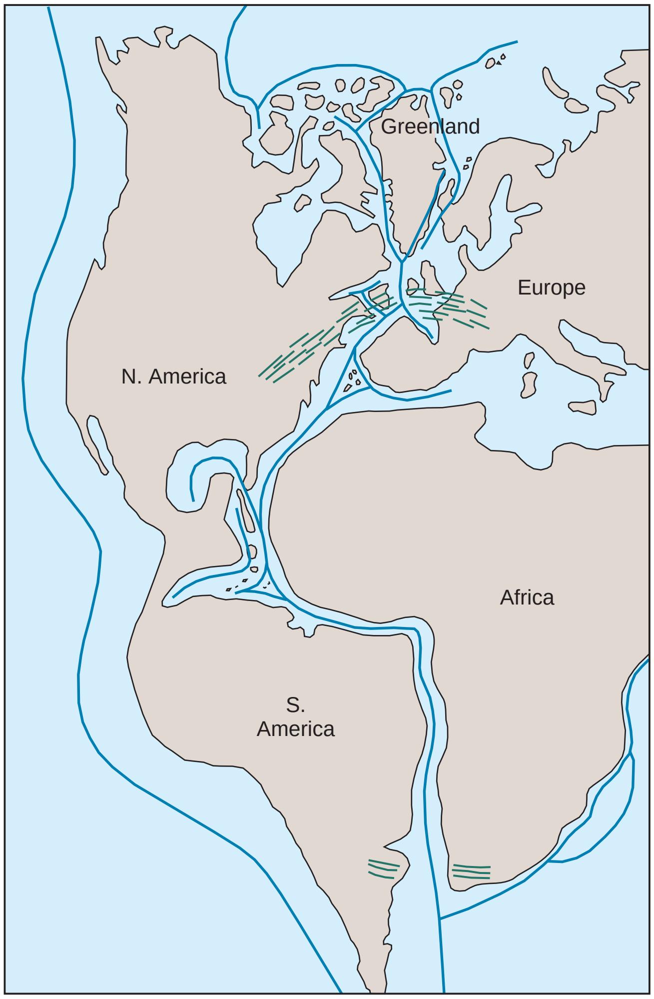
Modern plate tectonic theory is only a half a century old. But as far back as the nineteenth century, German meteorologist and geophysicist, Alfred Wegener, suggested that our continents are fragments of a single supercontinent. As good navigational charts became available, geographers could see the close correspondence between the outlines of the eastern coast of South America and the western coastline of Africa. Wegener proposed the first full-scale scientific theory describing the breakup of a single supercontinent, which he named Pangaea, into multiple continents that moved apart in a process called *continental drift* (Figure 11.32). He suggested that Pangaea existed intact as early as about 300 million years ago, in the Carboniferous Period.

A storm of controversy followed Wegener's proposal, but he had some loyal supporters. He presented several lines of hard scientific evidence for Pangaea, including the distribution patterns of fossils and present-day plant and animal species. But his explanation of the physical process that separated the continents was weak, and geologists soon showed that it was wrong.

In 1930, Wegener died of cold and exhaustion while on an expedition to the Greenland ice sheet. But in the 1960s, his theory was revived. Seismologists showed that thick lithospheric plates are in motion. Within a few years, Wegener's scenario was validated, but only by applying a mechanism for the process—seafloor spreading produced by mantle convection currents—that was never dreamed of in his time.

The continents are moving today. Data from orbiting satellites shows that rates of separation or of convergence between two plates are on the order of 5 to 10 cm (about 2 to 4 in.) per year, or 50 to 100 km (about 30 to 60 mi) per million years. At that rate, global geography must have been very different in past geologic eras than it is today.

Alfred Wegener proposed that today's continents had broken apart from a single supercontinent named Pangaea. Although many doubted his ideas, he was eventually proven right.



11.32 Wegener's Pangaea

Alfred Wegener's 1915 map fits together the continents that today border the Atlantic Ocean Basin. The sets of dashed lines show the fit of Paleozoic tectonic structures between Europe and North America and between southernmost Africa and South America.

Figure 11.33 shows a reconstruction of continental motions of the last 600 million years or so. Before Pangaea, the supercontinent Rodinia, which was fully formed about 700 million years ago, broke apart and its fragments were carried away in different directions. While still in motion, the continents briefly assembled into the supercontinent Pannotia. Eventually, Pangaea was formed. It then broke apart, creating Laurasia in the northern hemisphere, which contained the regions that are now North America and western Eurasia, and Gondwanaland south of the Equator, which contained the regions that are now South America, Africa, Antarctica, Australia, New Zealand, Madagascar, and peninsular India. Some interesting evidence suggests that there may have been yet another supercontinent before Rodinia.

11.33 A short history of the Earth's continents

▲ **600 million years ago** A supercontinent, Rodinia, split apart and oceans filled the basins. Continental fragments collided, thrusting up mountain ranges. Glaciers spread, twice covering the Equator. A new, but short-lived, polar supercontinent, Pannotia, formed.

▲ **200 million years ago** Dinosaurs roamed Pangaea, which stretched nearly from pole to pole and almost encircled Tethys, the oceanic ancestor of the Mediterranean Sea. The immense Panthalassic Ocean surrounded the supercontinent.

▲ **500 million years ago** A breakaway chunk of Pannotia moved north, splitting into three masses—Laurentia (North America), Baltica (northern Europe), and Siberia. In shallow waters, the first multicellular animals with exoskeletons appeared, and the Cambrian explosion of life began.

▲ **100 million years ago** Pangaea broke apart. The Atlantic poured in between Africa and the Americas. India split away from Africa, and Antarctica and Australia were stranded near the South Pole.

▲ **300 million years ago** Laurentia collided with Baltica and later with Avalonia (Britain and New England). The Appalachian Mountains arose along the edge of the supercontinent Pangaea.

▲ **50 million years ago** Moving continental fragments collided—Africa into Eurasia, pushing up the Alps, and India into Asia, raising the Himalayan Plateau. A meteorite wiped out the dinosaurs. Birds and once tiny mammals began to evolve rapidly.

▲ **Present day** Formation of the Isthmus of Panama and the split of Australia from Antarctica changed ocean currents, cooling global climates. North America and Eurasia circled the Arctic Ocean, restricting its circulation. Ice sheets waxed and waned in many cycles, with sea levels rising and falling (National Geographic Image Collection).

GEODISCOVERIES **Continents of the Past**

Follow today's continents from Precambrian to the present as they converge into a supercontinent and then split apart. An animation.

GEODISCOVERIES **Web Quiz**

Take a quick quiz on the key concepts of this chapter.

A Look Ahead

This chapter began by focusing on the processes by which the minerals and rocks of the Earth's surface are formed. As we have seen, these processes do not occur everywhere and at all times. Instead, there is a grand plan that organizes the formation and destruction of rocks and distributes the processes of the cycle of rock change in a geographic pattern. The grand plan is plate tectonics, the scheme for understanding the dynamics of the Earth's crust over millions of years of geologic time.

For geographers, the value of plate tectonics is that it provides the pattern for the largest and most obvious features of our planet's surface. These include its continents and oceans at the global scale, as well as its mountain ranges and basins at a continental scale. However, large landforms such as mountain ranges are made up of many smaller landforms—individual peaks, for example. In the next chapter, we will look at the continental surface in more detail, examining the processes that produce the regional- or local-scale volcanic and tectonic landforms that result when volcanoes erupt and rock layers are folded and faulted.

GEODISCOVERIES **Web Links**

View more rocks and minerals, learn more about the Heimaey volcanic eruption in Iceland, examine the formation of petroleum. Dive to the ocean floor and explore undersea tectonic landforms. Watch the continents move through the eons. Chart geologic time and discover ancient environments. It's all in this chapter's web links.

IN REVIEW EARTH MATERIALS AND PLATE TECTONICS

- At the center of the Earth lies the **core**—a dense mass of liquid iron and nickel that is solid at the very center. Enclosing the metallic core is the **mantle**, composed of ultramafic rock. The outermost layer is the **crust**. *Continental crust* consists of two zones—a lighter zone of felsic rocks atop a denser zone of mafic rocks. *Oceanic crust* consists only of denser, mafic rocks.
- **Minerals** are naturally occurring, inorganic substances, often with a crystalline structure, and largely composed of oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium.
- **Rocks** are naturally occurring assemblages of minerals. They fall into three major classes—igneous, sedimentary, and metamorphic.
- **Igneous rocks** are largely composed of silicate minerals. They are formed when **magma** cools and solidifies.
- *Felsic rocks* contain mostly felsic minerals and are least dense; *mafic rocks*, containing mostly mafic minerals, are denser; and *ultramafic* rocks are most dense. Because felsic rocks are least dense, they are generally found in the upper layers of the Earth's crust, while mafic and ultramafic rocks are generally found in lower layers.
- *Granite* (felsic, intrusive), *andesite* (felsic, extrusive), and *basalt* (mafic, extrusive) are three very common igneous rock types.
- If magma erupts on the surface to cool rapidly as lava, the rocks formed are *extrusive* and have a fine crystal texture. If the magma cools slowly below the surface as a **pluton**, the rocks are *intrusive* and the crystals are larger. Types of plutons include *batholiths, sills,* and *dikes.*
- **Sedimentary rocks** are formed in layers, or *strata*, composed of transported rock fragments called *sediment.* *Clastic sedimentary* rocks are composed of sediments that usually accumulate on ocean floors. As the layers are buried more and more deeply, water is pressed out and particles are cemented together. *Sandstone* and *shale* are common examples.
- *Chemical precipitation* also produces sedimentary rocks, such as *limestone.* Organic sediment is composed of tissues of plants and animals—*peat* is an example. Coal, petroleum, and natural gas are hydrocarbon compounds occurring in sedimentary rocks that we also term **fossil fuels**.
- **Metamorphic rocks** are formed when igneous or sedimentary rocks are exposed to heat and pressure. Shale is altered to *slate* or *schist*, sandstones become *quartzite*, limestone becomes *marble*, and intrusive igneous rocks or clastic sediments are metamorphosed into *gneiss.*
- In the **cycle of rock change**, there are two environments. Rocks are altered, fragmented, and deposited as sediment in the surface environment. In the deep environment, sediment or preexisting rock is altered by heat and pressure or melted to form magma. It reaches the surface environment by extrusion as lava or when it is revealed by erosion.
- Geologists trace the history of the Earth through the *geologic time scale*, which has divisions of *eons, eras, periods*, and *epochs.* The Cambrian period marks the beginning of widespread life on Earth.
- The *lithosphere*, the outermost shell of rigid, brittle rock, includes the crust and an upper layer of the mantle. Below the lithosphere is the *asthenosphere*, a region of the mantle in which mantle rock is soft or plastic. The lithosphere is divided into **lithospheric plates**.

- Continental land masses consist of active belts of mountain-making and inactive regions of old, stable rock. Mountain-building occurs by *volcanism* and *tectonic activity*. *Alpine chains* occur in two principal mountain belts—the circum-Pacific and Eurasian-Indonesian belts.
- *Continental shields* are regions of low-lying igneous and metamorphic rocks. They may be exposed or covered by layers of sedimentary rocks. Ancient *mountain roots* lie within some shield regions.
- The ocean basins are marked by a *midoceanic ridge* with its central *axial rift*. This ridge occurs at the site of crustal spreading. At *passive continental margins*, continental and oceanic lithosphere are joined together as part of the same lithospheric plate. At *active continental margins*, oceanic crust is forced down and under continental crust, producing volcanic and tectonic activity.
- Both *extensional* and *compressional tectonic activities* can lead to the formation of mountains. Extension occurs in the splitting of plates, when the crust thins, is fractured, and then pushed upward to produce block mountains.
- When lithospheric plates collide, compression occurs, shaping rock layers into *folds* that then break and move atop one another along *overthrust faults*.
- *Continental lithosphere* includes the thicker, lighter continental crust and a rigid layer of mantle rock beneath. *Oceanic lithosphere* is comprised of the thinner, denser oceanic crust and rigid mantle below.
- The lithosphere is fractured and broken into a set of **lithospheric plates**, large and small, that move with respect to each other.
- Where plates move apart, a **spreading boundary** occurs. At **converging boundaries**, plates collide. At *transform boundaries*, plates move past one another on a *transform fault*.
- When oceanic lithosphere and continental lithosphere collide, the denser oceanic lithosphere plunges beneath the continental lithospheric plate, a process called **subduction**. A trench marks the site of downplunging. Some subducted oceanic crust melts and rises to the surface, producing volcanoes.
- There are six major lithospheric plates—Pacific, American, Eurasian, African, Austral-Indian, and Antarctic.
- In *continental rupture*, extensional tectonic forces fracture and move a continental plate in opposite directions, creating a *rift valley*. Eventually, the rift valley widens and opens to the ocean. New oceanic crust forms as spreading continues.
- The closing of an ocean basin can cause two plates of lithospheric crust to collide, and subduction forms an *island arc* of volcanic islands.
- An *arc-continent collision* occurs when continued subduction draws a passive continental margin up against an island arc, forming an *orogen*.
- Eventually, the closing produces a *continent-continent collision*, in which two continental plates are welded together in a zone of metamorphic rock named a **continental suture**.
- The *Wilson cycle* of ocean-basin opening and closing has occurred many times in the geologic past. It is part of a cycle of formation of *supercontinents* in which the continents form one large land mass, then split apart, and eventually rejoin in a new supercontinent hundreds of millions of years later.
- Plate movements are thought to be powered by *radiogenic heat*. The exact mechanism is unknown, but may include *convection currents* in the plastic mantle rock of the asthenosphere; *gravity gliding* of plates away from an uplifted axial rift; and the gravitational pull of descending plates into a subduction zone.
- During the Permian Period, the continents were joined in a single, large supercontinent—Pangaea—that broke apart, leading eventually to the present arrangement of continents and ocean basins.
- Alfred Wegener assembled substantial evidence showing that the major continents were once assembled into a supercontinent called *Pangaea* that subsequently drifted apart.

KEY TERMS

core, p. 374
mantle, p. 374
crust, p. 375
mineral, p. 375
rock, p. 375
igneous rock, p. 376
magma, p. 376
pluton, p. 376
sedimentary rock, p. 376
fossil fuels, p. 378
metamorphic rock, p. 379
cycle of rock change, p. 382
lithospheric plates, p. 385
plate tectonics, p. 389
spreading boundary, p. 391
converging boundary p. 391
subduction, p. 391
continental suture, p. 395

REVIEW QUESTIONS

1. Describe the Earth's inner structure, from the center outward. What types of crust are present? How are they different? What is the *moho*?
2. Define the terms *mineral* and *rock*. Name the three major classes of rocks.

3. What are *silicate minerals*? Identify three types of silicate minerals based on color and density.
4. How do igneous rocks differ when magma cools (a) at depth and (b) at the surface?
5. What is *sediment*? Define and describe three classes of sediments.
6. Identify and describe three types of clastic sedimentary rocks.
7. How are sedimentary rocks formed by chemical precipitation?
8. What types of sedimentary deposits consist of hydrocarbon compounds? How are they formed?
9. What are *metamorphic rocks*? Describe at least three types of metamorphic rocks and how they are formed.
10. What are the units of the geologic time scale? Why is the Cambrian period important?
11. How do geologists use the term *lithosphere*? What layer underlies the lithosphere, and what are its properties? Define the term *lithospheric plate*.
12. What are the two basic subdivisions of continental masses?
13. What term is attached to belts of active mountain-making? What are the two basic processes by which mountain belts are constructed?
14. What is a *continental shield*? How old are continental shields? What two types of shields are recognized?
15. Describe how compressional mountain-building produces folds, faults, overthrust faults, and thrust sheets (nappes).
16. Compare oceanic and continental lithosphere. What is a *lithospheric plate*? Identify three types of plate boundaries.
17. Describe the process of subduction as it occurs at a converging boundary of continental and oceanic lithospheric plates. How is the continental margin extended? How is subduction related to volcanic activity?
18. What are *transform faults*? Where do they occur?
19. Name the six great lithospheric plates. Identify an example of a spreading boundary by general geographic location and the plates involved. Do the same for a converging boundary.
20. How does continental rupture produce passive continental margins? Describe the process of rupturing and its various stages.
21. How are island arcs formed? What type of plate collision is involved?
22. What is meant by the term *arc-continent collision*? Describe how it occurs.
23. How is the principle of convection thought to be related to plate tectonic motions? What role might gravity play in the motion of lithospheric plates?
24. What was Wegener's theory about "continental drift?" Why was it opposed at the time?
25. Referring to Figure 11.33, briefly summarize the history of the Earth's continents since about 600 million years ago.

VISUALIZING EXERCISES

1. Sketch a block or cross section of the Earth showing the following features: batholith, sill, dike, veins, lava, and volcano.
2. Sketch the cycle of rock change and describe the processes that act within it to form igneous, sedimentary, and metamorphic rocks.
3. Sketch a cross section of an ocean basin with passive continental margins. Label the following features: midoceanic ridge, axial rift, abyssal plain, continental rise, continental slope, and continental shelf.
4. Sketch a cross section showing a collision between oceanic and continental lithosphere at an active continental margin. Label the following features: oceanic crust, continental crust, mantle, oceanic trench, and rising magma. Indicate where subduction is occurring.
5. Sketch a continent–continent collision and describe the formation process of a continental suture. Provide a present-day example where a continental suture is being formed, and give an example of an ancient continental suture.
6. Examine Figure 11.30, which shows the Wilson cycle. Identify the plate boundaries shown on the diagrams. For each type of boundary, find the figure in the text that describes it.

ESSAY QUESTIONS

1. A granite is exposed at the Earth's surface, high in the Sierra Nevada Mountain Range. Describe how mineral grains from this granite might be released, altered, and eventually form a sedimentary rock. Trace the route and processes that would incorporate the same grains in a metamorphic rock.
2. Suppose astronomers discover a new planet that, like Earth, has continents and oceans. They dispatch a reconnaissance satellite to photograph the new planet. What features would you look for, and why, to detect past and present plate tectonic activity on the new planet?

Chapter 12
Volcanic and Tectonic Landforms

Located in the Russian Far East, the Kamchatka Peninsula is a land of great scenic beauty. Its two parallel mountain chains, rising to nearly 5000 m (about 15,000 ft) include 160 volcanoes, of which 29 are still active.

The peninsula is an example of a complex island arc where volcanoes have merged and intersected to create a volcanic land mass. It lies to the west of the Kuril-Kamchatka trench, where the Pacific plate plunges beneath the North American plate. Subduction and volcanic activity create the earthquakes and tsunamis frequently felt in the region.

Mutnovsky volcano is one of the most active volcanoes on the peninsula. It has erupted twice in the last decade, producing ash plumes and ash falls, as well as lahars of flowing ash. In fact, a 2007 mudflow from the volcano, possibly triggered by an earthquake, buried nearly two-thirds of the scenic Valley of the Geysers UNESCO world heritage site, covering most of its 90 geysers and many of its thermal pools.

With a population of about 400,000 in an area of nearly 500,000 km^2 (about 2000 mi^2), much of Kamchatka is untouched wilderness. More than a quarter of the land area is in natural parks and preserves.

A lake in a crater of Mutnovsky volcano, Kamchatka Peninsula, Russia.

Volcanic and Tectonic Landforms

Volcanic and tectonic processes create landforms ranging from lofty volcanic cones to block mountains and rift valleys. What kinds of volcanoes are there, and where do they occur? Why are active volcanoes environmental hazards? How do earthquakes signal tectonic activity? Why are they dangerous? How does erosion act on rock structures to produce landscapes of highlands and ridges, lowlands and valleys? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

The Indian Ocean Tsunami of 2004

One of the most dangerous side effects of tectonic activity is the **tsunami**—a great ocean wave produced by an undersea earthquake or volcanic explosion. When a tsunami arrives at a coastline, it causes a temporary and rapid rise of sea level. Ocean waters rush landward and surge far inland, destroying coastal structures and killing inhabitants. After some minutes, the waters retreat, continuing the devastation. Several surging waves can follow one after the other.

The most damaging tsunami recorded so far struck the Indian Ocean region in December 2004 following a massive undersea earthquake—9.0 on the Richter scale—in the Java trench, west of Sumatera. In Banda Aceh, a provincial capital about 230 km (140 mi) north of the epicenter, buildings toppled as residents ran into the streets. Hundreds died in the rubble, but then a giant tsunami washed over the city (Figure 12.1), killing thousands. As the wave moved down the Sumateran coastline, it killed many more, ultimately yielding an Indonesian death toll of more than 166,000.

It wasn't long before the wave began striking other coastlines. Thailand and Myanmar were hit first, and casualties were heavy on the packed beach resorts. The expanding wave, now traveling for two hours, next hit the eastern coast of Sri Lanka, devastating the entire coastal strip and killing at least 30,000 more. Soon after, India experienced the wave's wrath, reporting about 4000 dead in coastal cities and towns. About 6000 more deaths were recorded on the low islands of the Bay of Bengal.

It took three hours for the tsunami to reach the Maldives, a nation of low coral islands southwest of India, where about 100 lives were lost. After about six hours of travel time, the wave struck the coast of Africa. Damage was not as severe there as in Asia, but deaths were still recorded in Somalia, Kenya, and Tanzania. The wave was so powerful that it was still detectable with tide gauges as much as 36 hours later on reaching the Atlantic coasts of eastern North America and the Pacific islands of far-eastern Russia.

The earthquake arose in the Java trench, a subduction zone where the Australia tectonic plate plunges beneath the Eurasia plate. About 1000 km (600 mi) of fault ruptured, causing the seafloor to move upward about 5 m (16 ft). It was this rapid motion of a vast area of ocean bottom that generated the tsunami.

In deep ocean waters, the tsunami's motion is normally too gentle to be noticed, making tsunamis hard to detect in the open ocean. As the wave approaches land, however, it "feels the bottom" and slows, causing the wave to steepen and shorten. Ocean water flows inland at speeds of up to 15 m/s (34 mi/hr) for several minutes. Considering that each cubic meter of sea water weighs about 1025 kg (64 lb/ft^3), the power of the water surge is enormous.

No warning network was in place in the Indian Ocean to alert nations and their citizens of the impending disaster. One of the first efforts following the catastrophe was to start building such a network. With luck, the next great earthquake in the Java trench will find the world better prepared for its aftermath—another giant, deadly tsunami.

In July 2006, the Java trench rumbled again, this time with another undersea earthquake of magnitude 7.7 located 358 km (222 mi) south of Jakarta. The resulting 3-m (10-ft) tsunami was fortunately localized, but still about 1000 persons were killed or reported missing. In late September 2009, a 7.6-magnitude quake shook Padang, Sumatera, from an offshore epicenter west-northwest of the city. Fortunately, no tsunami was reported, although about 2500 people were killed or injured. Located at the edge of the Pacific Ring of Fire, Indonesia is fated to continue to suffer earthquakes and tsunamis long into the future.

A tsunami is a great ocean wave produced by an earthquake or volcanic explosion. The Indian Ocean Tsunami of 2004 killed more than 200,000 people and devastated coastlines from Indonesia to Tanzania.

12.1 The Indian Ocean Tsunami of 2004

▼ Before the tsunami, Banda Aceh, Indonesia, seen from space on June 23, 2004, is a city of small buildings, parks, and trees.

▼ Two days after the tsunami, the devastation caused by the earthquake and tsunami is complete. All that remains of most structures are their concrete floors. Trees are uprooted or stripped of leaves and branches.

▼ This satellite image shows Kalutara Beach, Sri Lanka, seen before the tsunami.

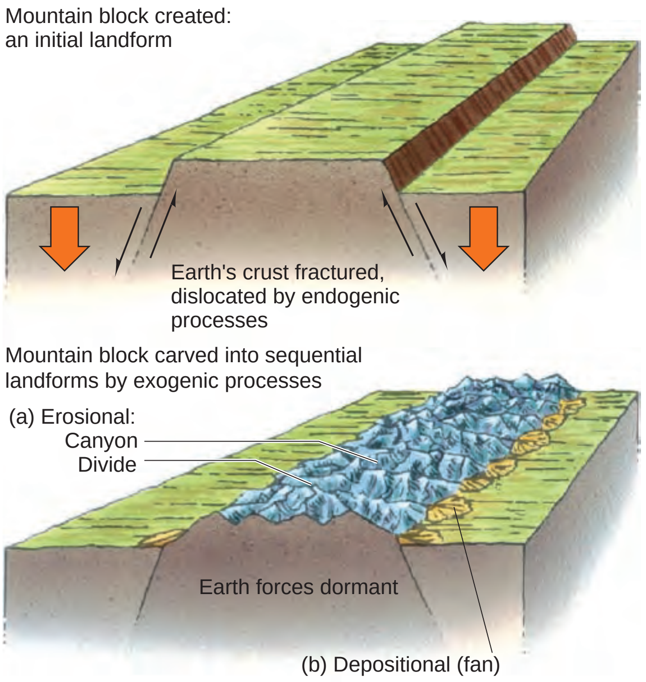
▼ An image of Kalutara Beach during the tsunami. Brown floodwaters still cover the land as the wave retreats, drawing streams of floodwater back to the ocean in surging currents.

Volcanic Landforms

Landforms are the surface features of the land—for example, mountain peaks, cliffs, canyons, plains, beaches, and sand dunes. Landforms are created by many different processes that we will describe in the remainder of this book. **Geomorphology** is the scientific study of the processes that shape landforms. In this chapter, we will look at landforms produced directly by volcanic and tectonic processes.

INITIAL AND SEQUENTIAL LANDFORMS

Continental landscapes reflect a tug-of war between two opposing processes. Volcanic and tectonic processes bring fresh rock to the planet's surface. We call these *endogenic processes* because they work from within the Earth. They produce *initial landforms*. In opposition are *exogenic processes* that work at the Earth's surface. They lower continental surfaces by removing and transporting mineral matter through running water, waves and



12.2 Initial and sequential landforms

An initial landform is created, here by tectonic activity, then carved into sequential landforms.

currents, glacial ice, and wind. Exogenic processes wear down initial landforms to create *sequential landforms*. Figure 12.2 shows how an initial landform, produced by crustal activity, is carved into sequential landforms by erosion.

Endogenic processes bring fresh rock to the surface and create initial landforms. Exogenic processes erode them to form sequential landforms.

Where does the power to lift molten rock and rigid crustal masses from within the Earth to the surface come from? Natural radioactivity in rock in the crust and mantle creates heat energy. This *radiogenic heat* is the fundamental energy source for the motion of lithospheric plates. Because the internal Earth forces act repeatedly, new initial landforms keep coming into existence as old ones are subdued. Later in this chapter, we'll look at landforms produced by tectonic activity. But first, we'll look at volcanoes.

VOLCANIC ACTIVITY

What exactly is a volcano? A **volcano** is a conical or dome-shaped initial landform that is built from lava emerging through constricted vents in the Earth's surface (Figure 12.3). *Volcanism*, or volcanic activity, constructs lofty cones of imposing mountain ranges as well as huge domes or plateaus of volcanic rock.

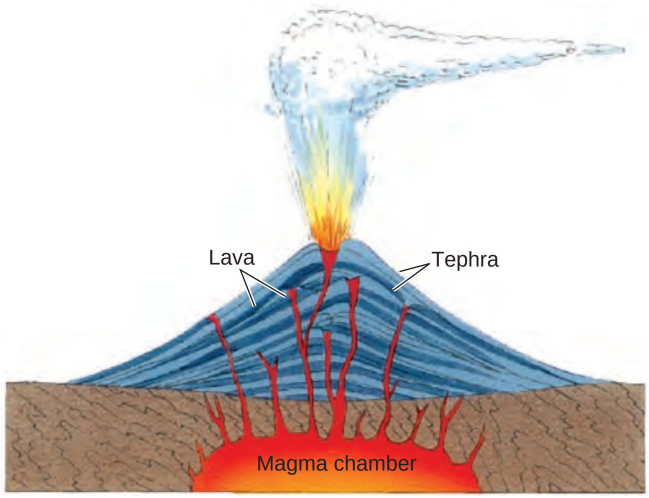
Volcanic eruptions are one of the most severe environmental hazards seen on our planet. During the Mount Pelée disaster on the Caribbean island of Martinique in 1902, for example, tens of thousands of lives were snuffed out in seconds. The destruction associated with volcanoes is caused by a number of related effects. Sweeping clouds of hot, incandescent gases descend volcano slopes at high speeds. Relentless lava flows can engulf whole cities. And showers of ash, cinders, and volcanic bombs (solidified masses of lava), all cause terrible devastation.

Volcanic eruptions can have extreme environmental impacts. Flows of hot gas, showers of ash, cinders, and bombs, violent earthquakes, and accompanying tsunamis can cause great loss of life.

Violent earthquakes are also associated with volcanism. And for the inhabitants of low-lying coasts, there is the peril of tsunamis generated by undersea volcanic explosions. Thanks to scientific monitoring, we're now reducing the toll of death and destruction from volcanoes. Still, not every volcano is well monitored or predictable.

Where are volcanoes located? If you study Figure 12.4, you can see the close relationship between volcanic activity and plate tectonics, with many volcanoes located above subduction zones and in axial rifts.

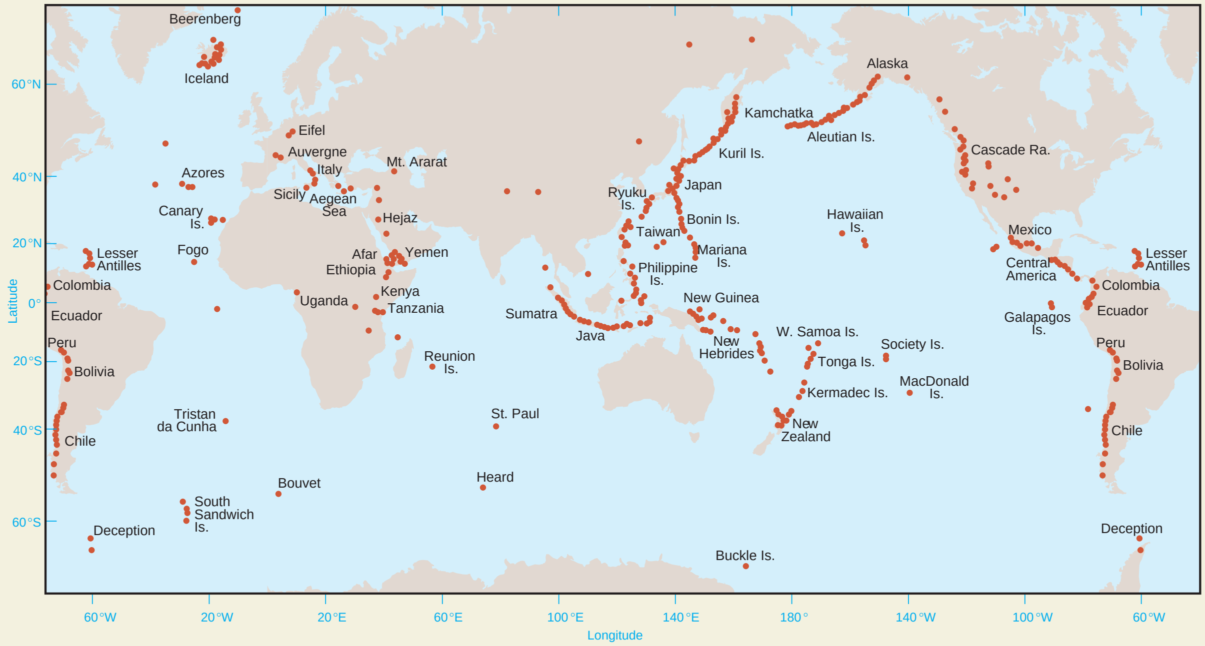
Volcanic activity is frequent along subduction boundaries, which accounts for the "ring of fire" around the Pacific Rim. Midocean spreading centers and continental rifts also show volcanic activity.



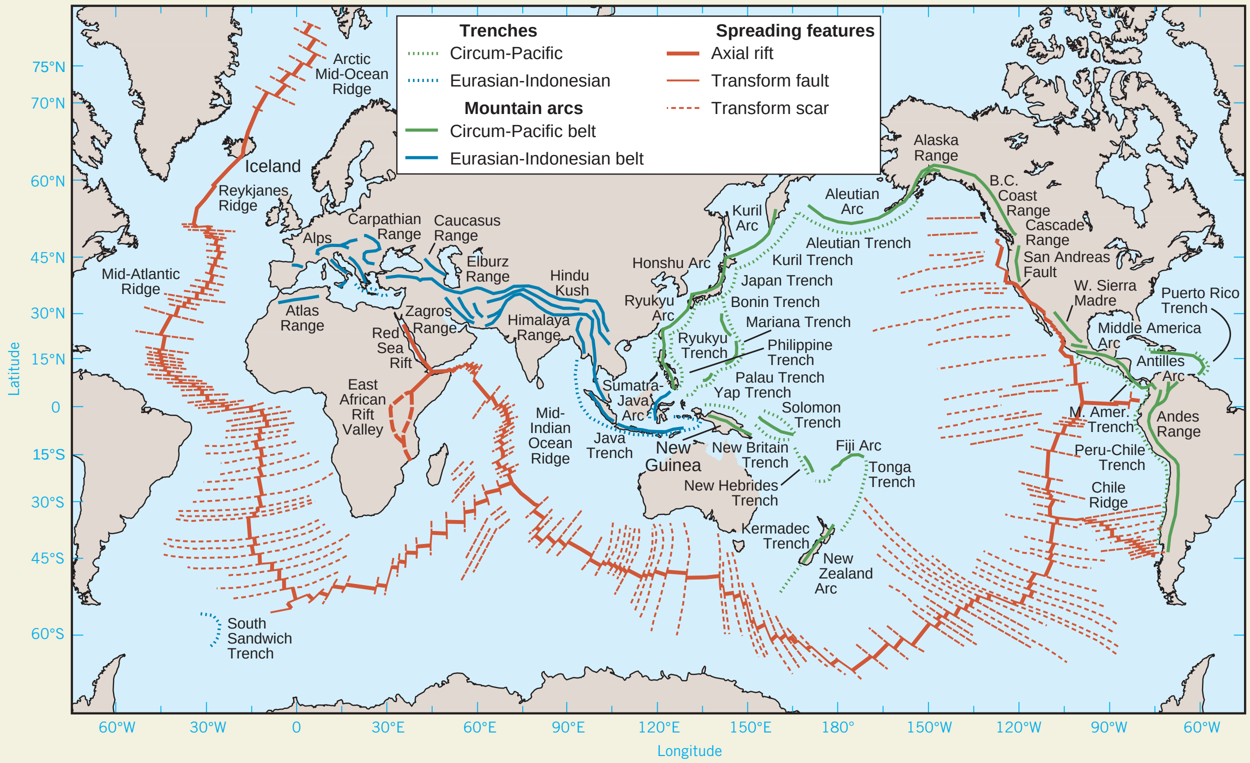
12.3 Anatomy of a volcano

This idealized cross section shows a type of volcano called a *stratovolcano*, composed of layers of lava and volcanic ash. The magma chamber feeds the volcano from beneath.

12.4 Volcanic activity of the Earth



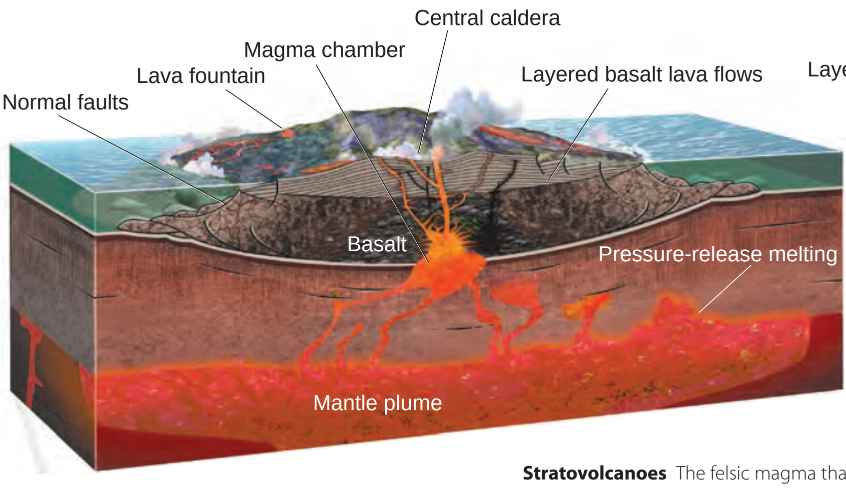
▲ The global pattern of volcanic activity is largely determined by plate tectonics. To verify this, compare the map of volcanic activity with the map of tectonic features. Dots show the locations of volcanoes known or believed to have erupted within the past 12,000 years. Each dot represents a single volcano or cluster of volcanoes.

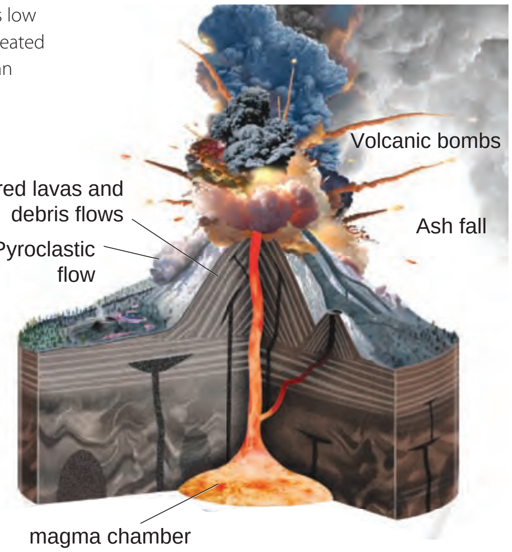


▲ This map shows the principal tectonic features of the world such as midoceanic ridges, trenches, and subduction boundaries. Many volcanoes occur along these features. In fact, the "ring of fire" around the Pacific Rim is the most obvious feature on both maps. Other volcanoes are located on or near oceanic spreading centers. Iceland is an example. In continental regions, spreading in East Africa has also produced volcanoes. We can also see hotspot activity in the Hawaiian Islands.

12.5 Stratovolcanoes and shield volcanoes

▼ **Shield volcanoes** The basaltic magma that forms shield volcanoes originates in the lower mantle. It has low viscosity, so it flows smoothly and easily. It emerges under low pressure, causing mostly gentle eruptions. Repeated eruptions build broad mountains that resemble a warrior's shield, giving shield volcanoes their name. They can become so massive that they bend the crust under their weight. The Hawaiian Islands are a familiar example.





▲ **Stratovolcanoes** The felsic magma that forms stratovolcanoes originates in subduction zones where descending oceanic lithosphere carries felsic sediments into the mantle where they melt. The magma is gassy and very viscous, so it is thick and flows with difficulty. It often plugs the vent and then emerges under high pressure, causing violent eruptions. Eruptions generally begin with violent explosions that expel the solid plug, producing thick deposits of tephra. Lava flows then follow, thus forming the interlayered strata that give the stratovolcano its name. Examples include Mount St. Helens in Washington State and Mount Etna in Italy.

STRATOVOLCANOES

Volcanic eruptions can be explosive or quiet. The nature of the eruption depends on the type of magma involved. There are two main types of igneous rocks—felsic and mafic—and each type builds a distinctive form of volcano—a *stratovolcano* or *shield volcano*, respectively (Figure 12.5).

Felsic lavas (rhyolite and andesite) are very thick and gummy, resisting flow. So, felsic lava doesn't usually flow very far from the volcano's event, building up steep slopes. When the volcano erupts, ejected particles of different sizes, known collectively as *tephra*, fall on the area surrounding the crater, creating a cone shape. The sluggish streams of felsic lava and layers of tephra produce a **stratovolcano**. Its tall cone steepens toward the summit, where you find the *crater*—a bowl-shaped depression. The crater is the principal volcano vent.

Felsic lavas from stratovolcanoes hold large amounts of gas under high pressure, so they can produce explosive eruptions (Figure 12.6). Sometimes the volcanic explosion is so violent that it destroys the entire central

12.6 Exploding volcanoes

▼ **Mount St. Helens** This stratovolcano of the Cascade Range in southwestern Washington erupted violently on the morning of May 18, 1980, emitting a great cloud of condensed steam, heated gases, and ash from the summit crater. Within a few minutes, the plume had risen to a height of 20 km (12 mi).

▼ **Crater Lake** Crater Lake, Oregon, is a water-filled caldera marking the remains of the summit of Mount Mazama, which exploded about 6600 years ago. Wizard Island (center foreground) was built on the floor of the caldera after the major explosive activity had ceased. It is an almost perfectly shaped cone of cinders capping small lava flows.

12.7 Ash cloud

A cloud of hot, dense volcanic ash, emitted by the Soufrière Hills volcano in 1997, courses down this narrow valley on the island of Montserrat in the Lesser Antilles. It killed about 20 people in small villages. Plymouth, the island's capital, was covered with hot ash and debris, causing extensive fires that devastated the evacuated city. The southern two-thirds of the small island were left uninhabitable.

portion of the volcano. Vast quantities of ash and dust fill the atmosphere for many hundreds of square kilometers around the volcano. The only thing remaining after the explosion is a great central depression, called a *caldera*. Although some of the upper part of the volcano is blown outward in fragments, most of it settles back into the new caldera.

Explosive stratovolcanoes also emit *glowing avalanches* (*glowing clouds*) such as the Soufrière Hills eruption of 1997 on Montserrat (Figure 12.7). These clouds of white-hot gases and fine ash travel rapidly down the flank of the volcanic cone, searing everything in their path. A glowing cloud from the 1902 eruption of Mount Pelée on Martinique issued without warning, sweeping down on the city of St. Pierre and killing all but two of its 30,000 inhabitants.

Most of the world's active stratovolcanoes lie within the circum-Pacific mountain belt, where there is active subduction of the Pacific, Nazca, Cocos, and Juan de Fuca plates. One good example is the volcanic arc of Sumatra and Java, which lies over the subduction zone between the Australian plate and the Eurasian plate.

Stratovolcanoes are tall, steep cones built of layers of felsic lava and volcanic ash. Felsic magma can contain gases under high pressure, so felsic eruptions are often explosive.

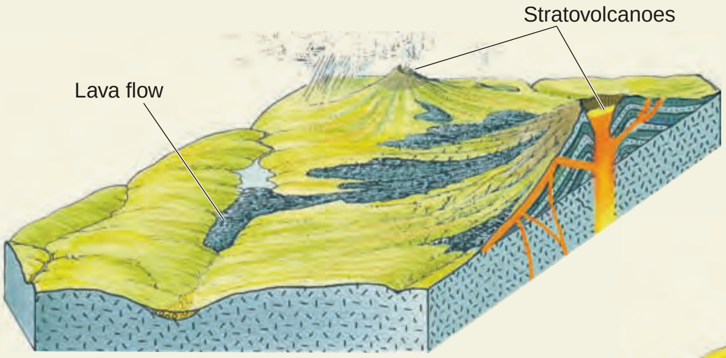
Over time, exogenic processes erode stratovolcanoes, creating new landscapes (Figure 12.8). Erosion strips away their conical forms, leaving masses of resistant volcanic rock that continue to wear down. Ultimately, a landscape of *lava mesas* and *volcanic necks* with *dikes* remains.

SHIELD VOLCANOES

In contrast to the thick, gassy felsic lava that forms stratovolcanoes, mafic lava (basalt) is not very viscous and holds little gas. Eruptions of basaltic lava are usually quiet, and the lava travels long distances to spread out in thin layers. Typically, then, large basaltic volcanoes are broadly rounded domes with gentle slopes (Figures 12.5). They are called **shield volcanoes**. Most of the lava flows from fissures (long, gaping cracks) on the flanks of the volcano. The volcanoes of Hawaii are good examples, as shown by the profile of Mauna Loa in Figure 12.9.

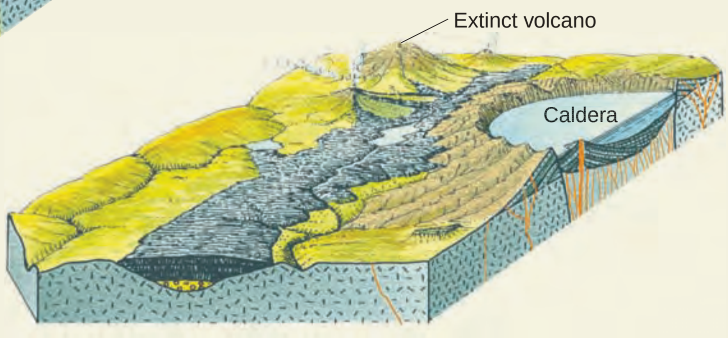
The chain of Hawaiian volcanoes was created by the motion of the Pacific plate over a *hotspot*—a plume of upwelling basaltic magma deep within the mantle. Motion of a lithospheric plate over a hotspot produces a long trail of islands and sunken islands called *guyots*. This process is shown in Figure 12.10. The Hawaiian

12.8 Erosion of stratovolcanoes

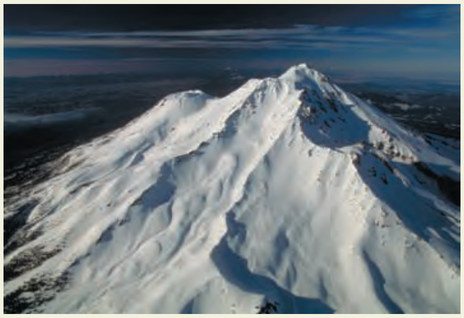


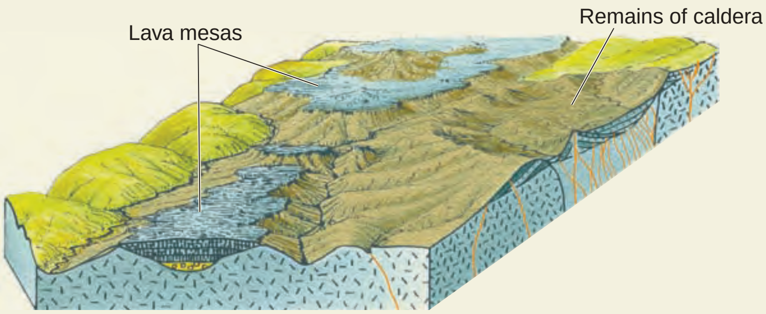
▲ **Active volcanoes** These active volcanoes are in the process of building. They are initial landforms. Lava flows from the volcanoes, spreading down into a stream valley and forming a lake behind a lava dam.

▼ **Waning volcanic activity** After some time, the largest volcano has been destroyed in an explosive eruption, leaving behind a large caldera. A lake occupies the caldera, and a small cone has been built inside. The other volcano has now become extinct. It has been dissected by streams and has lost its smooth conical form.

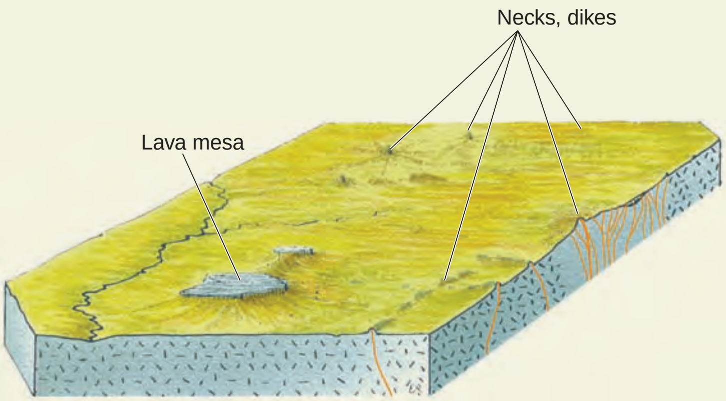


▶ **Mount Shasta** in the Cascade Range, northern California, is a partly dissected stratovolcano. It has been eroded by streams and small alpine glaciers. On the far side of the peak is a more recent subsidiary volcanic cone, called Shastina.





▲ **Deeply eroded volcanoes** All volcanoes are now extinct and have been deeply eroded. The caldera lake has been drained, and the rim has been worn to a low, circular ridge. The lava flows have resisted erosion far better than the rock of the surrounding area. They now stand high above the general level of the region as *lava mesas*.

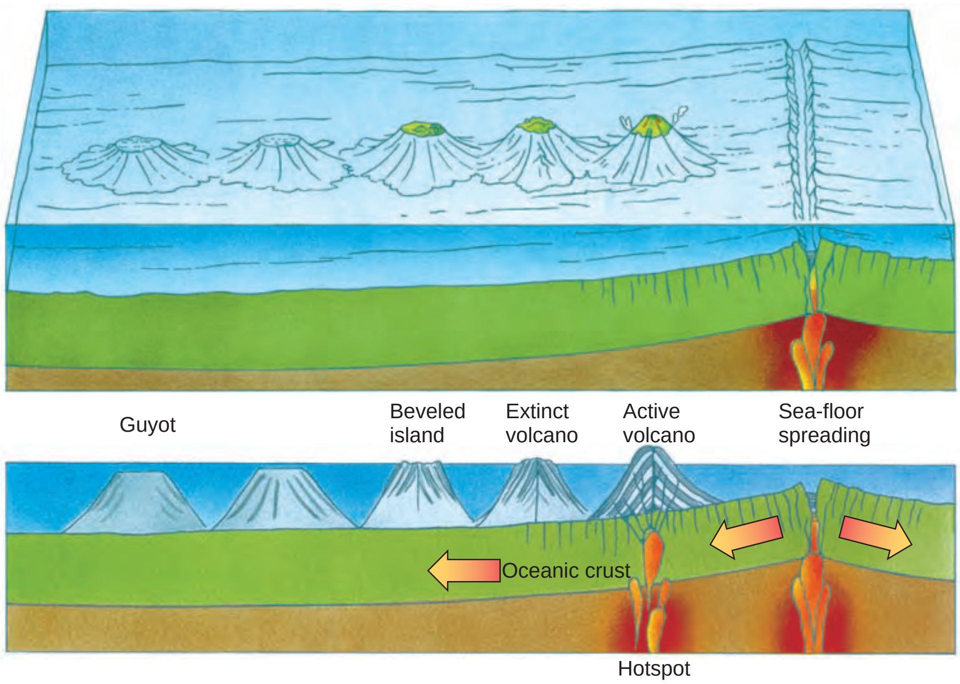


▲ **Advanced erosion** All that remains now of each volcano is a small, sharp peak, called a *volcanic* neck. This is the remains of the lava that solidified in the feeder pipe of the volcano.

◀ **Ship Rock,** New Mexico, as shown here in winter, is a volcanic neck enclosed by a weak shale formation. The peak rises about 520 m (about 1700 ft) above the surrounding plain. In the foreground and to the left, you can see wall-like dikes extending far out from the central peak.

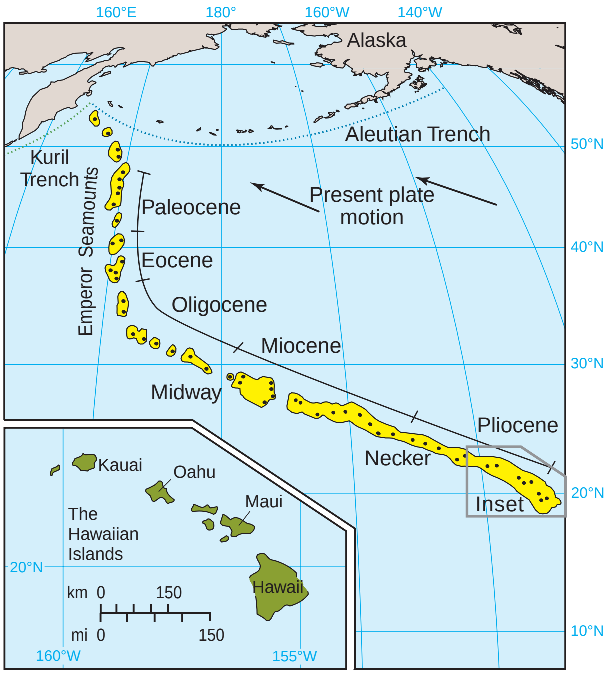
12.9 Hawaiian shield volcanoes

On the distant skyline is the summit of Mauna Loa volcano. The shield volcanoes of Hawaii have gently rising, smooth slopes that flatten near the top, producing a broad-topped volcano. Their domes rise as high as 4000 m (about 13,000 ft) above sea level, but if you include the basal portion below sea level, they are more than twice that high. In width they range from 16 to 80 km (10 to 50 mi) at sea level and up to 160 km (about 100 mi) at the submerged base. In the foreground is the summit cone of Mauna Kea, a smaller volcano on the north flank of Mauna Loa (National Geographic Image Collection).



12.10 Hotspot volcano chain

A chain of volcanic islands is formed as oceanic crust moves across a hotspot of rising magma. As the hot mantle rock rises, magma forms in bodies that melt their way through the lithosphere and reach the seafloor. Each major pulse of the plume sets off a cycle of volcano formation. However, the motion of the oceanic lithosphere eventually carries the volcano away from the location of the deep plume, and so it becomes extinct. Erosion processes wear the volcano away, and ultimately it becomes a low island. Continued attack by waves and slow settling of the island reduce it to a coral-covered platform. Eventually only a sunken island, or *guyot*, exists.



12.11 Hawaiian seamount chain

The Hawaiian seamount chain in the northwest Pacific Ocean Basin is 2400 km (about 1500 mi) long and trends northwestward with age. The sharp bend to the north is caused by a sudden change of direction of the Pacific plate. Dots are summits. The enclosing colored area marks the bases of the volcanoes at the ocean floor.

trail is shown in Figure 12.11. Several other long trails of volcanic seamounts cross the Pacific Ocean Basin following parallel paths that reveal the plate motion.

A few basaltic volcanoes also occur along the mid-oceanic ridge, where seafloor spreading is in progress. Iceland, in the North Atlantic Ocean, provides an outstanding example (Figure 12.12). Other islands of basaltic volcanoes located along or close to the axis of the mid-Atlantic Ridge are the Azores, Ascension, and Tristan da Cunha.

Shield volcanoes show erosion features that are quite different from those of stratovolcanoes (Figure 12.13). The gentle slopes of the original volcano are replaced by steep canyons and sharp ridges as erosion dissects the mountain mass.

If a hotspot lies beneath a continental lithospheric plate, it can generate enormous volumes of basaltic lava that emerge from numerous vents and fissures and accumulate layer upon layer. These basalt layers, called *flood basalts*, can become thousands of meters thick and cover thousands of square kilometers (Figure 12.14).

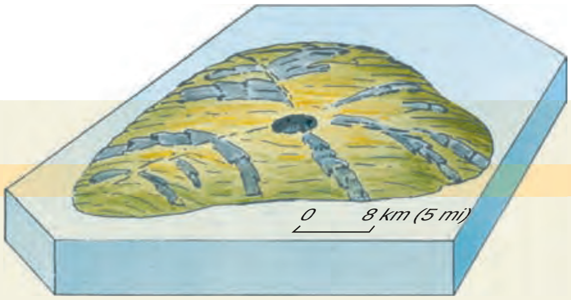
Hotspots are plumes of rising basaltic magma that generate volcanic activity. In the ocean, they generate seamounts and islands. On land, they cover large regions with flood basalts.

12.12 Vestmannaeyjar after the Heimay volcanic eruption

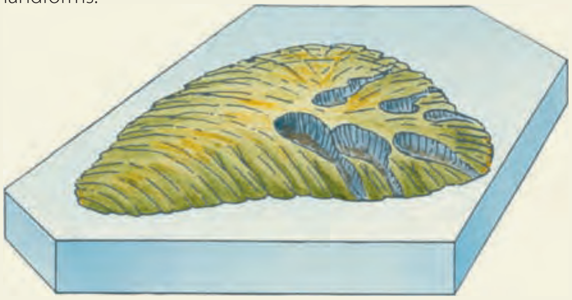
Iceland is constructed entirely of recent eruptions of basalt emerging from the Mid-Atlantic ridge. In January 1973, the volcano beneath Heimaey Island erupted, emitting tephra at a rate of 100 m^3/sec (about 3500 ft^3/sec) and building a broad cone that reached 100 m (about 300 ft) above sea level. Named Edfell, the cone appears on the right, surrounded by lava flows extending into the ocean. Edfell's older sister, Helgafell, is on the left, with the town of Vestmannaeyjar behind it. Note the tongue of fresh lava from Eldfell invading the right side of the town (National Geographic Image Collection).

12.13 Erosion of shield volcanoes

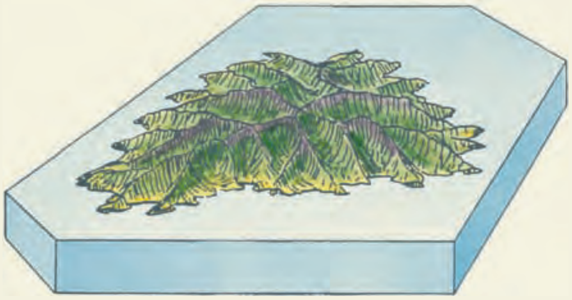
▼ This Landsat image shows the island of Kauai, the oldest of the Hawaiian shield volcanoes. You can see the radial pattern of streams and ridge crests leading away from the central summit. The intense red colors are lush vegetation. A few puffs of white clouds crown the ridge crests.



▲ The active volcano and its central depression are initial landforms.



▲ In the early stage of erosion, radial streams cut deep canyons into the flanks of the extinct volcano. These canyons open out into deep, steep-walled amphitheaters.



▶ Eventually, the original surface of the shield volcano is entirely obliterated, leaving a rugged mountain mass made up of sharp-crested divides and deep canyons.

12.14 Flood basalts

An important American example of flood basalts is found in the Columbia Plateau region of southeastern Washington, northeastern Oregon, and westernmost Idaho. Here, basalts of Cenozoic age cover an area of about 130,000 km^2 (about 50,000 mi^2)—nearly the same area as the state of New York. Each set of cliffs in the photo is a major lava flow. Vertical cracks form in the lava as it cools, creating tall columns.

EYE ON THE LANDSCAPE **What else would the geographer see?** The still water (A) and narrow shoreline (B) show that the water body in this photo is a lake. In fact, the Columbia River has been extensively developed for hydropower generation with the building of many large dams. Vegetation is sparse (C), since the region lies in the rain shadow of the Cascades.

FOCUS ON REMOTE SENSING

Remote Sensing of Volcanoes

Volcanoes are always attractive subjects for remote sensing. As monumental landforms, they have distinctive shapes and appearances that are easy to recognize in satellite imagery. They are also very dynamic subjects with the capacity to erupt in spectacular fashion, providing smoke plumes, ash falls, and lava flows. Figure 12.15 provides four examples of volcanoes as they appear in remotely sensed images from four different sensor systems.

Mount Vesuvius This image (Figure 12.15) was acquired by the ASTER instrument on NASA's Terra satellite platform. Spatial resolution is 15 by 15 m (49 by 49 ft). Vegetation appears bright red, with urban areas in blue and green tones. The magnitude of development around the volcano shows that the impact of a major eruption would be particularly catastrophic. If sudden, thousands of deaths would be expected.

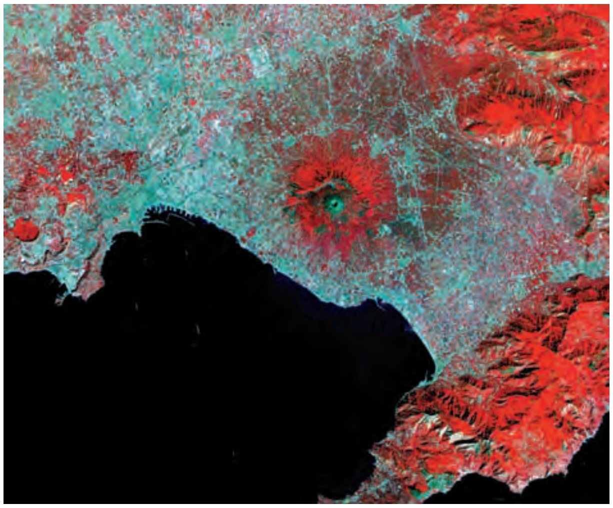
Mount Fuji This striking image of Mount Fuji was acquired by the Shuttle Radar Topography Mission interferometric synthetic aperture radar. This type of radar sends simultaneous pulses of radio waves toward the ground from two antennas spaced 60 m (about 200 ft) apart. Very slight differences in the return signals can be related to the ground height. In this way, the radar can map elevations very precisely. The image simulates a viewpoint above and to the east of Tokyo. A color scale is assigned to elevation, ranging from white to green to brown. The vertical scale is doubled for visualization, so Mount Fuji and surrounding peaks appear twice as steep as they actually are.

Popocatepetl The close-up image of Popocatepetl (far left) was acquired by Landsat-7 at a spatial resolution of 30 by 30 m (98 by 98 ft). Snow and ice flank the summit crater. Canyons carved into the volcano lead away from the summit. The lower slopes are thickly covered with vegetation, which appears green in this image. The surrounding plain shows intensive agricultural development.

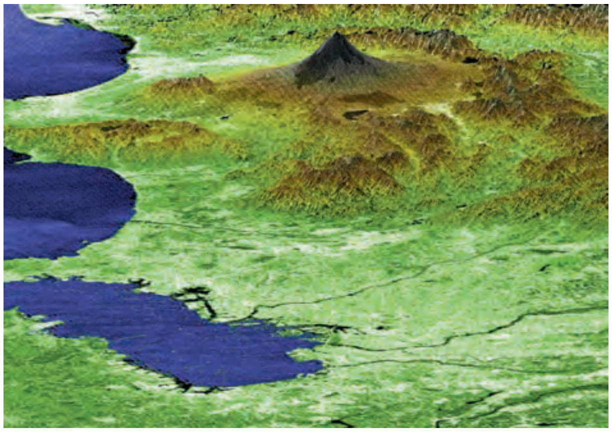
The eruption of Popocatepetl in 2000 was captured by the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) on December 19, 2000, at a spatial resolution of 1 by 1 km (0.62 by 0.62

Remote sensing provides images of volcanoes and their settings. Space-borne imagers can monitor eruptions in progress.

12.15 Remote sensing of volcanoes



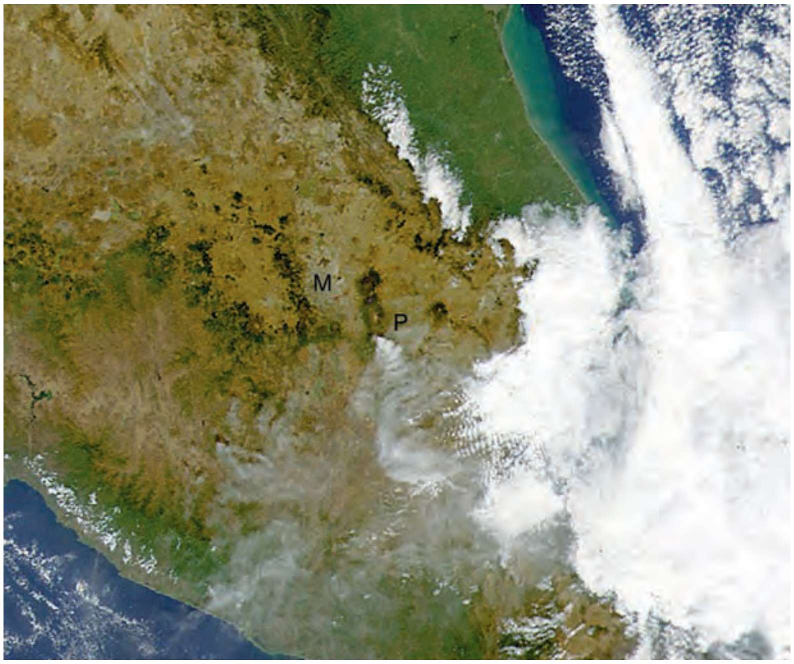
▲ **Mount Vesuvius imaged by ASTER** This famous volcano erupted in the year 79 A.D., ejecting a huge cauliflower-shaped cloud of ash and debris that rapidly settled to the Earth. The nearby Roman city of Pompeii was buried in as much as 30 m (100 ft) of ash and dust, leaving an archeological treasure that was not discovered until 1748. In recent history, major eruptions were recorded in 1631, 1794, 1872, 1906, and 1944.



▲ **Mount Fuji imaged by the Shuttle Radar topography Mission** Mount Fuji lies within striking distance of a large population center—Tokyo, Japan, located about 100 km (about 60 mi) to the northeast. Although it has the symmetry of a simple cone, it is actually a complex structure with two former volcanic cones buried within its outer form. Mount Fuji is considered an active volcano, with 16 eruptions since 781 A.D. Its last eruption, in 1707, darkened the noontime sky and shed dust on the present-day Tokyo region.

mi). This global-scale imager pictured the width of southern Mexico from the Pacific to the Caribbean in true color. Popocatepetl (P) is shown very near the center of the image, emitting a smoke plume moving south and east. A large cloud bank lies to the east and obscures much of the right-hand side of the image. High, thin cirrus clouds overlie part of the plume. Mexico City (M) is visible north and west of the volcano as a gray-brown patch flanked by north-south mountain ranges.

▲ **Popocatepetl imaged by Landsat-7** Located only 65 km (40 mi) from Mexico City, the "smoking mountain" of the Nahuatl language is within the view of nearly 30 million people.



▲ **Eruption of Popocatepetl imaged by SeaWiFS** On December 18, 2000, Popocatepetl came to life. Following its last eruption in 1994, the volcano was under constant monitoring, and about half the population in the valleys directly below the volcano was evacuated, with no injuries reported.

Cinder cones are small volcanoes that form when frothy basalt magma is ejected under high pressure from a narrow vent, producing tephra. The rain of tephra accumulates around the vent to form a roughly circular hill with a central crater. Cinder cones rarely grow more than a few hundred meters high. An exceptionally fine example of a cinder cone is Wizard Island (Figure 12.6), which was built on the floor of Crater Lake long after the caldera was formed.

GEODISCOVERIES **Volcanoes**
Watch and compare the eruptions of shield volcanoes and stratovolcanoes in this video. Concludes with footage of the fiery, explosive eruption of Mount St. Helens.

HOT SPRINGS, GEYSERS, AND GEOTHERMAL POWER

Where hot rock material is near the Earth's surface, it can heat nearby ground water to high temperatures. When the ground water reaches the surface, it provides *hot springs* at temperatures not far below the boiling point of water (Figure 12.16). At some places, jet-like emissions of steam and hot water occur at intervals from small vents—producing *geysers* (Figure 12.17). Since the water that emerges from hot springs and geysers is largely ground water that has been heated in contact with hot rock, this water is recycled surface water. Little, if any, is water that was originally held in rising bodies of magma.

12.16 Mammoth Hot Springs
Small terraces ringed by mineral deposits hold steaming pools of hot water as the spring cascades down the slope. This example of geothermal activity is from Yellowstone National Park, Wyoming.

12.17 Old Faithful Geyser
An eruption of Old Faithful Geyser in Yellowstone National Park, Wyoming.

The heat from masses of lava close to the surface in areas of hot springs and geysers provides a source of energy for electric power generation. Here the ground water has been heated intensely, but because of the overlying pressure of the rock, it remains in a liquid state. To generate power, wells are drilled to tap the hot, pressurized water, which flashes into steam when it is released at the surface. The steam then drives turbines that generate electric power (Figure 12.18).

12.18 Geothermal power plant
The geothermal power plant at Svartsengi, Iceland, heats seven towns and a NATO base, and provides electric power as well. The bathers in the foreground are enjoying the warm, briny, mineral-rich waters of a runoff pond (National Geographic Image Collection).

GEODISCOVERIES **Remote Sensing and Tectonic Landforms Interactivity**

Choose the "volcanoes" option to inspect some of the Earth's major volcanoes located in developed areas. Identify craters and lava flows, and fly over Mount St. Helens.

Tectonic Landforms

There are two basic forms of tectonic activity: compression and extension. *Compression* occurs when lithospheric plates are squeezed together along converging lithospheric plate boundaries, while *extension* happens along continental and oceanic rifting, where plates are being pulled apart.

Compression and extension are two forms of tectonic activity. Compression occurs at converging lithospheric plate margins, while extension occurs along continental and oceanic rifting.

FOLD BELTS

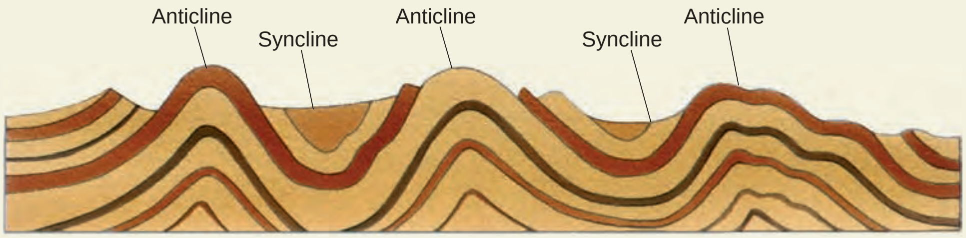
Let's start by looking at folding produced by compression. When two continental lithospheric plates collide, the plates are squeezed together at the boundary. The crust crumples, creating **folds**. The Jura Mountains of France and Switzerland, shown in Figure 12.19, are an example of relatively young—geologically speaking—open folds. The folds create a set of alternating *anticlines*, or up-arching bends, and troughs, called *synclines*.

When fold belts are eroded, they create a **ridge-and-valley landscape** (Figure 12.20), like the eastern side of the Appalachian Mountains from Pennsylvania to Alabama. In this landscape, weaker formations such as shale and limestone are eroded away, leaving hard strata, such as sandstone or quartzite, to stand in bold relief as long, narrow ridges. These folds are continuous and even-crested, producing almost parallel ridges. In some regions, however, the fold crests plunge, rising up in places and dipping down in others. This provides a pattern of curving mountain crests and valleys.

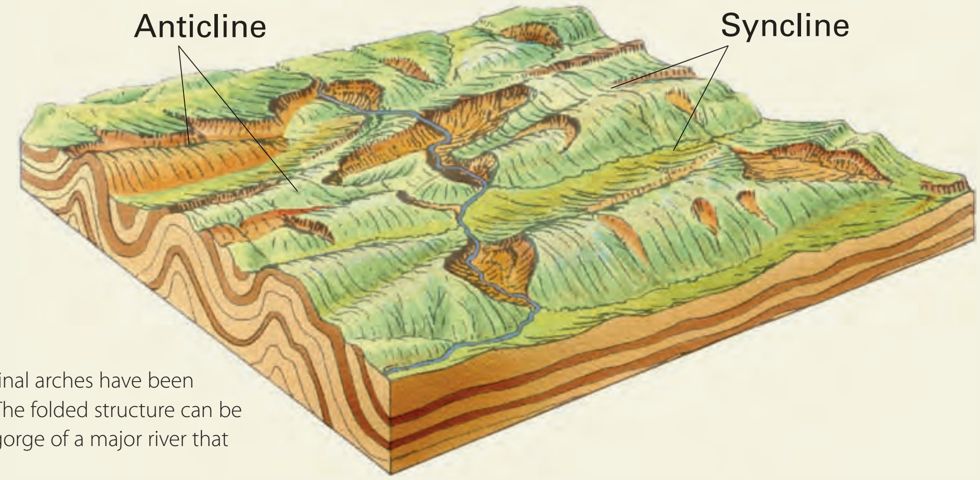
Fold belts create a ridge-and-valley landscape of alternating ridges of resistant rock and valleys of weak rock. Upfolds are anticlines, and downfolds are synclines.

Note that anticlines are not always ridges. If a resistant rock type at the center of the anticline is

12.19 Folds of the Jura Mountains



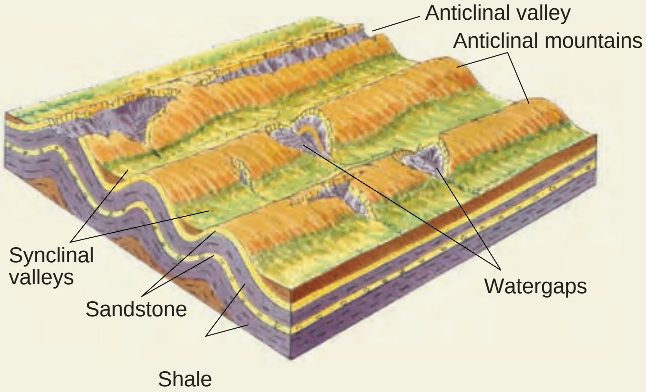
▲ **Anticline and syncline** The initial landform associated with an anticline is a broadly rounded mountain ridge, and the landform corresponding to a syncline is an elongated, open valley.



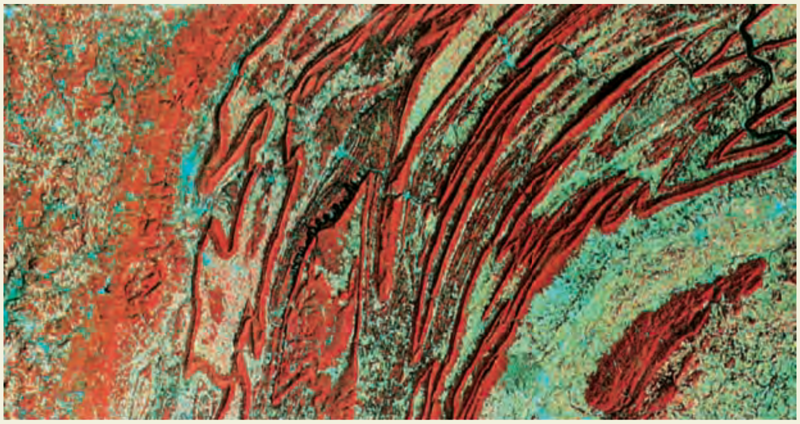
▶ **Erosion process** Some of the anticlinal arches have been partially removed by erosion processes. The folded structure can be seen clearly in the walls of the winding gorge of a major river that crosses the area.

12.20 Erosion of folded strata

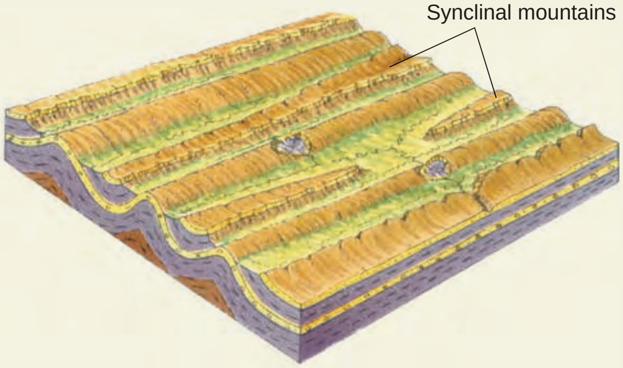
Deep erosion of simple, open folds produces a *ridge-and-valley landscape*. Folds that dip downward or rise upward produce zigzag ridges following erosion.



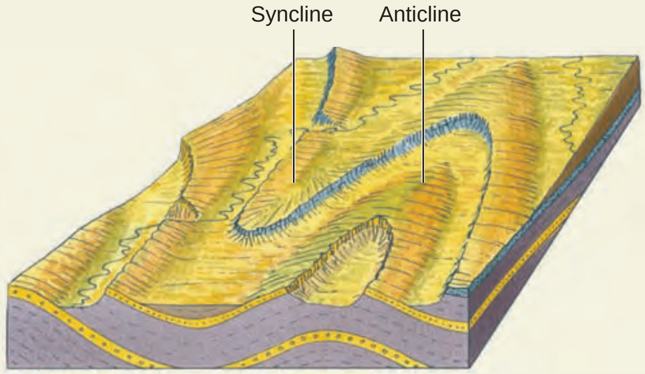
▲ Weaker formations such as shale and limestone are eroded away, leaving long, narrow ridges of hard strata, such as sandstone or quartzite. At some locations, the resistant rock at the center of the anticline is eroded through to reveal softer rocks underneath, creating an anticlinal valley.



▲ **Ridge-and-valley landscape** This Landsat image shows the ridge-and-valley country of south-central Pennsylvania in color-infrared. The land surface shows zigzag ridges formed by bands of hard quartzite. The strata were crumpled during a continental collision that took place over 200 million years ago.



▲ Synclinal mountains can also be formed after continued erosion, when resistant rock at the center of a syncline is exposed. The resistant rock stands up as a ridge.



▲ Plunging folds that have been eroded lead to zigzag ridges.

eroded through to reveal softer rocks underneath, an *anticlinal valley* may form. A *synclinal mountain* is also possible. It occurs when a resistant rock type is exposed at the center of a syncline, and the rock forms a ridge.

GEODISCOVERIES **Folding**
A video focusing on the Appalachian Mountains shows a landscape of ridges and valleys created by folding. View the development of anticlinal and synclinal mountains and valleys. See how plunging folds produce zigzag and hairpin ridges.

FAULTS AND FAULT LANDFORMS

A **fault** is a fracture created in the brittle rocks of the Earth's crust, as different parts of the crust move in different directions. *Fault lines* can sometimes be followed along the ground for many kilometers. Most major faults extend down into the crust for at least several kilometers.

Faults are evidence of relative movement between the rock on either side of the fault. Rock on either side suddenly slips along the *fault plane*, generating earthquakes. A single fault movement can cause slippage of as little as a centimeter or as much as 15 m (about 50 ft) (Figure 12.21). These movements typically happen many years or decades apart, or even several centuries apart. But when we add up all these small motions over long time spans, they can amount to tens or hundreds of kilometers. There are four main types of faults: normal, transcurrent, reverse, and overthrust faults.

In a fault, rocks break apart and move along a fault plane. Normal faults are caused by extension and produce downdropped blocks (grabens) and upthrown blocks (horsts).

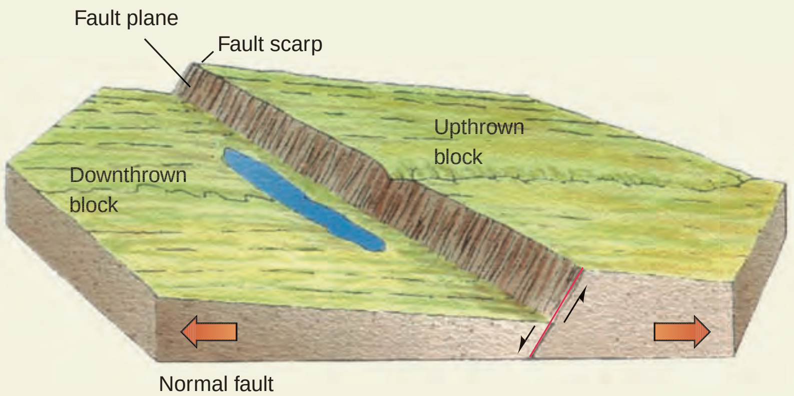
Normal faults are a common type of fault produced by crustal rifting (Figure 12.22). They usually occur as a set of parallel faults creating *fault scarps*, *grabens*, and *horsts*. Where normal faulting occurs on a grand scale, it produces ranges of *block mountains* flanked by down-dropped lowland basins.

When lithospheric plates slide past one another horizontally along major transform faults, we refer to these faults as **transcurrent faults**, or *strike-slip faults*

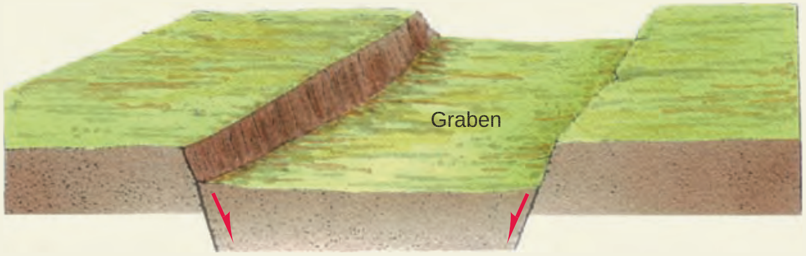
12.21 Fault scarp

This fault scarp was formed during the Hebgen Lake, Montana, earthquake of 1959. In a few moments, a displacement of 6 m (20 ft) took place on a normal fault.

12.22 Faults and fault scarps



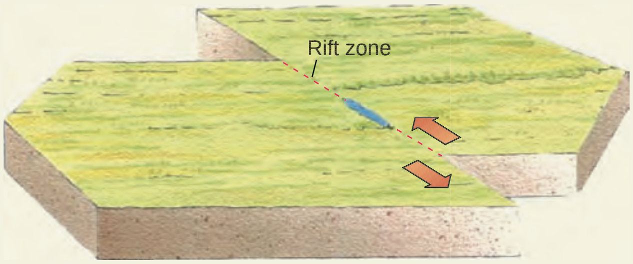
◀ **Normal fault** The crust on one side of a normal fault is raised relative to the other. This creates a steep, straight, cliff-like feature called a fault scarp. Fault scarps range in height from a few meters to a few hundred meters. In some cases, they can be 300 km (about 200 mi) long.



◀ **Graben** A narrow block dropped down between two normal faults creates a graben—a trench with straight, parallel walls. Grabens are found in regions of crustal speading, such as the East African Rift Valley system. They are also seen flanking seafloor spreading axes.

◀ **Horst** A narrow block left elevated between two normal faults is a horst—making block-like plateaus or mountains, often with a flat top but steep, straight sides.

12.23 Transcurrent faults



▲ **Transcurrent fault** Movement along a transcurrent fault is mostly horizontal, so we don't see a scarp, or at most we see a very low one. We can usually only trace a thin fault line across the surface, although in some places the fault is marked by a narrow trench, or rift.

▶ **San Andreas fault in Southern California** This transcurrent fault is here expressed as a narrow trough. It marks the active boundary between the Pacific plate and the North American plate. The Pacific plate is moving toward the northwest, carrying a great portion of the state of California and all of Lower (Baja) California with it.

(Figure 12.23). The *San Andreas fault* is a famous active transcurrent fault. You can follow it for about 1000 km (about 600 mi) from the Gulf of California to Cape Mendocino. Throughout many kilometers of its length, the San Andreas fault appears as a straight, narrow scar. In some places this scar is a trench-like feature, and elsewhere it is a low scarp.

Reverse and overthrust faults are caused by compression. In a reverse fault, an overhanging scarp that slumps downward is formed. In an overthrust fault, one rock mass slides up and over another.

Figure 12.24 illustrates the *reverse fault* and the *overthrust fault*. Both are caused by crustal compression. The San Fernando, California, earthquake of 1971 was generated by slippage on a reverse fault. When compression is severe, for example, in a continent-continent collision, rock layers can ride over each other on a low-angle overthrust fault. Repeated faulting can produce a great rock cliff hundreds of meters high. Because fault planes extend hundreds of meters down into the bedrock, their landforms can persist even after several million years of erosion. Figure 12.25 diagrams the effect of erosion on a fault scarp.

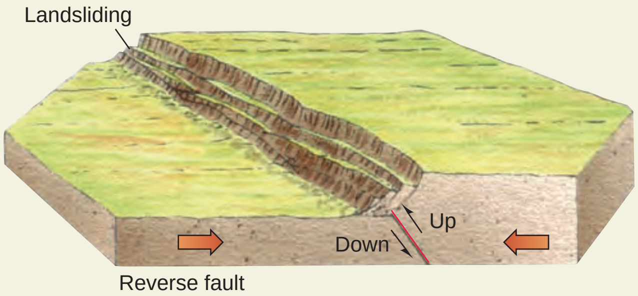
GEODISCOVERIES **Major Types of Faulting**
See how crustal extension and compression create normal, reverse, and overthrust faults in this animation. Watch a transcurrent fault form at the boundary of two lithospheric plates moving in opposite directions.

THE EAST AFRICAN RIFT VALLEY SYSTEM

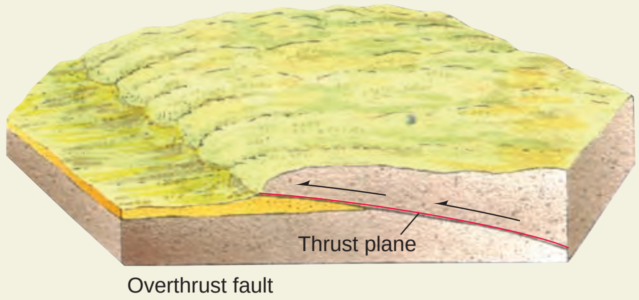
The Rift Valley of East Africa provides an example of extension and normal faulting at a continental scale. Here, continental lithosphere is beginning to rupture and split apart in the first stage of forming a new ocean basin. The Rift Valley is basically a series of linked and branching grabens, but with a more complex history that includes building volcanoes on the graben floor.

Figure 12.26 shows a map of the East African Rift Valley system. It is about 3000 km (1900 mi) long and extends from the Red Sea southward to Lake Nyassa.

12.24 Reverse and overthrust faults



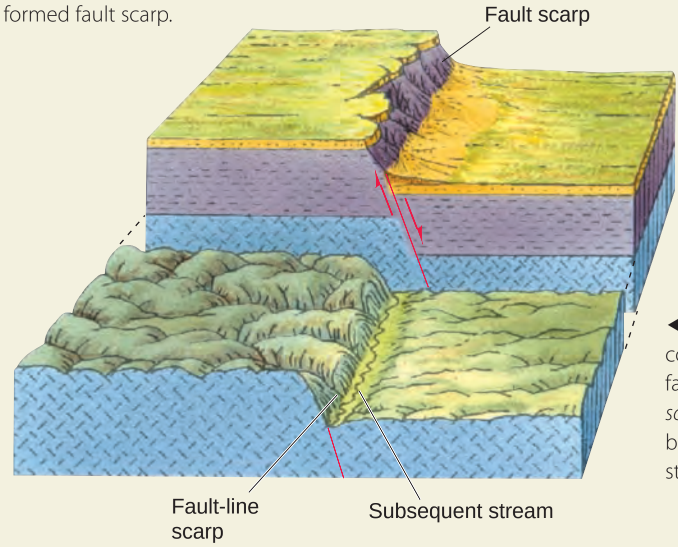
▲ **Reverse fault** The fault plane along a reverse fault is inclined such that one side rides up over the other. Reverse faults produce fault scarps similar to those of normal faults. But because the scarp tends to be overhanging, there's a much greater risk of a landslide.



▲ **Overthrust fault** Overthrust faults involve mostly horizontal movement. One slice of rock rides over the adjacent ground surface. A thrust slice may be up to 50 km (30 mi) wide.

12.25 Fault scarp evolution

▶ A recently formed fault scarp.

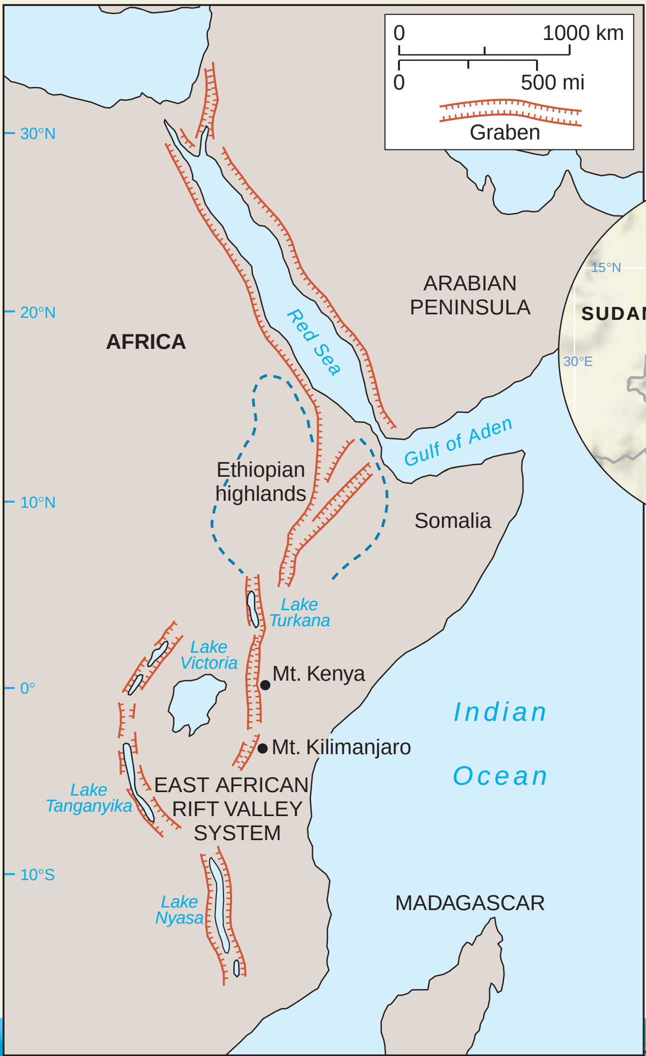


◀ Even though the cover of sedimentary strata has been completely removed, exposing the ancient shield rock, the fault continues to produce a landform, known as a *fault-line scarp*. Because the fault plane is a zone of weak rock that has been crushed during faulting, it is occupied by a subsequent stream.

Along this axis, the Earth's crust is being lifted and spread apart. The rift valleys are like keystone blocks of a masonry arch that have slipped down between neighboring blocks because the arch has spread apart somewhat. Thus, the floors of the rift valleys are above the elevation of most of the African continental surface. Major rivers and several long, deep lakes—Lake Nyassa and Lake Turkana, for example—occupy some of the valley floors.

The sides of the rift valleys typically consist of fault scarps and multiple fault steps (Figure 12.26). Sediments from the adjacent plateaus make thick fills in the floors of the valleys. Two great stratovolcanoes have been built close to the Rift Valley east of Lake Victoria. One is Mount Kilimanjaro, whose summit rises to over 6000 m (about 19,000 ft). The other, Mount Kenya, is only a little lower and lies right on the Equator.

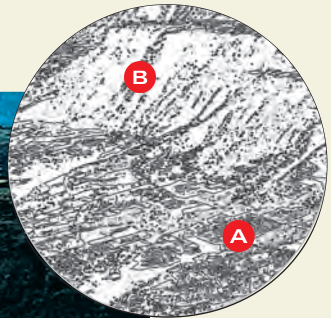
12.26 The Rift Valley system of East Africa



◀ **Map of the Rift Valley system** Stretching from the northern end of the Red Sea to Lake Nyassa in Malawi, the Rift Valley system is a series of grabens that mark the early stages of a continental rupture. In several locations, lakes have formed in the bottoms of the grabens.

▼ **The Rift Valley wall** Multiple fault scarps give the landscape a stepped appearance.

EYE ON THE LANDSCAPE What else would the geographer see?
The local agriculture exploits the stepped landscape at the edge of the Rift Valley with cultivated fields (A) laid out on the flat tops of terraces. Given the mix of fallow and still-green fields, this photo is probably from the end of the growing season. Note also the flat faces of the slopes on the fault scarps between gullies (B). These are likely to be remnants of the original planes of motion, given the recent geologic age of the Rift Valley.



Earthquakes

You've probably seen the destruction wrought by **earthquakes** on the television news. Californians know about this first-hand, and several other areas in North America have also experienced strong earthquakes. Earthquakes range from faint tremors to wild motions that shake buildings apart.

Most earthquakes are produced by sudden slip movements along faults. These happen because rock on both sides of the fault is slowly bent over many years by tectonic forces. Energy builds up in the bent rock, just as it does in a bent archer's bow. When that pent-up energy reaches a critical point, the fault slips and relieves the strain. Rocks on opposite sides of the fault move in different directions, instantaneously releasing a large quantity of energy in the form of *seismic waves*. These waves radiate outward, traveling through the Earth's surface layer and shaking the ground. (The term *seismic* means "pertaining to earthquakes.") Like ripples produced when a pebble is thrown into a quiet pond, these waves gradually lose energy as they travel outward in all directions.

An earthquake is a seismic wave motion transmitted through the Earth. It is produced by sudden slippage on a fault.

In 1935, seismologist Charles F. Richter devised the scale of earthquake magnitudes that bears his name. Figure 12.27 shows how the *Richter scale* relates to the energy released by earthquakes. In 1977, Hiroo Kanamori devised a more accurate way to calculate this energy and revised the rating of a number of large earthquakes.

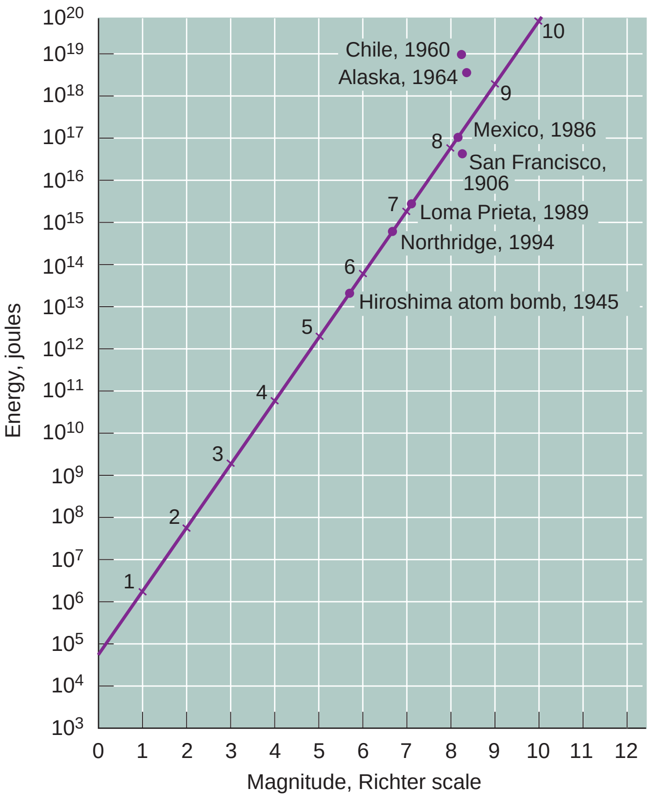
The Richter scale is used to measure the energy released by earthquakes.

EARTHQUAKES AND PLATE TECTONICS

Figure 12.28 compares a map showing the centers of large earthquakes observed during a six-year period with a map of tectonic features. The pattern of earthquakes follows subduction boundaries, transform boundaries, island arcs, mountain arcs, and axial rifts, showing the relationship between earthquakes and tectonic activity.

The recent earthquake in L'Aquila, Abruzzo, Italy, magnitude 6.3, occurred along the central Apennine mountain chain, running down the center of the peninsular nation (Figure 12.29).

Earthquakes are frequent at spreading and converging boundaries of lithospheric plates. Transcurrent faults on transform boundaries are also sites of earthquakes.



12.27 Great earthquakes on the Richter scale

The Richter scale describes the quantity of energy released by a single earthquake. Scale numbers range from 0 to 9, but there is really no upper limit other than nature's own energy release limit. For each whole unit of increase (say, from 5.0 to 6.0), the quantity of energy released increases by a factor of 32. The most severe earthquake measured is the Chilean earthquake of 1960. It rated 8.3 on the Richter scale, adjusted to 9.5 by Kanamori. The great San Francisco earthquake of 1906 is now rated as magnitude 7.9.

These mountains are part of a complex collision between the African plate and Eurasian plate. Close to 300 people died and over 1000 were injured, mostly in collapsed buildings.

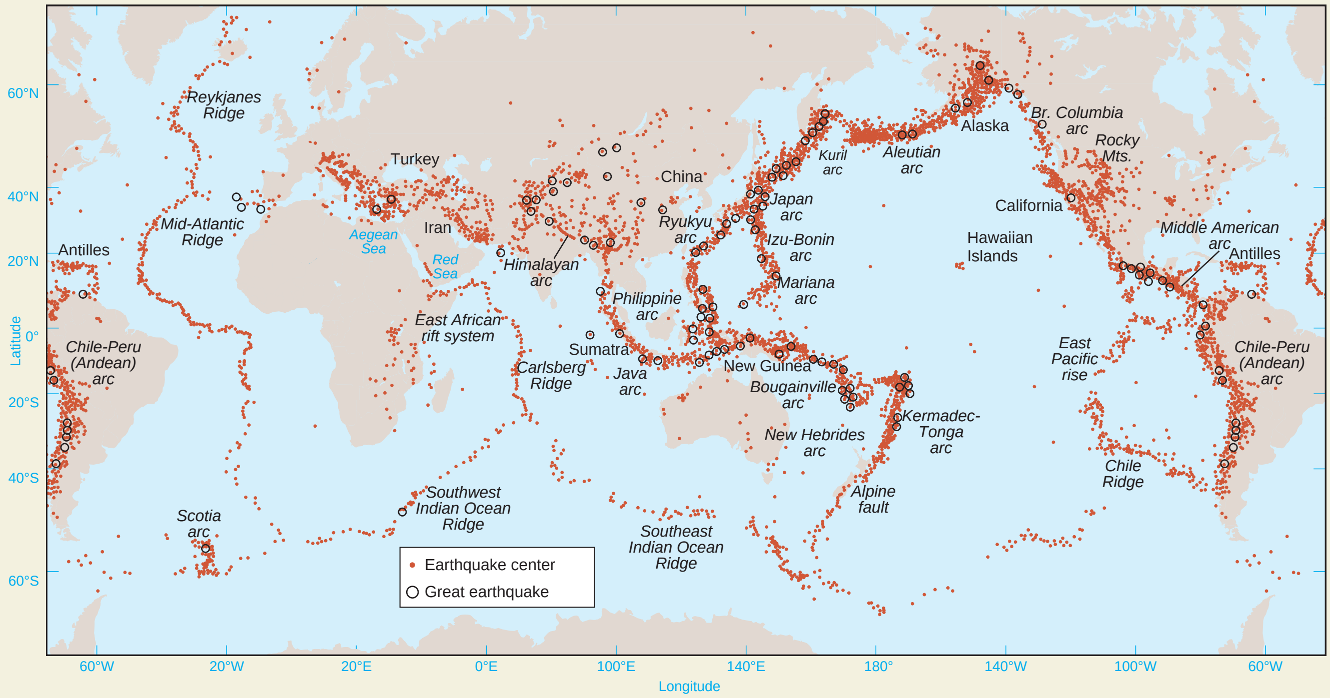
A few earthquake centers are scattered over the continental plates, far from active plate boundaries. We aren't certain why these occur. In many cases, no active fault is visible. For example, the great New Madrid earthquake of 1811 was centered in the Mississippi River floodplain in Missouri. It produced three great shocks in close succession, rated from 8.1 to 8.3 on the Richter scale. The earth movements caused the Mississippi River to change its course and even run backwards in a few stretches for a short time.

EARTHQUAKES ALONG THE SAN ANDREAS FAULT

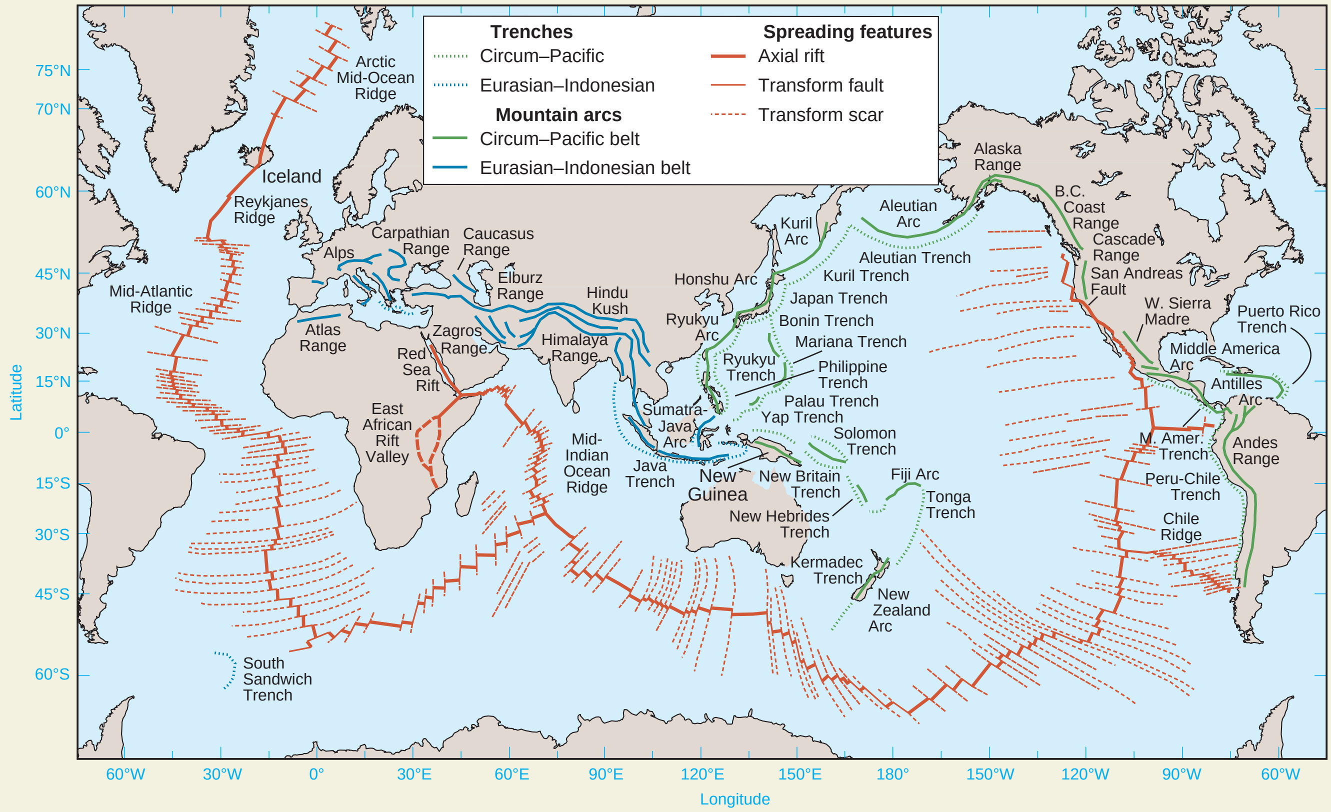
Over a hundred years have passed since the great San Francisco earthquake of 1906. That disaster was

12.28 Earthquake locations and plate boundaries

▼ **Earthquake locations** This world map plots earthquake center locations over a six-year period. Center locations of all earthquakes originating at depths of 0 to 100 km (62 mi) are shown by red dots. Each dot represents a single location or a cluster of centers. Black circles identify centers of earthquakes of Richter magnitude 8.0 or greater during an 80-year period.



▼ **Tectonic features** If you compare the map of earthquake locations with the tectonic features, you can see that seismic activity is associated with lithospheric plate motion. Intense seismic activity occurs along converging lithospheric plate boundaries where oceanic plates are undergoing subduction. Axial rifts also show numerous earthquakes.



12.29 L'Aquila earthquake

The earthquake of April 2009 destroyed many ancient and historic buildings in the city of L'Aquila, Italy, trapping many unfortunate inhabitants in the debris. Damage was widespread in the city and nearby locations.

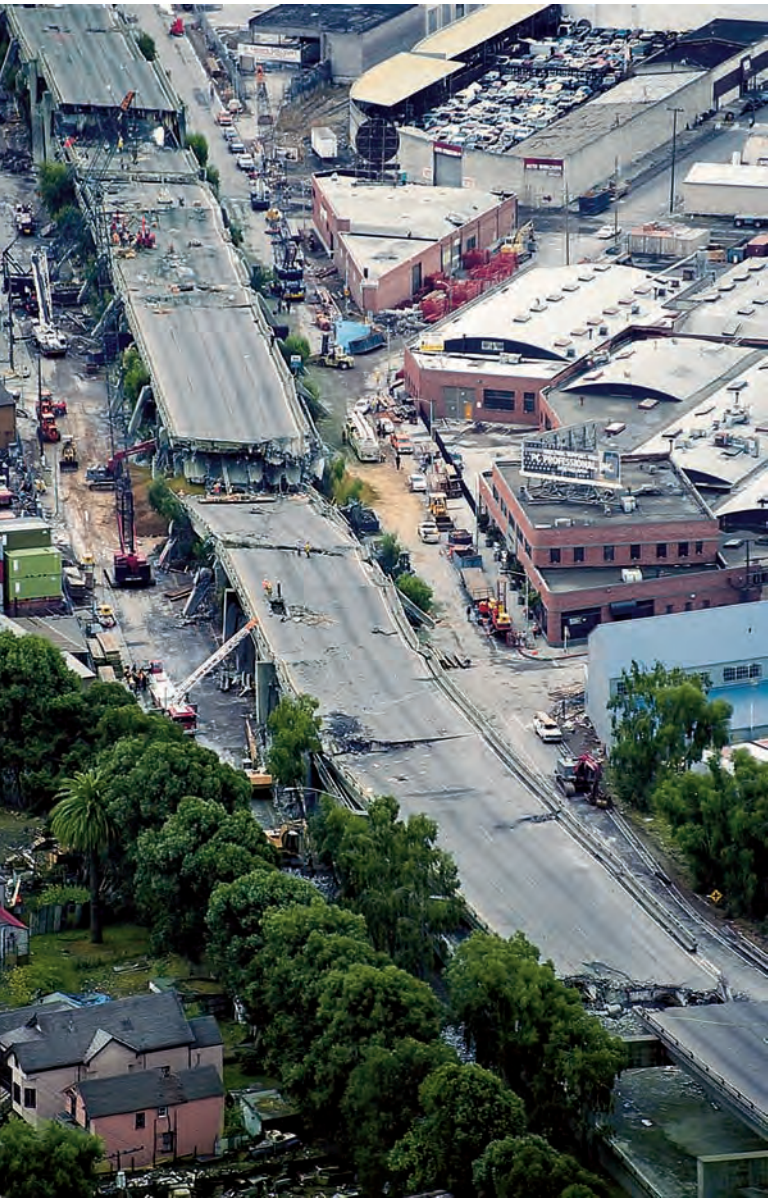
generated by movement on the San Andreas fault. Since then, this sector of the fault has been locked—that is, rocks on the two sides of the fault have been held together without sudden slippage. In the meantime, the two lithospheric plates that meet along the fault have been moving steadily with respect to each other. This means that a huge amount of unrelieved strain energy has already accumulated in the crustal rock on either side of the fault.

The San Andreas fault and related faults in Southern and central California are potential sources of great earthquakes occurring in densely populated regions.

On October 17, 1989, the San Francisco Bay area was severely jolted by an earthquake with a Richter magnitude of 7.1. The earthquake's epicenter was located near Loma Prieta peak, about 80 km (50 mi) southeast of San Francisco, at a point only 12 km (7 mi) from the city of Santa Cruz, on Monterey Bay. The city of Santa Cruz suffered severe structural damage to older buildings. In the distant San Francisco Bay area, destructive ground shaking proved surprisingly severe. Buildings, bridges, and viaducts on landfills were particularly hard hit (Figure 12.30). Altogether, 62 lives were lost in this earthquake, and the damage was estimated to be about $6 billion. In comparison, the 1906 earthquake took a toll of 700 lives and caused property damage equivalent to about 30 billion present-day dollars.

Geologists state that the Loma Prieta slippage, though near the San Andreas fault, probably has not relieved more than a small portion of the strain on the fault. We can't predict when there'll be another major earthquake in the San Francisco region—but it is inevitable that there will be one. As each decade passes, the probability of that event becomes greater.

Along the Southern California portion of the San Andreas fault, a recent estimate placed the likelihood that a very large earthquake will occur within the next 30 years at about 50 percent. In 1992, three severe earthquakes occurred in close succession along active local faults a short distance north of the San Andreas fault in the southern Mojave Desert. They



12.30 Earthquake damage in Oakland, California

This section of the double-decked Nimitz Freeway (Interstate 880) in Oakland, California, collapsed during the Loma Prieta earthquake, crushing 39 people in their cars.

led seismologists to speculate that a major slip on the nearby San Andreas fault is even more likely to occur in the near future.

For residents of the Los Angeles area, an additional serious threat lies in the large number of active faults nearby. Movements on these local faults have produced more than 40 damaging earthquakes since 1800, including the Long Beach earthquakes of the 1930s and the San Fernando earthquake of 1971. The San Fernando earthquake measured 6.6 on the Richter scale and severely damaged structures near the earthquake center.

In 1987 an earthquake of magnitude 6.1 struck the vicinity of Pasadena and Whittier, located within about 20 km (12 mi) of downtown Los Angeles. The Northridge earthquake of 1994, at 6.7 on the Richter scale, produced the strongest ground motions ever recorded in an urban setting in North America and the greatest financial losses from an earthquake in the United States since the San Francisco earthquake of 1906 (Figure 12.31). Sections of three freeways were closed, including the busiest highway in the country, I-5.

A slip along the San Andreas fault, some 50 km (31 mi) to the north of the densely populated region of Los Angeles, will release an enormously larger quantity of energy than these local earthquakes. Although the city is some distance from the fault, it would be severely affected. The intensity of ground shaking might not be much different than the San Fernando earthquake, for example, but it will last much longer and cover a much wider area of the Los Angeles region. The potential for damage and loss of life is enormous.

TSUNAMIS

As we've seen, tsunamis, or *seismic sea waves*, can be caused by major earthquakes, usually centered on a subduction plate boundary. The sudden movement of the seafloor near the earthquake source generates the tsunami wave train. Tsunamis are sometimes called "tidal waves," but since they have nothing to do with tides, the name is quite misleading. The 2004 Indian Ocean tsunami, described in this chapter's opening section, is an example of the devastation that a tsunami can be cause.

Volcanic explosions can also produce strong tsunamis. Krakatoa, a volcanic island in Indonesia, violently erupted in 1883, generating tsunamis that killed more than 36,000 people living in low coastal areas of Sumatra and Java. Underwater slumps of rock and sediment on continental slopes and at volcano margins can also generate large tsunamis.

Landforms and Rock Structure

Over the world's vast land area, you'll see many types of rock and rock structures (Figure 12.32). In many cases, rock structure controls the locations of uplands and lowlands, as well as the routes of streams and rivers.

Rock structure affects landforms because different types of rocks are worn down by erosion at different rates. Some rock types are easily eroded, while others are more resistant. For example, we usually find weak rocks under valleys and strong rocks under

12.31 Northridge earthquake

This parking structure on the campus of California State University at Northridge was badly damaged in the earthquake of January, 1994. Here students return to classes about a month after the earthquake.

hills, ridges, and uplands (Figure 12.33). Among rock types, igneous rocks, sandstone, and conglomerate resist erosion, while claystone, mudstone, and shale erode easily. In humid climates, limestone is a weak rock, but in dry climates, it resists erosion.

As rocks erode, landforms emerge that reflect the resistance of different rock types to erosion. Weak rocks form valleys, while strong rocks form ridges.

LANDFORMS OF HORIZONTAL STRATA AND COASTAL PLAINS

Vast areas of the ancient continental shields are covered by thick sequences of horizontal sedimentary rock layers. These strata were deposited in shallow inland seas at various times in the 600 million years following the end of Precambrian time. After crustal uplift, these areas became continental surfaces.

In arid climates, vegetation is sparse, and weathered rock and soil cover much of the land surface. When rainfall occurs, it is often in the form of torrential downpours from thunderstorms. As the water runs off, it carries sediment downslope, producing erosion. The intense runoff rapidly carves small stream basins that rapidly dissect the landscape into distinctive landforms. Figure 12.34 shows the landforms that result in an arid landscape of flat-lying strata—*cliffs, plateaus, mesas, buttes*, and *badlands*.

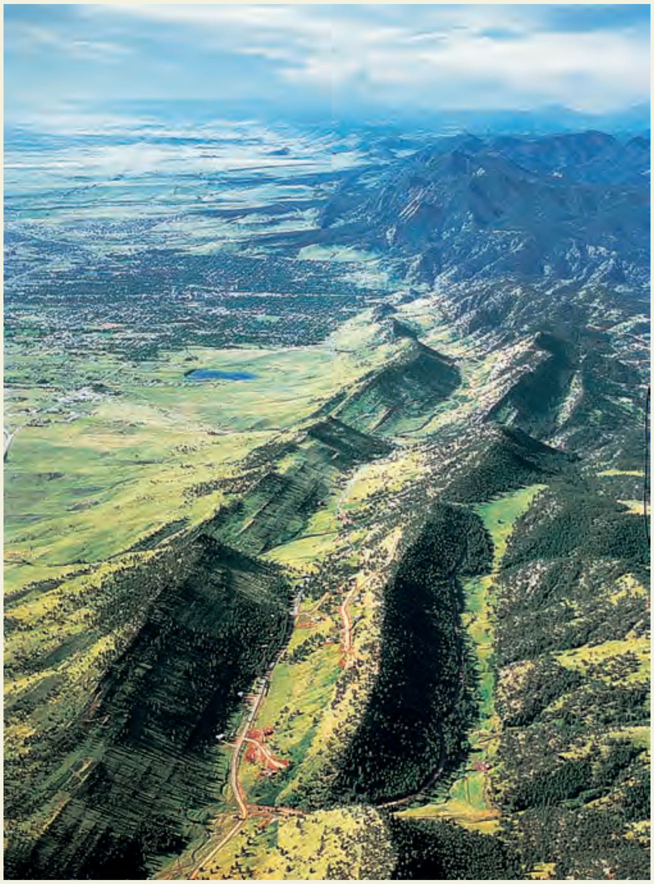
Cliffs, plateaus, mesas, and buttes are landforms of flat-lying strata in arid regions.

Coastal plains are found along passive continental margins that are largely free of tectonic activity. Below these plains, the strata are nearly horizontal, sloping gently toward the ocean. Often these sediments are unconsolidated and offer little resistance to erosion, with clay forming lowlands and sandy ridges forming lines of low hills called *cuestas* (Figure 12.35).

Coastal plains exhibit alternating belts of cuestas and lowlands. Consequent streams flow to the sea across the belts, fed by subsequent streams that drain the cuestas and lowlands.

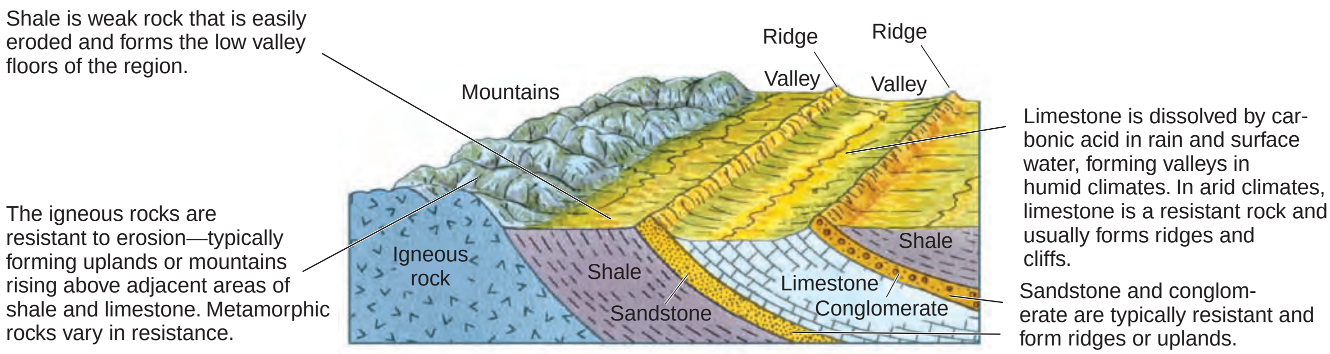
12.32 Landforms and rock structure

▲ Rapley monocline, Utah, shows an upwarp of rock layers with tilted beds cut into flatiron shapes by erosion.



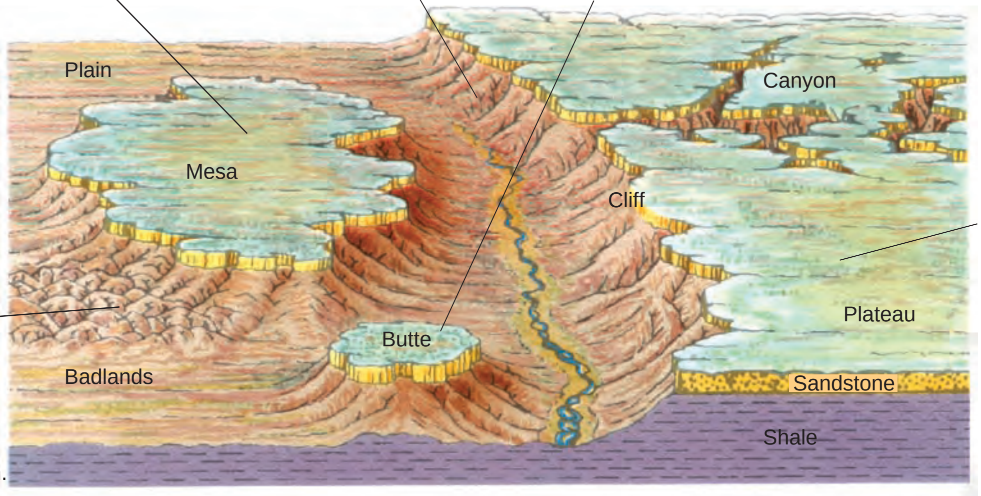
▲ Sandstone formations of the Colorado front range are tilted upward and eroded to form hogback ridges.

◀ Stone Mountain, Georgia, is a striking erosional remnant of resistant igneous rock about 2.4 km (1.5 mi) long that rises 193 m (650 ft) above the surrounding piedmont plain (National Geographic Image Collection).



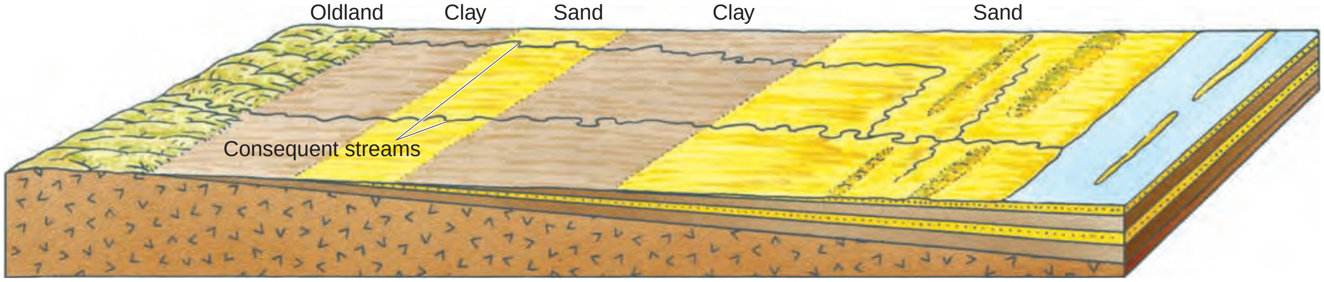
12.33 Landforms and rock resistance

Landforms evolve as weaker rock is eroded, leaving the more resistant rock standing as ridges or mountains.

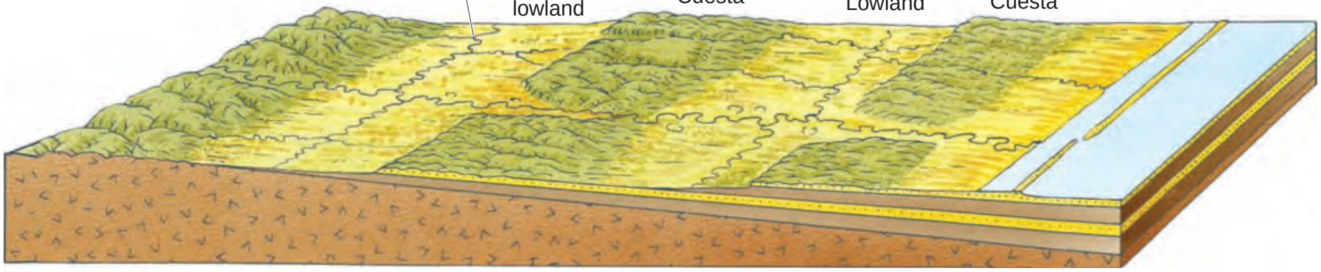


12.34 Arid climate landforms

▼ Streams flow on the new land surface directly seaward, down the gentle slope. These are consequent streams, with courses controlled by the initial slope of the land.



▼ More easily eroded strata (usually clay or shale) are rapidly worn away, making lowlands. Between them rise broad belts of hills called cuestas, which lie above layers of sand, sandstone, limestone, or chalk. The lowland lying between the area of older rock—the oldland—and the first cuesta is called the inner lowland.



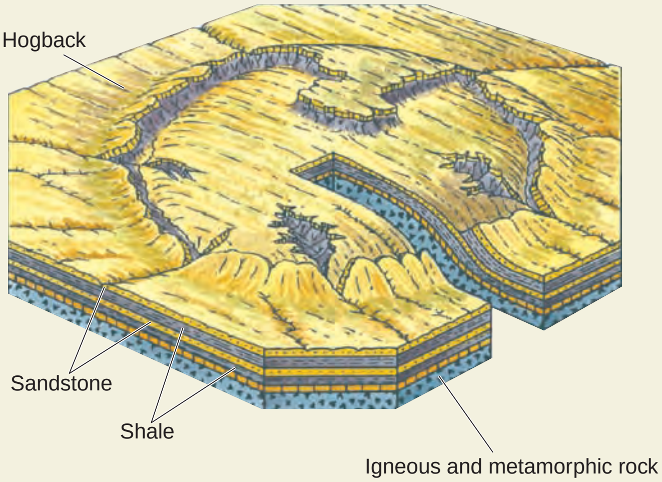
▲ Subsequent streams develop along the lowlands, parallel with the shoreline. They take their position along any belt or zone of weak strata.

12.35 Development of a broad coastal plain

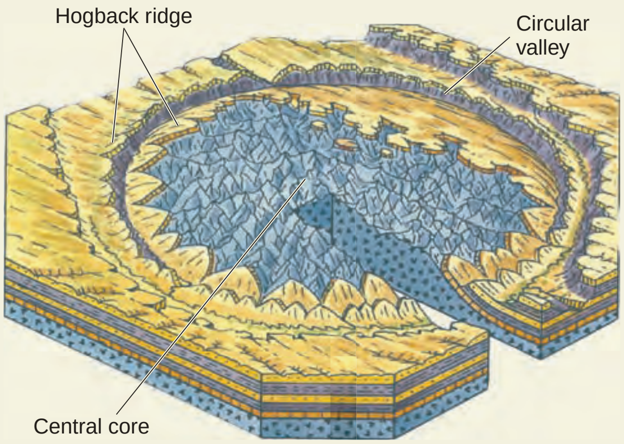
The diagram shows a coastal zone that has recently emerged from beneath the sea, with layers of sediments.

12.36 Erosion of domes

▼ The strata are partially eroded from the summit region of the dome, exposing older strata beneath. Eroded edges of steeply dipping strata form sharp-crested sawtooth ridges called *hogbacks*.



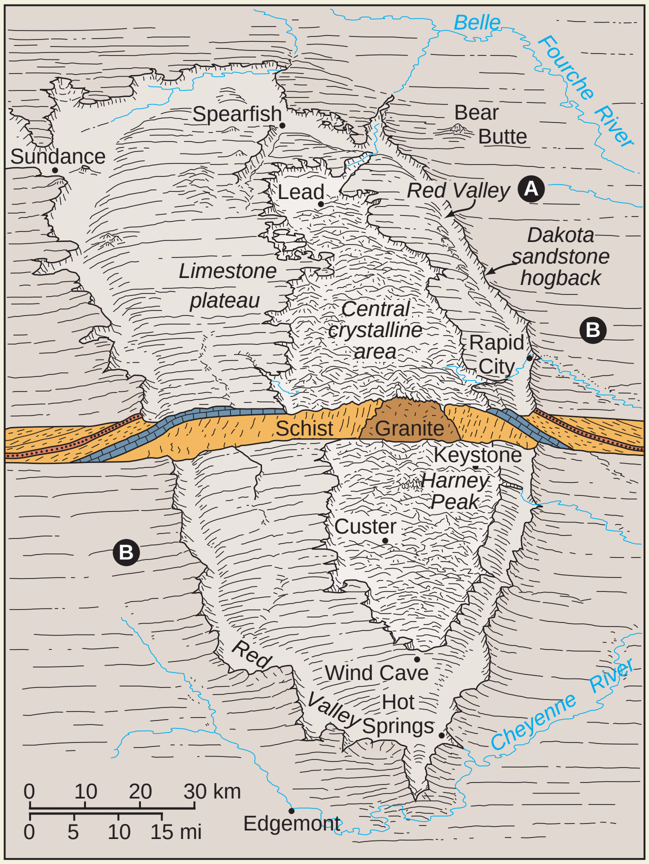
▼ When the last of the strata have been removed, the ancient shield rock is exposed in the central core of the dome. This igneous or metamorphic rock is resistant to erosion and develops a mountainous terrain.



▼ **The Black Hills dome** The Black Hills consist of a broad, flat-topped dome deeply eroded to expose a core of igneous and metamorphic rocks.

A Encircling the dome is the Red Valley, which is underlain by weak shale that is easily washed away.

B On the outer side of the Red Valley is a high, sharp hogback of Dakota sandstone, rising some 150 m (about 500 ft) above the level of the Red Valley. Farther out toward the margins of the dome, the strata are less steeply inclined and form a series of cuestas.



As the sediments first emerge, *consequent streams* drain the gentle slope, heading straight to the ocean. As the belts of less resistant strata erode, *subsequent streams* develop and connect to the consequent streams. The coastal plain of the United States is a major geographical region, ranging in width from 160 to 500 km (about 100 to 300 mi) and extending for 3000 km (about 2000 mi) along the Atlantic and Gulf coasts.

LANDFORMS OF WARPED ROCK LAYERS

In the last section we looked at cases where the sedimentary rock layers are horizontal or gently sloping. But in some regions, rock layers may be warped upward or downward. We saw an example of this earlier in the chapter, when we looked at fold belts, in which rock layers are folded to form anticlines and synclines.

Another distinctive land-mass type is created when strata are forced upward into a dome. **Sedimentary domes** can be found in various places within the covered shield areas of the continents. Igneous intrusions of rocks at great depths may be responsible for some domes. For others, upward motion on deep faults may have been the cause. Figure 12.36 shows how domes are eroded over time to create *hogback ridges* and *circular valleys*.

An example of a large and rather complex dome is the Black Hills dome of western South Dakota and eastern Wyoming (Figure 12.36). At the center of the structure is a mountainous core of upwarped intrusive and metamorphic rocks revealed by erosion. The region is a very attractive summer resort, with richly forested mountains and beautiful open parks in the surrounding valleys. In the northern part of the central core, there are valuable ore deposits. At the historic town of Lead is the fabulous Homestake Mine, one of the world's richest gold-producing mines. The west-central part of the Black Hills consists of a limestone plateau deeply carved by streams. The plateau represents one of the last remaining sedimentary rock layers to be stripped from the core of the dome.

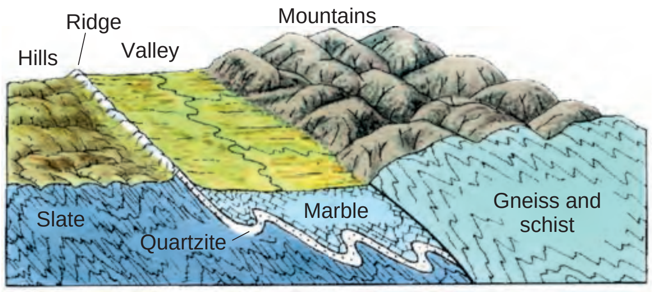
The Black Hills dome of South Dakota is a sedimentary dome that is eroded to produce hogback ridges, a circular valley, and a mountainous core of igneous and metamorphic rocks.

METAMORPHIC BELTS

Earlier in the chapter we saw how fold belts produce a ridge-and-valley landscape when they have been eroded. If the strata have been tightly folded and altered into metamorphic rocks during a continental collision, we'll still get a landscape with a strong grain of ridges and valleys. But because the strata have been exposed to variations in pressure and have been fractured and faulted in different ways, the ridges and valleys won't be as sharp or as straight as in belts of open folds. Even so, the resistant rocks will form highlands and ridges, while the weak rocks will form lowlands and valleys. Figure 12.37 shows typical erosional forms associated with parallel belts of metamorphic rocks, such as schist, slate, quartzite, and marble.

Slate and marble are weak metamorphic rocks that underlie valleys. Schist, gneiss, and quartzite are more resistant and underlie uplands and ridges.

Parts of New England, particularly the Taconic and Green Mountains of eastern New York, western Massachusetts, and Vermont, illustrate the landforms eroded on an ancient metamorphic belt. The larger valleys trend north and south and are underlain by marble. These are flanked by ridges of gneiss, schist, slate, or quartzite.



12.37 Metamorphic belts

Marble forms valleys in this humid environment, while slate and schist make hill belts. Quartzite stands out boldly and may produce conspicuous narrow hogbacks. Areas of gneiss form highlands.

EXPOSED BATHOLITHS AND MONADNOCKS

Batholiths are huge bodies of intrusive igneous rock, formed deep below the Earth's surface. Some of these batholiths are eventually uncovered by erosion and appear at the surface. Because batholiths are typically composed of resistant rock, they are eroded into hilly or mountainous uplands. A good example is the Idaho batholith, a granite mass exposed over an area of about 40,000 sq km (about 16,000 sq mi)—a region almost as large as New Hampshire and Vermont combined. Another example is the Sierra Nevada batholith of California, which makes up most of the high central part of that great mountain block. The Canadian shield includes many batholiths, large and small.

Sugar Loaf Mountain, which rises above the city of Rio de Janeiro, Brazil, is a small granite dome-like projection of a batholith that underlies the area. Such granite projections are often found surrounded by ancient metamorphic rocks into which the granite was intruded.

Figure 12.38 shows the features created when batholiths are exposed at the surface. We call isolated mountains or hills produced in this way **monadnocks**. The name is taken from Mount Monadnock in southern New Hampshire.

GEODISCOVERIES Web Quiz

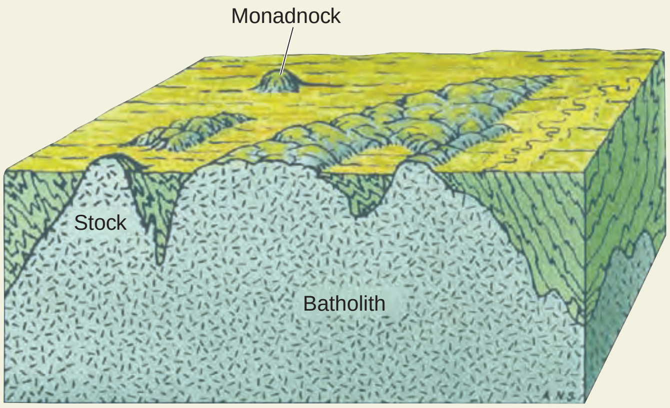
Take a quick quiz on the key concepts of this chapter.

12.38 Batholiths and monadnocks

▲ **Sugar Loaf Mountain** The monolithic rock dome of Sugar Loaf graces the harbor of Rio de Janeiro, Brazil.

▲ **Mount Monadnock** This is the beautiful New Hampshire mountain for which all monadnocks are named (National Geographic Image Collection).

▶ **Exposed batholiths** Batholiths appear at the land surface after long-continued erosion has removed thousands of meters of overlying rocks. Small projections of the granite intrusion appear first and are surrounded by older rock. Larger projections are sometimes roots of ancient volcanoes called stocks.



A Look Ahead

In the last two chapters, we have surveyed the Earth's crust and the geologic processes that shape it. We have seen how the rocks and minerals of the Earth are formed in the cycle of rock transformation, and we have seen how plate tectonics powers that cycle and provides the geographical pattern of mountain ranges, ocean basins, and continental shields occurring on the Earth's surface. We have examined initial landforms of volcanic and tectonic activity, and looked at how erosion acting on rocks of different resistances has produced the landscapes of mountains, valleys, and plains that we see today.

In our next chapters, we will zoom in from the broad scale of landscapes to a finer scale at which individual landform-creating processes act. First will be the processes of weathering, which breaks rock into small particles, and mass wasting, which moves them downhill as large and small masses under the influence of gravity. Then we will turn to running water in two chapters that describe the behavior of rivers and streams and their work in shaping landforms. In our two final chapters, we will examine landforms created by waves, wind, and glacial ice.

GEODISCOVERIES Web Links

Tour volcanoes, from Vesuvius to Kilauea, at this chapter's web links. Spot new earthquakes and find out more about earthquake and tsunami hazards. Tour field sites from New York to New Mexico to view rock structures. Learn more about the Black Hills dome and Idaho batholith. It's all ready for you to explore.

IN REVIEW VOLCANIC AND TECTONIC LANDFORMS

- A **tsunami** is a great ocean wave created by an earthquake or volcanic explosion. It causes a rapid and temporary rise of sea level that floods coastal regions and retreats, causing great destruction. The Indian Ocean tsunami of 2004 sent a swath of death from its source in the Java trench off Sumatra to the shorelines of Thailand, India, and even Africa.
- **Landforms** are the surface features of the land, and **geomorphology** is the scientific study of landforms.
- *Endogenic processes* of volcanic and tectonic activity shape *initial landforms*, while *exogenic processes*, such as erosion and deposition by running water, waves, wind, and glacial ice, sculpt *sequential landforms*. Endogenic processes are ultimately powered by *radiogenic heat*.
- **Volcanoes** are landforms marking the eruption of lava at the Earth's surface. Volcanic eruptions are a very severe form of environmental hazard. Most volcanoes are located near subduction zones and on axial rifts.
- **Stratovolcanoes**, formed by the emission of thick, gassy, felsic lavas and showers of *tephra*, have steep slopes and tend toward explosive eruptions that can form *calderas*. Most active stratovolcanoes lie along the Pacific rim, where subduction of oceanic lithospheric plates is occurring. Erosion of stratovolcanoes ultimately leaves a landscape of *lava mesas*, *volcanic necks*, and *dikes*.
- **Shield volcanoes** result from eruption of basaltic (mafic) lavas. Because these lavas are more fluid and contain little gas, they form broadly rounded domes.
- At a *hotspot*, an upwelling plume of basaltic magma creates shield volcanoes. As an oceanic lithospheric plate moves over the hotspot, a chain of volcanic islands, like the Hawaiian chain, is formed. Hotspots under continents build large accumulations of *flood basalts*. Some basaltic volcanoes occur along the mid-oceanic ridge.
- As shield volcanoes become extinct and erode, their rounded forms are replaced by steep canyons and sharp ridges.
- Where hot rock material close to the surface heats ground water to high temperatures, we find *hot springs* and *geysers*.
- Remote sensing of volcanoes reveals their distinctive shapes and appearances. Satellite instruments can detect and monitor volcanic eruptions.
- The two forms of tectonic activity are compression and extension. *Compression* occurs at lithospheric plate collisions. *Extension* occurs with continental and oceanic rifting.
- At first, compression produces **folds–anticlines** (upbends) and **synclines** (troughs).
- Eroded fold belts create a **ridge-and-valley landscape** as weaker rocks become valleys and stronger rocks form mountain ridges. Where an anticline contains weak rocks at its core, erosion may create an *anticlinal valley*. Synclinal mountains occur where resistant rocks in the center of a syncline are exposed.
- **Faults** are fractures in crustal rock created when different crustal parts move in different directions. Movement occurs on the *fault plane*.
- *Normal faults* are commonly produced by crustal rifting. They produce *fault scarps, grabens*, and *horsts*.
- Transcurrent faults occur where crustal parts move horizontally past each other. The San Andreas fault is an example.
- *Reverse* and *overthrust faults* are created by compression.
- The East African Rift Valley is a good example of continental-scale extension and normal faulting. It is a system of branching grabens flanked by fault scarps arising from the first stages of continental rupture.
- Earthquakes occur when rock layers, bent by tectonic activity, suddenly fracture and move, creating *seismic waves*. The energy released by an earthquake is measured by the Richter scale.
- Many earthquakes are associated with tectonic features. But some large earthquakes occur within continental plates, far from plate boundaries.
- The San Andreas fault is a major transcurrent fault located near two great urban areas—Los Angeles and San Francisco. The potential for a severe earthquake on this fault is high, and the probability of a major Earth movement increases every year.
- Major earthquakes and volcanic eruptions can cause *tsunamis* that travel from their source in ever-widening circles. Large tsunamis can create vast destruction and take many lives.
- Rock structure affects landforms because some rock types are more resistant to erosion than others. Weak rocks form valleys, and strong rocks form hills, ridges, and mountains.
- In arid regions of horizontal strata, resistant rock layers produce vertical *cliffs* separated by gentler slopes on less resistant rocks. *Plateaus, mesas*, and *buttes* are formed.
- On gently sloping coastal plain strata, erosion removes weaker strata to form lowlands, leaving more resistant strata to form *cuestas*.
- Where rock layers are warped upward into a **dome**, erosion produces a circular arrangement of rock layers outward from the center of the dome. Resistant strata form *hogbacks*, and weaker rocks form lowlands. Igneous rocks are often revealed in the center.

- In fold belts, the sequence of *synclines* and *anticlines* brings a linear pattern of rock layers to the surface. Resistant strata form ridges, and weaker strata form valleys.
- In metamorphic belts, weak layers of shale, slate, and marble underlie valleys, while gneiss and schist form uplands. Quartzite stands out as a ridge-former.
- Exposed batholiths are often composed of uniform, resistant igneous rock and produce mountainous regions. **Monadnocks** of intrusive igneous rock stand up above a plain of weaker rocks.

KEY TERMS

tsunami, p. 406
landforms, p. 407
geomorphology, p. 407
volcano, p. 408
stratovolcano, p. 410
shield volcano, p. 411
fold, p. 419
ridge-and-valley landscape, p. 419
fault, p. 420
normal fault, p. 421
transcurrent fault, p. 421
earthquake, p. 425
coastal plain, p. 429
sedimentary dome, p. 433
monadnock, p. 433

REVIEW QUESTIONS

1. How and where did the Indian Ocean tsunami of 2004 arise? What areas were affected?
2. Define the terms *landform* and *geomorphology*.
3. Explain the difference between initial and sequential landforms, defining and using the terms *endogenic* and *exogenic*.
4. What is a *volcano*? Why are volcanic eruptions environmental hazards?
5. How is the global pattern of volcanic activity related to plate tectonics?
6. What is a *stratovolcano*? What is its characteristic shape, and how is it formed?
7. What is a *shield volcano*? How is it different from a stratovolcano? Give an example of a shield volcano.
8. Do shield volcanoes erode differently from stratovolcanoes? Compare the types of landforms that result as they erode away.
9. What is a *hotspot*? What produces it? What landforms result from a hotspot on land? in the ocean?
10. Describe the stages in the life cycle of a basaltic shield volcano of the Hawaiian type. How did the Hawaiian seamount chain arise?
11. What is the origin of hot springs and geysers? What is the source of steam used in generating geothermal power?
12. How is remote sensing used to study volcanoes?
13. How does a *ridge-and-valley landscape* arise? Explain the formation of the ridges and valleys. Where in the United States can you find a ridge-and-valley landscape?
14. What is a *normal fault*? What landforms are produced by normal faults?
15. How does a *transcurrent fault* differ from a normal fault? What landforms would you expect to find along a transcurrent fault? How are transcurrent faults related to plate tectonic movements?
16. Identify and describe two types of faults produced by crustal compression.
17. Describe the East African Rift Valley system as an example of crustal extension. Include the terms *normal fault* and *graben* in your answer.
18. What is an *earthquake*, and how does it arise? What scale is used to describe the power of an earthquake? In what plate tectonic settings do earthquakes occur?
19. Briefly summarize the geography and recent history of the San Andreas fault system in California. What are the prospects for future earthquakes along the San Andreas fault?
20. Why is there often a direct relationship between landforms and rock structure?
21. Which of the following types of rocks—shale, limestone, sandstone, conglomerate, igneous rocks—tend to form lowlands? uplands?
22. Explain the formation of cliffs, plateaus, mesas, buttes, and badlands in arid landscapes of horizontal strata.
23. What is a *coastal plain*? Describe the strata you might find on a coastal plain. Identify two landforms found on coastal plains.
24. What types of landforms are associated with sedimentary domes? How are they formed? Provide an example of an eroded sedimentary dome and describe it briefly.
25. Which of the following types of rocks—schist, slate, quartzite, marble, gneiss—tend to form lowlands? uplands?

VISUALIZING EXERCISES

1. Sketch a cross section through a normal fault, labeling the fault plane, upthrown side, downthrown side, and fault scarp.
2. Sketch a cross section through a fold belt showing rock layers in different colors or patterns. Label anticlines and synclines.
3. Identify and sketch a typical landform of flat-lying rock layers found in an arid region.
4. What types of landforms and drainage patterns develop on batholiths? Provide a sketch of a batholith. What is the difference between a batholith and a monadnock?

ESSAY QUESTIONS

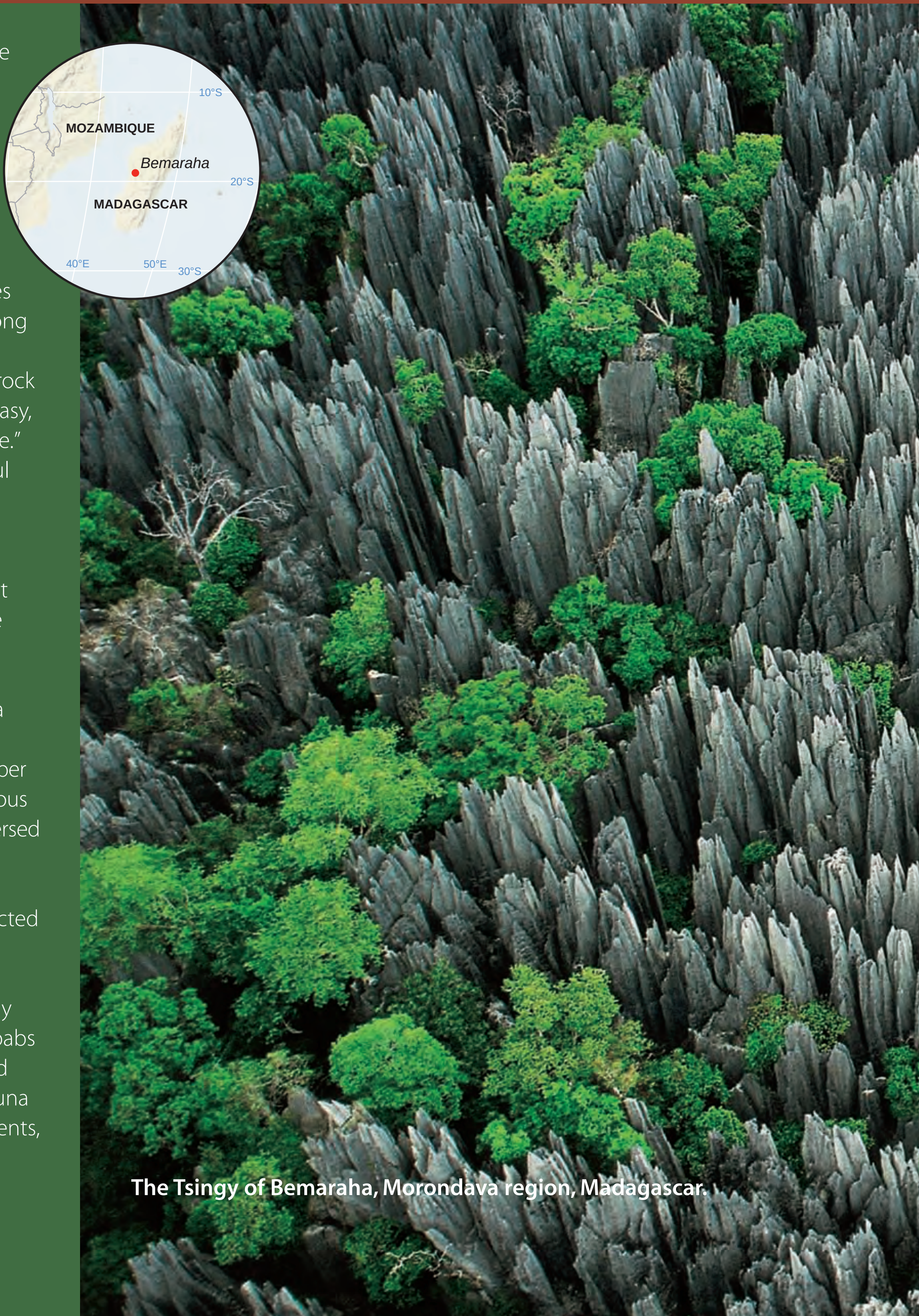
1. Write a fictional news account of a volcanic eruption. Select a type of volcano—composite or shield—and a plausible location. Describe the eruption and its effects as it was witnessed by observers. Make up any details you need, but be sure they are scientifically correct.
2. Imagine the following sequence of sedimentary strata—sandstone, shale, limestone, and shale. What landforms would you expect to develop in this structure if the sequence of beds is (a) flat-lying in an arid landscape; (b) slightly tilted as in a coastal plain; (c) folded into a syncline and an anticline in a fold belt; (d) fractured and displaced by a normal fault? Use sketches in your answer.
3. A region of ancient mountain roots, now exposed at the surface, includes a central core of plutonic rocks surrounded on either side by belts of metamorphic rocks and foreland folds. What landforms would you expect for this landscape and why?

Chapter 13
Weathering and Mass Wasting

These sharp pinnacles, some as tall as 30 m (95 ft), are formed by solution of pure limestone exposed to the natural carbonic acid in rainwater. The pinnacles, sometimes referred to as a "rock forest," are thought to form when rainwater penetrates and dissolves the limestone along vertical joints, dissecting the bedrock into tall columns. The rock forest is called "tsingy" in Malagasy, which means "walking on tiptoe." The tsingy is a rare but beautiful form of *karst*—a landscape of unique landforms created by solution of limestone.

The tsingy of Bemahara is part of a UNESCO World Heritage site located on a limestone plateau in west-central Madagascar. The climate is tropical wet-dry, with a long dry season and a short, but very wet rainy season in December to March. The dense, dry deciduous forests of the region are interspersed with grasslands maintained by burning for cattle grazing.

The tsingy area is well-protected because of its inaccessibility—which is also a reason that the tsingy flora and fauna are poorly known. Wild bananas and baobabs are among the tree species, and among the animals, the rare fauna includes amphibians, birds, rodents, and lemurs. Many species are endemics.



The Tsingy of Bemaraha, Morondava region, Madagascar.

Weathering and Mass Wasting

Rock weathers into fragments that can be transported by gravity or moved by the freezing and thawing of water. What are the processes that turn hard rocks into rubble and make them soft and weak? How does gravity act on wet and dry earth materials to make them move downhill? What is permafrost, and how is it involved with creating distinctive arctic landforms? How will global warming affect the arctic? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

The Madison Slide

For some 200 vacationers camping in a deep canyon on the Madison River just downstream from Hebgen Lake, not far west of Yellowstone National Park, the night of August 17, 1959, began quietly, with almost everyone safely bedded down in their tents or camping trailers. Up to a certain point, it was everything a great vacation should be—that point in time was 11:37 P.M., Mountain Standard Time. At that moment, not one but four terrifying forms of disaster were set loose on the sleeping vacationers—earthquake, landslide, hurricane-force wind, and raging flood. The earthquake, which measured 7.1 on the Richter scale, was the cause of it all. The first shocks, lasting several minutes, rocked the campers violently in their trailers and tents. Those who struggled to go outside could scarcely stand up, let alone run for safety.

Then came the landslide. A dentist and his wife watched through the window of their trailer as a mountain seemed to move across the canyon in front of them, trees flying from its surface like toothpicks in a gale. Then, as rocks began to bang against the sides and top of their trailer, they got out and raced for safer ground. Later, they found that the slide had stopped only a few car lengths from the trailer. Pushed by the moving mountain was a vicious blast of wind. It swept upriver, tumbling trailers end over end.

Then came the flood. Two women schoolteachers, sleeping in their car only a few feet from the riverbank, awoke to the violent shaking of the earthquake. Puzzled and frightened, they started the engine and headed for higher ground. As they did so, they were greeted by a great roar coming from the mountainside above and behind them. An instant later, their car was completely engulfed by a wall of water that surged up the riverbank, then quickly drained back. Although the two women managed to drive the car to safety, others were not so lucky.

The Madison Slide, triggered by an earthquake, sent a huge mass of rock rubble into the canyon of the Madison River. By damming the river, the slide formed Earthquake Lake.

After the first surge of water, generated as the landslide mass hit and blocked the river channel, the river began a rapid rise. Great surges of water were overtopping the Hebgen Dam, located upstream, as earthquake aftershocks rocked the water of Hebgen Lake back and forth along its length. In the darkness of night, the terrified survivors of the flood had no idea what was happening or why. The water had risen 10 m (about 30 ft) above ground level in just minutes.

The *Madison Slide*, as the huge earth movement was later named, had a bulk of 28 million m^3 (37 million yd^3) of rock (Figure 13.1). It consisted of a chunk of the south wall of the canyon, measuring over 600 m (about 2000 ft) in length and 300 m (about 1000 ft) in thickness. The mass descended more than half a kilometer (about a third of a mile) to the Madison River, its speed estimated at 160 km (100 mi) per hour. Pulverized into rock debris, the slide crossed the canyon floor, its momentum carrying it over 120 m (about 400 ft) in vertical distance up the opposite canyon wall. Acting as a huge dam, the slide caused the Madison River to back up, forming a new lake. In three weeks' time, the lake was nearly 100 m (330 ft) deep. Today it is a permanent feature, named Earthquake Lake.

The Madison Slide is an example of *mass wasting*—the downhill motion of rock and soil under the influence of gravity. Although a rock avalanche is very rapid, other types of mass wasting are slower and less dramatic. However, they all act to carve and shape the landscape into distinctive landforms.

GEODISCOVERIES **The Impact of Earthquakes**
Review this video from Chapter 12 for a tour of the Madison Slide disaster site.

13.1 The Madison Slide

▶ Seen from the air, the Madison Slide forms a great dam of rubble across the Madison River canyon. The slide was triggered by an earthquake.

▼ The landslide missed these cottages, but the rising lake soon floated them away.

Weathering

In the last few chapters, we've looked at the Earth's crust—its mineral composition, its lithospheric plates, and the landforms created by volcanic and tectonic activity. Now let's examine the shallow surface layer in which life exists. We'll look first at how rocks are softened and how they break up. Later, we'll see how the resulting rock materials move downhill under the force of gravity.

Weathering is the combined action of physical weathering, in which rocks are fractured and broken, and chemical weathering, in which rock minerals are transformed to softer or more soluble forms.

Weathering describes the combined action of all processes that cause rock to disintegrate physically and decompose chemically because of exposure near the Earth's surface. There are two types of weathering. In **physical weathering**, rocks are fractured and broken apart. In **chemical weathering**, rock minerals are transformed from types that were stable when the rocks were formed to types that are now stable at the temperatures and pressures of the Earth's surface. Weathering produces **regolith**—a surface layer of weathered rock particles that lies above solid, unaltered rock—and also creates a number of distinctive landforms.

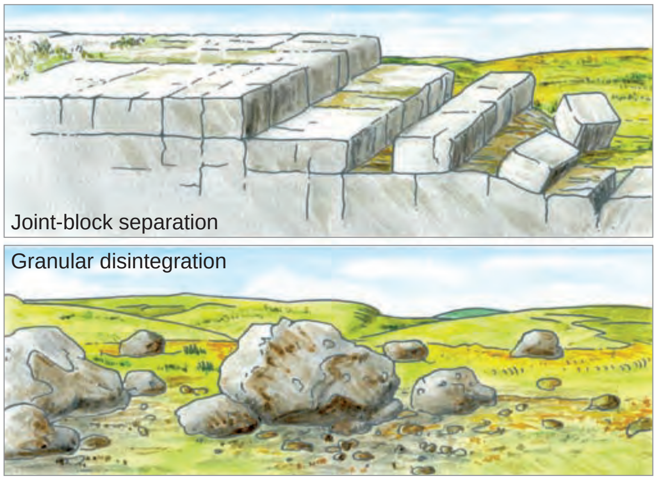
FROST ACTION

One of the most important physical weathering processes in cold climates is *frost action*. Unlike most liquids, water expands when it freezes. If you've ever left a bottle of water chilling in the freezer overnight only to find a mass of ice surrounded by broken glass the next morning, you've seen this phenomenon first-hand. As water in the pore spaces of rocks freezes and thaws repeatedly, expansion can break even extremely hard rocks into smaller fragments (Figure 13.2).

Water penetrates fractures in bedrock. These fractures, called *joints*, are created when rocks are exposed to heat and pressure, then cool and contract. Joints typically occur in parallel and intersecting planes, creating

13.2 Frost cracking

Repeated growth of ice crystals in cracks during freeze–thaw cycles can break open rocks. This frost-cracked boulder is in the San Andres Mountains of New Mexico (National Geographic Image Collection).



13.3 Bedrock disintegration

Joint-block separation and *granular disintegration* are two common forms of bedrock disintegration.

natural surfaces of weakness in the rock (Figure 13.3). Frost action then causes *joint-block separation*. Water invades sedimentary rocks along their stratification planes, or *bedding planes*. Joints often cut bedding planes at right angles, and relatively weak stresses will separate the joint blocks. Water can also freeze between mineral grains in igneous rocks, separating the grains to create a fine gravel or coarse sand of single mineral particles. This process is called *granular disintegration*.

All climates that have a winter season with cycles of freezing and thawing show the effects of frost action. On high mountain summits and in the arctic tundra, large angular rock fragments can accumulate in a layer that completely blankets the hard rock underneath. The result is a *rock sea*, or *rock glacier* that is constantly churned by frost action (Figure 13.4). On cliffs of bare rock, frost action can detach angular blocks that fall to the base of the cliff. These loose fragments are called *talus*, and if block production is rapid, a *talus slope* of coarse rubble forms (Figure 13.4).

When water freezes in bedrock joints and bedding planes, it expands and can split rocks apart. Talus slopes of angular rock fragments accumulate below cliffs and outcrops exposed to such frost action.

SALT-CRYSTAL GROWTH

A similar physical weathering process occurs in dry climates. *Salt-crystal growth* in rock pores can disintegrate rock, and this process carves out many of the niches, shallow caves, rock arches, and pits seen in sandstones of arid regions. During long drought periods, ground water moves to the rock surface by *capillary action*—a process in which the water's surface tension causes it to be drawn through fine openings and passages in the rock. The same surface tension gives water droplets their round shape. The water evaporates from the sandstone pores, leaving behind tiny crystals of minerals like halite (sodium chloride), calcite (calcium carbonate), or gypsum (calcium sulfate). Over time, the force of these growing crystals breaks the sandstone apart, grain by grain.

Rock at the base of cliffs is especially susceptible to salt-crystal growth (Figure 13.5). Salt crystallization also damages masonry buildings, concrete sidewalks, and streets. Salt-crystal growth occurs naturally in arid and semiarid regions, but in humid climates, rainfall dissolves salts and carries them downward to ground water.

In arid climates, slow evaporation of ground water from outcropping sandstone surfaces causes the growth of salt crystals. Crystal growth breaks the rock apart grain by grain, producing niches, shallow caves, and rock arches.

OTHER PHYSICAL WEATHERING PROCESSES

Unloading, or *exfoliation*, is another widespread process that weathers rocks. Rock that forms deep beneath the Earth's surface is compressed by the rock above. As the upper rock is slowly worn away, the pressure is reduced, so the rock below expands slightly. This expansion makes the rock crack in layers parallel to the surface, creating a *sheeting structure*. In massive rocks like granite or marble, thick, curved layers or shells of rock peel free from the parent mass below, producing an *exfoliation dome* (Figure 13.6). Thermal expansion from hot fires can also generate or enhance exfoliation.

Although first-hand evidence is lacking, it seems likely that daily temperature changes also break up surface layers of rock that have already been weakened by other weathering agents. Most rock-forming minerals expand when heated and contract when cooled, so intense heating by the Sun during the day alternating with nightly cooling exerts disruptive forces on the rock.

Plant roots can also break up rock as they wedge joint blocks apart. You've probably seen concrete sidewalk blocks that have been fractured and uplifted by the growth of tree roots. This process also happens when roots grow between rock layers or joint blocks.

CHEMICAL WEATHERING

Chemical reactions can turn rock minerals into new minerals that are softer and bulkier and therefore easier to erode. And some acids can dissolve minerals, washing them away in runoff. These processes are examples of *chemical weathering*.

13.4 Rock fragments in motion

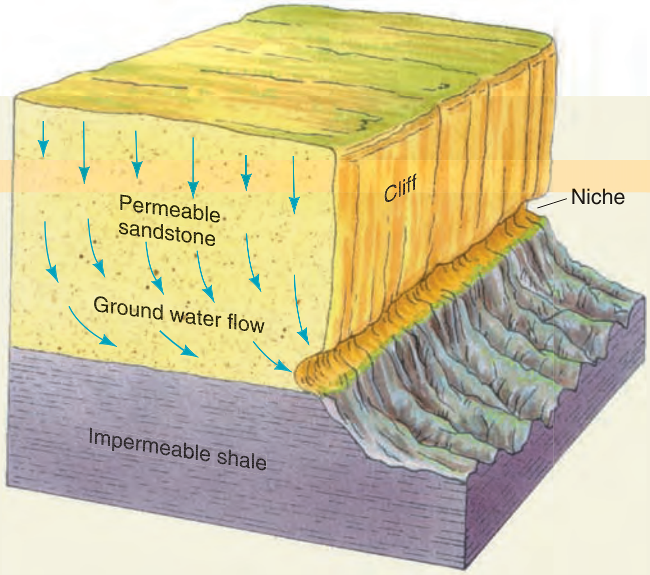
▶ **Rock glacier** Where blocky sandstones outcrop on slopes, frost action and gravity can produce moving fields of angular blocks that are sometimes called *rock glaciers*. Although the more intense freeze–thaw cycles of the Ice Age probably formed this example, the lack of vegetation or even lichens suggests that this rock mass is still moving. From the ridges of eastern Pennsylvania (National Geographic Image Collection).

▼ **Talus cones** Frost action has caused these cliffs to shed angular blocks of rock that accumulate in *talus cones*. In the foreground is the shore of Lake Louise in the Canadian Rockies.

EYE ON THE LANDSCAPE **What else would the geographer see?** An obvious feature is the sedimentary rock beds (A) that form the cliffs. In this case, they are ancient sedimentary rocks that were thrust over and above younger rocks of the plains during an arc-continent collision. At (B) you can see a small, shrunken glacier, coated with gray blocks of talus.

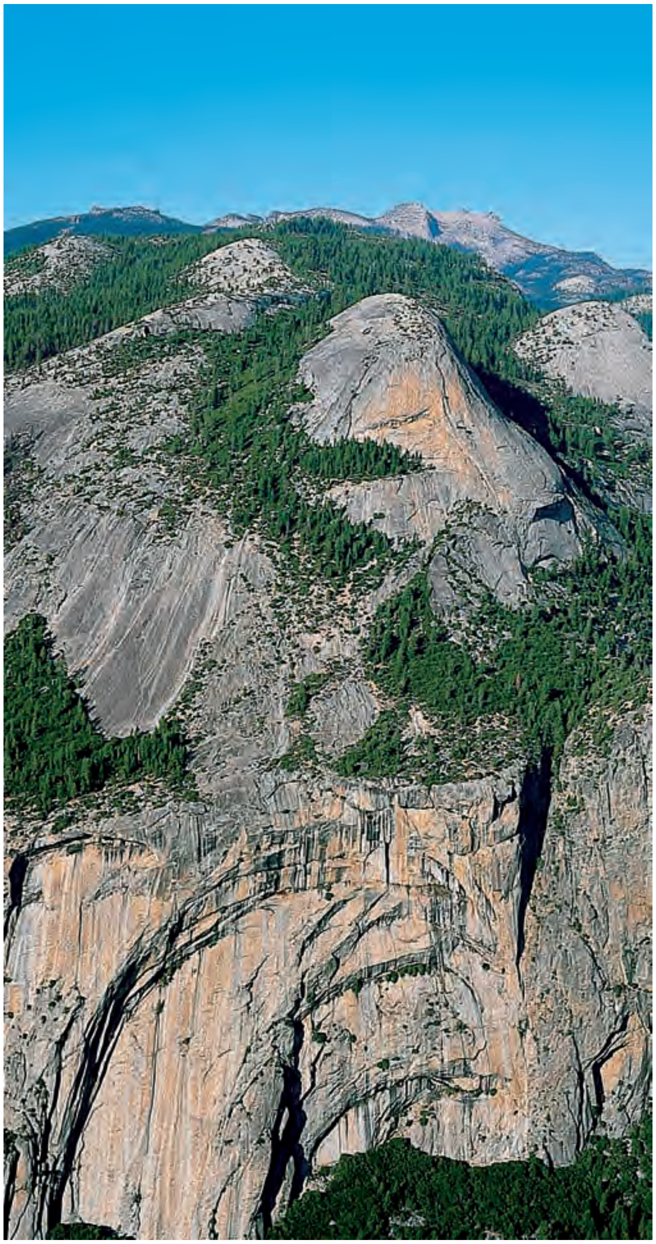
13.5 Salt-crystal growth

▶ **Niche formation** In dry climates there is a slow seepage of water from the cliff base. Salt-crystal growth separates the grains of permeable sandstone, breaking them loose and creating a *niche*.



◀ **Cliff dwellings** Many of the deep niches or cave-like recesses formed by salt-crystal growth in the southwestern United States were occupied by Native Americans. Their cliff dwellings gave them protection from the elements and safety from armed attack. This is the White House Ruin, a large niche in sandstone in the lower wall of Canyon de Chelly, Arizona (National Geographic Image Collection).

▶ **Sandstone pillars** Where ground water is close to the surface, it can be wicked up through porous sandstone by evaporation. As the water evaporates, tiny salt crystals grow and break the sand grains loose. This erodes the rock close to the ground, leaving less weathered rock above perched on a pillar. Nubian sandstone, Karnasai Valley, Chad.



13.6 Exfoliation

As the burden of overlying rock layers is removed by erosion, rock expands and can fracture in sheets parallel to the rock surface. Exfoliation sheets are readily visible in the lower part of this photo of North Dome and Royal Arches in Yosemite National Park, California. Here, individual rock sheets may be as thick as 15 m (50 ft). When sheeting structure forms over the top of a single large knob or hill of massive rock, an *exfoliation dome* is produced. Domes are among the largest of the landforms shaped by weathering.

13.7 Granular disintegration of granite

Although there is not much rainfall in dry climates, water still penetrates the granite along planes between crystals of quartz and feldspar. Chemical weathering breaks individual feldspar grains away from the main mass of rock, leaving the rounded forms shown. The grain-by-grain breakup forms a fine desert gravel consisting largely of quartz and partially decomposed feldspar crystals. Alabama Hills, Owens Valley, California.

Chemical reactions proceed more rapidly at warmer temperatures, so chemical weathering is most effective in the warm, moist climates of the equatorial, tropical, and subtropical zones. There, *hydrolysis* and *oxidation*, working over thousands of years, have decayed igneous and metamorphic rocks down to depths as great as 100 m (about 300 ft). The decayed rock material is soft, clay-rich, and easily eroded. In dry climates, oxidation and hydrolysis weather exposed granite to produce many interesting boulder and pinnacle forms (Figure 13.7).

Acid action is another form of chemical weathering. *Carbonic acid* is a weak acid formed when carbon dioxide dissolves in water. It is found in rainwater, soil water, and stream water, and it slowly dissolves some types of minerals. Carbonate sedimentary rocks, such as limestone and marble, are particularly susceptible to carbonic acid action, producing many interesting surface forms. Carbonic acid in ground water dissolves limestone, creating underground caverns and distinctive landscapes that form when these caverns collapse.

In urban areas, sulfur and nitrogen oxides pollute the air. When these gases dissolve in rainwater, we get acid precipitation, which rapidly dissolves limestone and chemically weathers other types of building stones, stone sculptures, building decorations, and tombstones (Figure 13.8). Soil acids that form as microorganisms digest organic matter also rapidly dissolve basaltic lava in the wet low-latitude climates (Figure 13.9).

In chemical weathering, the minerals that make up rocks are chemically altered or dissolved. The end products are often softer and bulkier forms that are more susceptible to erosion and mass movement.

13.8 Chemical weathering of tombstones

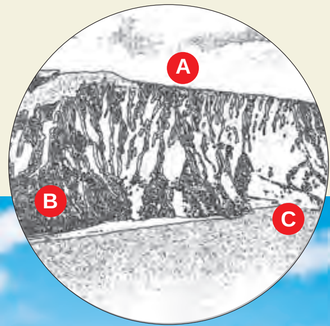
▲ This marble tombstone is from a burying ground in Massachusetts. It has been strongly weathered, weakening the lettering (National Geographic Image Collection).

▲ This marker is made of slate and is much more resistant to weathering. The engraved letters are clear and sharp, even though the tombstone is almost a century older (National Geographic Image Collection).

13.9 Solution weathering of basalt

The steep walls of many narrow coastal ravines are deeply grooved by chemical weathering of the basaltic lava on the Napali Coast, Kauai, Hawaii.

EYE ON THE LANDSCAPE **What else would the geographer see?** Kauai is the oldest of the Hawaiian Islands. The rounded dome shape of the island, shown by its outline (A), is characteristic of shield volcanoes. The red-brown colors of the soil exposed on lower slopes (B) are from iron oxides and indicate Oxisols. Pocket beaches and an arch at (C) are products of wave action.



Mass Wasting

So far, we've looked at a selection of processes that alter rock chemically or break them into fragments. But what happens to these pieces once they've been loosened from the parent rock? The rock fragments are subjected to gravity, running water, waves, wind, and the flow of glacial ice. In this chapter we'll concentrate on the effect of gravity, and we'll return to the other effects in the following chapters.

Gravity pulls down continuously on all materials across the Earth's surface. Unweathered rock is usually so strong and well supported that it remains fixed in place. But when a mountain slope becomes too steep, rock masses can break free and fall or slide into valleys below. In cases where huge masses of bedrock are involved, towns and villages in the path of the slide can be catastrophically damaged. These events are one form of **mass wasting**—the spontaneous downhill movement of soil, regolith, and rock caused by gravity.

Mass wasting is spontaneous movement of soil, regolith, and rock under the influence of gravity. There are many forms of mass wasting, depending on the speed of the motion and the amount of water involved.

Because soil, regolith, and many forms of sediment are poorly held together, they are much easier to move than hard, unweathered bedrock. On most slopes, at least a small amount of downhill movement is going on constantly.

The processes of mass wasting and the landforms they produce are quite varied and tend to grade one into another. Figure 13.10 shows the forms of mass wasting that we will describe in this chapter, sorted by the material that is moving, the amount of water involved, and the speed of the movement.

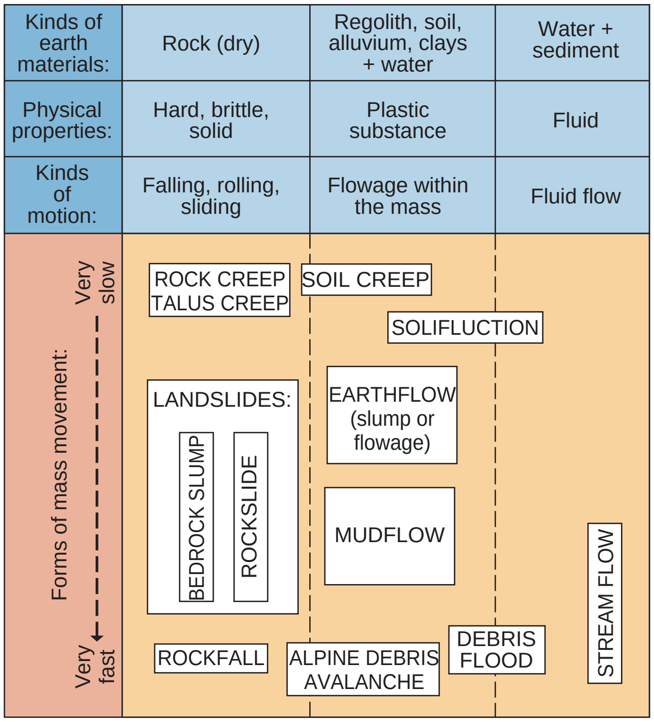
GEODISCOVERIES **Slope Stability and Mass Wasting Interactivity**

Examine the factors influencing mass wasting and view examples of earthflows, landslides, and debris flows. Check out the angle of repose for various Earth materials.

SLOPES

Mass wasting happens on *slopes*—patches of the land surface that are inclined from the horizontal. Slopes guide the flow of surface water downhill and fit together to form stream channels. Nearly all natural surfaces slope to some degree.

Most slopes are covered with regolith, which grades downward into solid, unaltered rock, known simply as **bedrock**. *Sediment* consists of rock or mineral particles that are transported and deposited by fluids, which can be water, air, or even glacial ice. Regolith and sediment are the parent materials of soil. Figure 13.11 shows a typical hillslope that forms one wall of the valley of a small stream. Water and gravity transport regolith downhill to form *colluvium*. Streamflow transports sediment along the stream valley and deposits the sediment as *alluvium*.



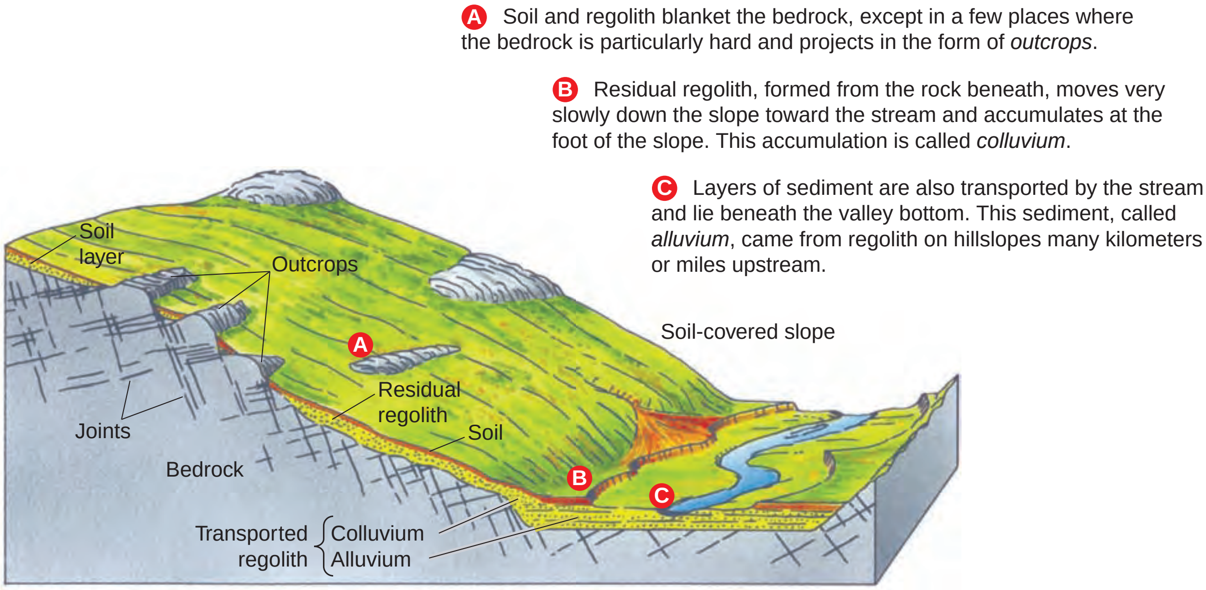
13.10 Processes and forms of mass wasting

On almost every soil-covered slope, soil and regolith will slowly move downhill. This is called **soil creep**. The process is triggered when soil and regolith are disturbed by alternate drying and wetting, growth of ice needles and lenses, heating and cooling, trampling and burrowing by animals, and shaking by earthquakes. Gravity pulls on every such rearrangement, and the particles very gradually work their way downslope. In some layered rocks such as shales or slates, edges of the strata seem to "bend" in the downhill direction (Figure 13.12).

Slopes are mantled with residual regolith, which accumulates at the foot of slopes as colluvium. Regolith that is transported by moving water is termed alluvium.

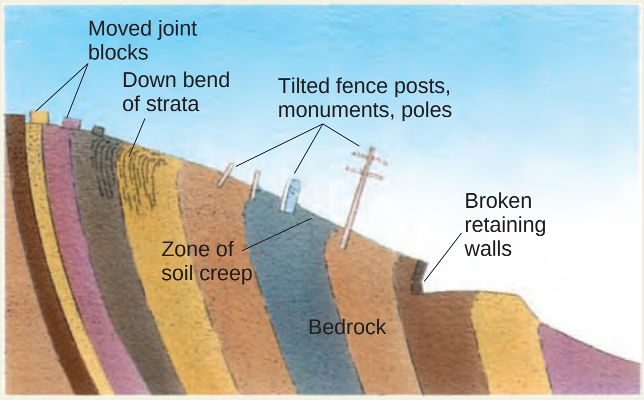
EARTHFLOW

In humid climates, water-saturated soil, regolith, or weak shale can move down a steep slope in just a few hours. This is an **earthflow** (Figure 13.13). It's common to see shallow earthflows, affecting only the soil and



13.11 Soil, regolith, and outcrops on a hillslope

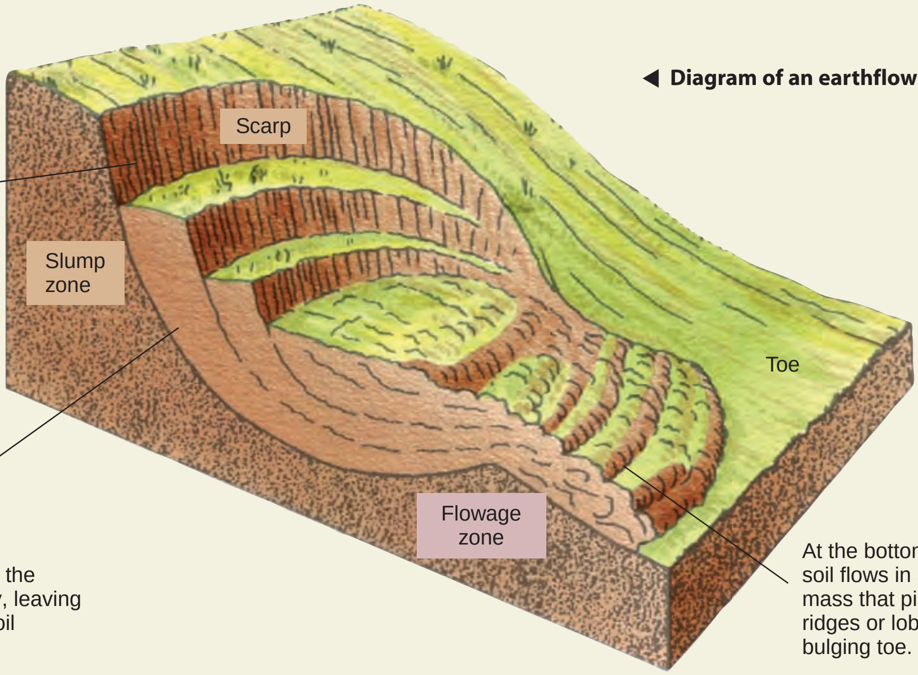
13.12 Soil creep



▲ The slow, downhill creep of soil and regolith shows up in many ways on a hillside. Joint blocks of distinctive rock types can be found far downslope from the outcrop.

▶ Slow, downhill creep of regolith on this mountainside near Downieville, California, has caused vertical rock layers to seem to bend rightward. This is not true plastic bending but is the result of downhill creep of many rock pieces on small joint cracks.

13.13 Earthflow



◀ **Diagram of an earthflow**

▲ **Earthflow at La Conchita** Nestled between the beach and a high bluff of unstable regolith, the town of La Conchita, California, has experienced periodic earthflows following heavy rains for several decades. The most recent earthflow, in 2005, overtopped a fortified retaining wall, marked here by the three steel I-beams projecting above the ground. The earthflow pushed this home off its foundations.

regolith, on sod-covered and forested slopes that have been saturated by heavy rains. An earthflow can affect a few square meters, or it may cover an area of a few hectares (several acres). If the bedrock of a mountainous region is rich in clay, earthflows can involve millions of metric tons of bedrock moving like a great mass of thick mud.

During heavy rains, earthflows can block highways and railroad lines. The flows aren't usually a threat to life because they move slowly, but they can often severely damage buildings, pavements, and utility lines that have been constructed on unstable slopes.

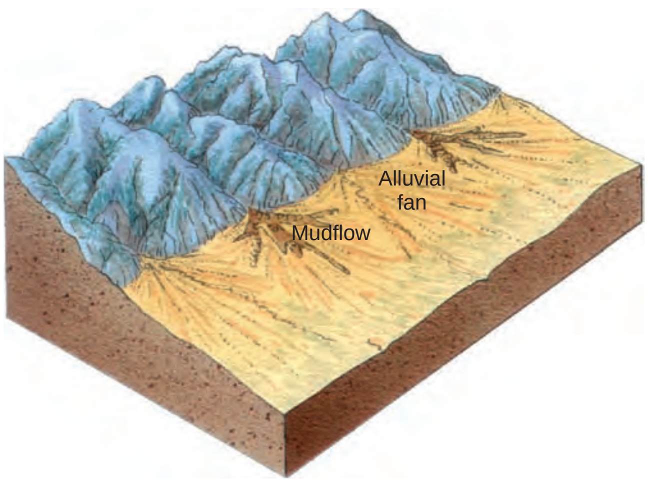
An earthflow is a mass of water-saturated soil that moves slowly downhill. Earthflows can block highways and railroads and severely damage or destroy buildings.

GEODISCOVERIES Earthflows

Watch this animation to see how an earthflow creates scarps and slump terraces.

MUDFLOW AND DEBRIS FLOOD

One of the most spectacular forms of mass wasting and a potentially serious environmental hazard is the **mudflow**. This mud stream pours swiftly down canyons in mountainous regions (Figure 13.14). In deserts, thunderstorms produce rain much faster than it can be absorbed by the soil. Without vegetation to protect soil slopes, the excess water runs off, picking up fine particles to form a thin mud that flows down to the canyon floors and then follows the stream courses. As it flows, it picks up additional sediment, becoming thicker and thicker until it is too thick to flow farther. Great boulders are carried along, buoyed up in the mud. Roads, bridges, and houses in the canyon floor are engulfed and destroyed. The mudflow can severely damage property and even cause death as it emerges from the canyon and spreads out.



13.14 Mudflows in an arid environment

Thin, stream-like mudflows occasionally emerge from canyon mouths in arid regions. The mud spreads out on the fan slopes below in long, narrow tongues.

Mudflows are rapid events in which water, sediment, and debris cascade down slopes and valleys to lower elevations. They are produced by very heavy rainfall or snowmelt caused by volcanic activity.

Mudflows on the slopes of erupting volcanoes are called *lahars*. Heavy rains or melting snow turn freshly fallen volcanic ash and dust into mud that flows downhill (Figure 13.15). Herculaneum, a city at the base of Mount Vesuvius, was destroyed by a mudflow during the eruption of A.D 79. At the same time, the neighboring city of Pompeii was buried under volcanic ash.

Mudflows vary in consistency. They range from the thickness of concrete emerging from a mixing truck to more watery consistencies, similar to the floodwaters of a turbid river. The watery type of mudflow is called a *debris flood* or *debris flow* (Figure 13.16) in the western United States. Debris flows are common in Southern California, with disastrous effects. They can carry anything from fine particles and boulders to tree trunks and limbs. On steep slopes in mountainous regions, these flows are called *alpine debris avalanches*. The intense rainfall of hurricanes striking the southeastern United States will often cause debris avalanches in the hollows and valleys of the Blue Ridge and Smoky Mountains.

LANDSLIDE

A large mass of bedrock or regolith sliding downhill is known as a **landslide**. Large, disastrous landslides are possible wherever mountain slopes are steep (Figure 13.17). In Switzerland, Norway, or the Canadian Rockies, for example, villages built on the floors of steep-sided valleys have been destroyed when millions of cubic meters of rock descended without warning. This chapter's opening section described a landslide in a similar environment and its consequences.

Unlike mudflows and earthflows, which are triggered by heavy rain, landslides are set off by sudden rock failures or earthquakes (Figure 13.18). Landslides can also result when the base of a slope is made too steep by excavation or river erosion. Landslides range from *rockslides* of jumbled bedrock fragments to *bedrock slumps* in which most of the bedrock remains more or

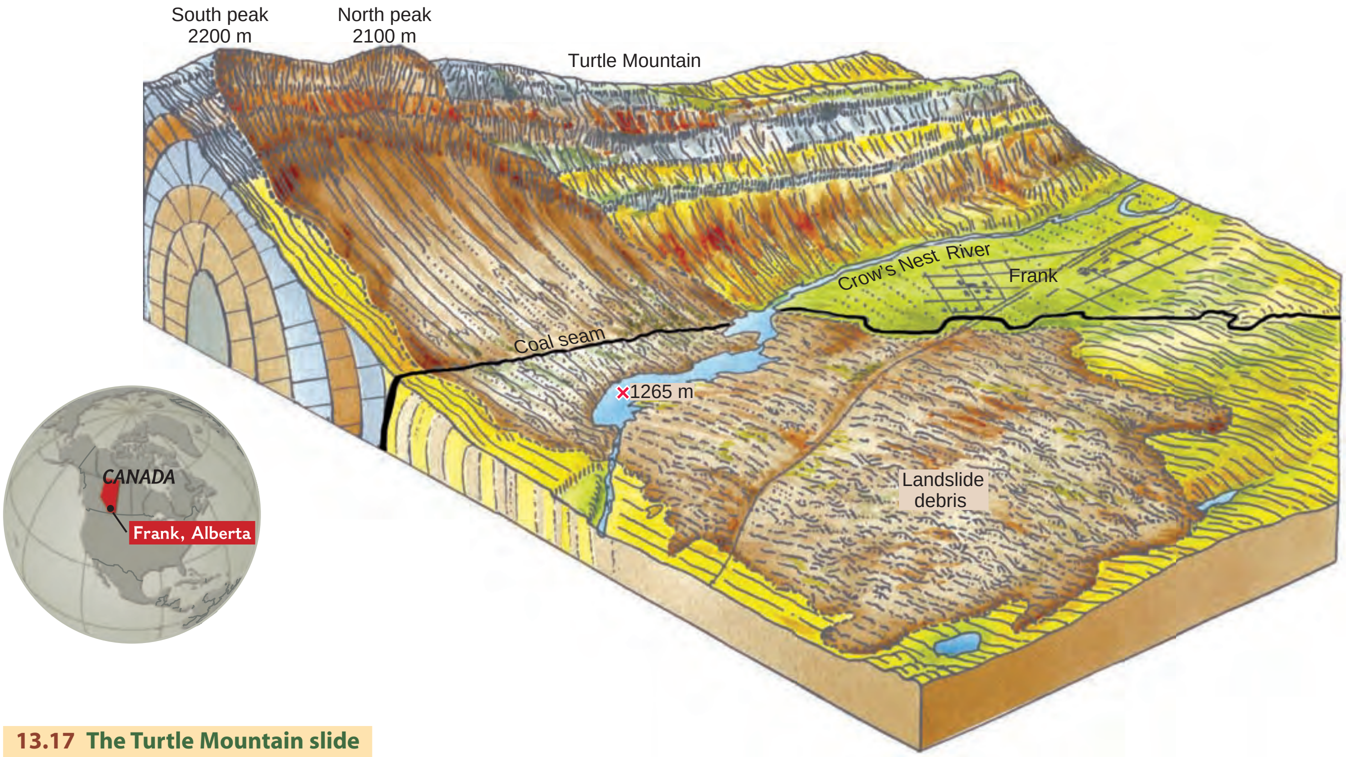
In a landslide, a large mass of rock suddenly moves from a steep mountain slope to the valley below. Landslides are triggered by earthquakes or rock failures rather than heavy rains.

13.15 Mudflow

More than 20,000 lives were lost when a volcanic mudflow—known as a *lahar*—swept through the town of Armero, Colombia. The mudflow was caused by a minor volcanic eruption of Nevado del Ruiz, which melted the snow and ice on its summit and created a cascade of mud and debris that engulfed the town. Many homes were simply swept away (National Geographic Image Collection).

13.16 Debris flow

Heavy rains saturate the soil and regolith of steep slopes, which then flow rapidly down narrow creek valleys and canyons, carrying mud, rocks, and trees. This *debris flow*, also known as an *alpine debris avalanche*, struck the village of Schlans, Switzerland, in November of 2002.



13.17 The Turtle Mountain slide

A classic example of an enormous, disastrous landslide is the Turtle Mountain slide, which took place near Frank, Alberta, in 1903. A huge mass of limestone slid from the face of Turtle Mountain between South and North peaks, descended to the valley, then continued up the low slope of the opposite valley side until it came to rest as a great sheet of bouldery rock debris. The slide was caused by the mountain's unstable geological structure, and Turtle Mountain is now actively monitored for potential movement.

13.18 Santa Tecla landslide

On January 13, 2001, an earthquake measuring 7.6 on the Richter triggered a landslide in Santa Tecla, El Salvador, killing hundreds. The earthquake was centered off the southern coast of El Salvador and was felt as far away as Mexico City. In the shaking, a steep slope above the neighborhood of Las Colinas collapsed, creating a wave of earth that carved a path of destruction through the town. The landslide swept across the ordered grid of houses and streets, burying hundreds of homes and their inhabitants. The same earthquake also triggered other landslides in the region, with additional loss of life and property.

less intact as it moves. In a rockslide, rubble travels down a mountainside at amazing speed. Geologists think this speed is possible because there is a layer of compressed air trapped between the slide and the ground surface. This air layer reduces friction, so the rubble can move faster.

INDUCED MASS WASTING

Human activities can induce mass wasting processes by creating unstable piles of waste soil and rock and by removing the underlying support of natural masses of soil, regolith, and bedrock. Mass movements produced by human activities are called *induced mass wasting*.

In Los Angeles County, California, roads and home sites have been bulldozed out of the deep regolith on very steep hillsides and mountainsides. The excavated regolith is piled up to form nearby embankments. But when these embankments become saturated by heavy winter rains, they can give way. This produces earthflows, mudflows, and debris floods that travel down the canyon floors and spread out, burying streets and houses in mud and boulders. Figure 13.19 shows an example of induced mass wasting—a coastal earthflow in the Palos Verdes Hills of Los Angeles, California.

Human activities can induce mass wasting by piling up unstable materials or undercutting slopes or rock masses. Cutting and filling to extract mineral resources is termed scarification.

Artificial forms of mass wasting are distinguished from the natural forms because they use machinery to raise earth materials against the force of gravity. Explosives produce disruptive forces many times more powerful than the natural forces of physical weathering. Industrial societies now move great masses of regolith and bedrock from one place to another using this technology. We do this to extract mineral resources or to move earth when constructing highway grades, airfields, building foundations, dams, canals, and various other large structures. Both activities destroy the preexisting ecosystems and plant and animal habitats. When the removed materials are then used to build up new land on adjacent surfaces, they bury ecosystems and habitats.

Scarification is a general term for excavations and other land disturbances produced to extract mineral resources. Strip mining is a particularly destructive scarification activity, and Figure 13.20 describes the problems

13.19 Induced earthflow

This aerial view shows houses on Point Fermun, in Palos Verdes, California, disintegrating as they slide downward toward the sea. Both large and small earthflows have been induced or aggravated by human activities in this region. The largest was this one, known as the Portuguese Bend "landslide" that affected an area of about 160 hectares (about 400 acres). It was caused when sedimentary rock layers slipped on an underlying layer of clay. It moved 20 m (about 70 ft) in three years, causing damage totaling some $10 million. Geologists believe that infiltrating water from septic tanks and irrigation water applied to lawns and gardens was responsible for the earthflow, weakening the clay layer enough to start and sustain the flowage.

13.20 Strip mining

▼ **Kentucky coal mine** This aerial view depicts the impact of strip mining on the landscape. Overburden is simply shoveled away and piled up to reveal the coal seam. Reclamation is costly and difficult (National Geographic Image Collection).

▼ **Earth-moving equipment** Huge power shovels and trucks move coal and overburden. This giant truck is filled with coal at a Montana strip mine (National Geographic Image Collection).

it can create. As a result, strip mining is under strict control in most locations. Nonetheless, scarification is on the increase, driven by an ever-increasing human population and a rising demand for coal and industrial minerals.

Processes and Landforms of Arctic and Alpine Tundra

The treeless arctic and alpine tundra environment is severely cold in winter (Figure 13.21). In the tundra, soil water is solidly frozen for many months. During the short summer season, however, the surface thaws, leaving the soil saturated and vulnerable to mass wasting and water erosion. With the return of cold temperatures, the freezing of soil water exerts a strong mechanical influence on the surface layer, creating a number of distinctive landforms. The tundra environment is a unique natural system because it is often found close to glacial ice, near tongue-like alpine glaciers, and along the fringes of ice sheets. We call this a **periglacial** environment (*peri*, meaning "near").

13.21 Permafrost tundra

Musk oxen graze a landscape of tundra on Victoria Island, Nunavut, Canada, at sunset. The ground is permanently frozen beneath the grassy vegetation (National Geographic Image Collection).

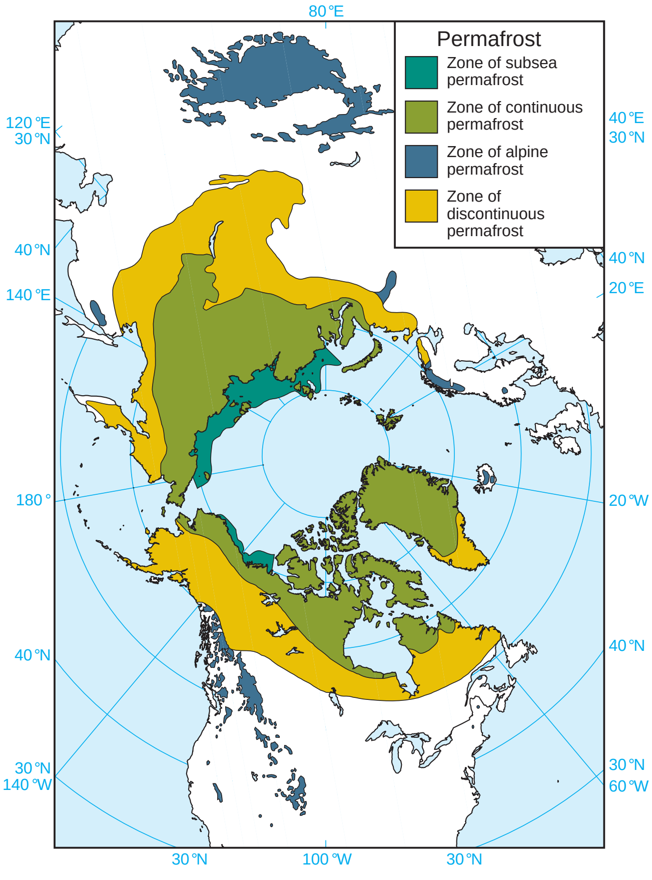
PERMAFROST

Ground and bedrock that lie below the freezing point of fresh water (0°C; 32°F) all year round are called **permafrost**. "Ground" includes clay, silt, sand, pebbles, and boulders. Solid bedrock permanently below freezing is also included in permafrost. Water is commonly found in pore spaces in the ground, and in its frozen state it is known as *ground ice*.

Permafrost includes ground, water, and bedrock that is permanently below freezing. The active layer of permafrost is the shallow surface layer that freezes and thaws each year.

Figure 13.22 is a map showing the distribution of permafrost in the northern hemisphere. Permafrost reaches to a depth of 300 to 450 m (about 1000 to 1500 ft) in the continuous zone near lat. 70° N. Much of this permanently frozen zone is inherited from the last Ice Age and will eventually thaw unless a glacial period returns.

Permafrost terrains have a shallow surface layer, known as the **active layer**, which thaws with the changing seasons. The active layer ranges in thickness from about 15 cm (6 in.) to about 4 m (13 ft), depending on the latitude and nature of the ground. It contains plant roots as well as the water and nutrients needed to support them. Below the active layer is the *permafrost table*, marking the upper surface of the permanently frozen zone.



13.22 Permafrost map

The map shows the distribution of permafrost in the northern hemisphere, divided into four zones. *Alpine permafrost* is found at high elevations where temperatures are always below freezing. *Continuous permafrost* coincides largely with the tundra climate, but it also includes a large part of the boreal forest climate in Siberia. *Discontinuous permafrost*, which occurs in patches separated by frost-free zones under lakes and rivers, occupies much of the boreal forest climate zone of North America and Eurasia. *Subsea permafrost* lies beneath the Arctic Sea offshore of the Asian coast and the coasts of Alaska, the Yukon, and the Northwest Territories in North America.

GROUND ICE

The amount of *ground ice* present below the permafrost table varies greatly from place to place. At great depth, pores in the rock hold little if any frozen water. Near the surface, ground ice can take the form of a body of almost 100 percent ice, and lenses, wedges, veins, or thick, massive beds of ice are common.

A common form of ground ice is the *ice wedge* (Figure 13.23). Ice wedges form as ice accumulates in vertical wedges in deep cracks in the frozen ground. Ice wedges are typically interconnected into a system of polygons, called *ice-wedge polygons* (Figure 13.24). Another is the *ice lens*. At the end of the warm season, meltwater accumulates at the bottom of the active layer, on the permafrost table. It then freezes into a more-or-less horizontal layer of ice that can grow and persist. Ice lenses form under other conditions as well.

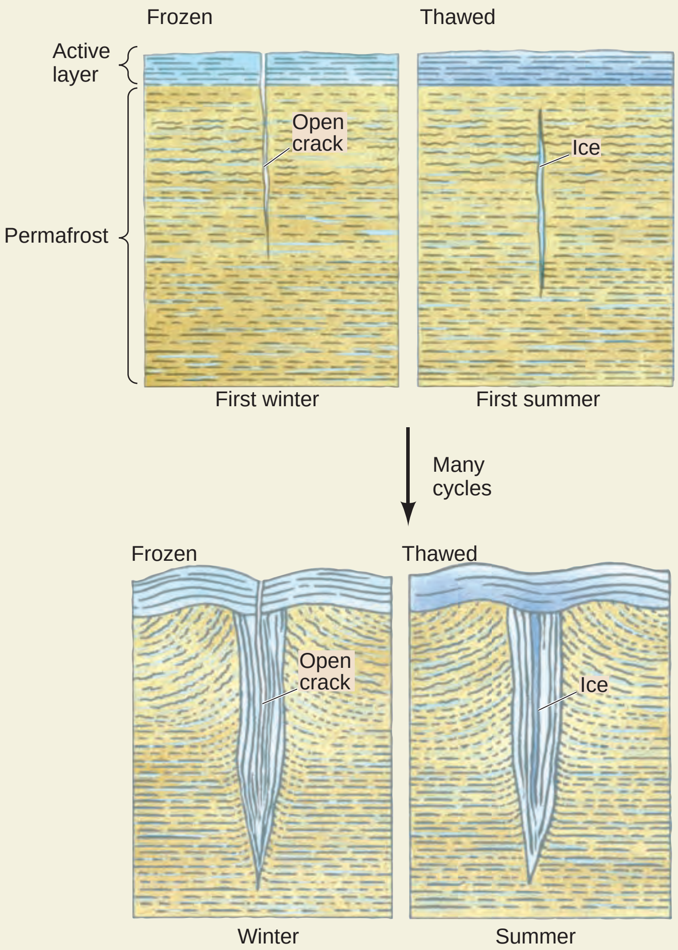
Even in the areas of deepest continuous permafrost there are isolated pockets—called *taliks*—that never fall below the freezing point. Some of these pockets occur within permafrost as lenses of persistent unfrozen water. Others are large features underlying lakes and rivers. Water at the bottom of most lakes and flowing rivers, in spite of a winter ice cover, remains at or near 0°C, keeping the ground below these features unfrozen. The depth of the talik under a lake depends primarily on the width of the lake (Figure 13.25). Under a small lake, the talik may be bowl-shaped and extend downward some tens of meters.

Another remarkable ice-formed feature of the arctic tundra is a conspicuous conical mound, called a *pingo* (Figure 13.26). The pingo has an ice core and slowly grows in height as more ice accumulates, forcing the overlying sediments upward. In extreme cases, pingos reach heights of 50 m (164 ft), with a base diameter of 600 m (about 2000 ft).

Ice wedges form in vertical cracks in permafrost opened by intense winter cold. They are often interconnected as ice-wedge polygons.

13.23 Ice wedge

▼ **Formation of an ice wedge** Ice wedges are thought to originate in cracks that form when permafrost shrinks during extreme winter cold. Surface water enters the crack during the spring melt and then rapidly freezes, widening the crack.



▲ After several hundred winters, the ice wedge has grown and continues to grow as the same seasonal sequence is repeated. The ice wedge thickens until it becomes as wide as 3 m (about 10 ft) and as deep as 30 m (about 50 ft).

▼ Exposed by river erosion, this great wedge of solid ice fills a vertical crack in floodplain silt along the Yukon River, near Galena in western Alaska.

GEODISCOVERIES **Periglacial Ice Wedges**
Watch an ice wedge form as permafrost cracks open in the bitter cold of winter, fill with water during spring thaw, and refreeze. An animation.

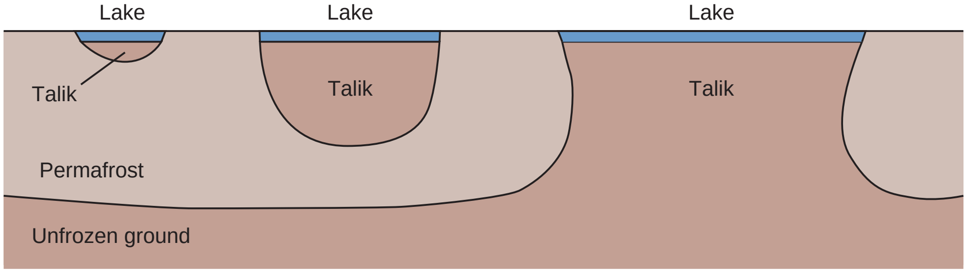
ENVIRONMENTAL PROBLEMS OF PERMAFROST

Human activity degrades the permafrost environment by burning or scraping away layers of decaying matter and plants from the surface of the tundra or arctic forest. Because this surface layer has been removed, the summer thaw extends deeper into the ground, so ice wedges and other forms of ground ice melt in the summer and waste downward. Meltwater mixes with silt and clay to form mud, which is then eroded and transported by streams, leaving trench-like morasses. This total activity is called *thermal erosion.*

When the natural surface cover is removed over a large expanse of nearly flat arctic tundra, the ground can subside as the permafrost melts. Shallow depressions form, fill with water, and create shallow lakes.

13.24 Ice-wedge polygons

These polygons are formed by the growth of ice wedges. Alaskan north slope, near the border of Alaska and Yukon.



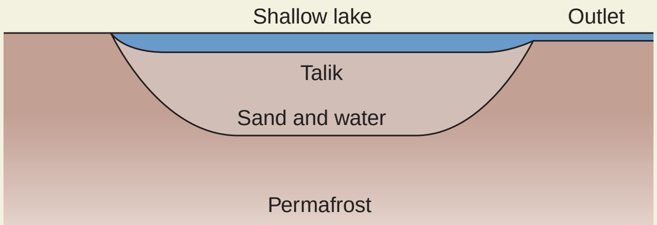
13.25 Taliks

Areas of unfrozen ground, called *taliks*, underlie lakes and rivers in permafrost terrains. Under a small lake, the talik may be bowl-shaped and extend downward some tens of meters. The taliks of larger lakes can actually connect with unfrozen ground at depth, making a "hole" in the permafrost. (The vertical dimension is greatly exaggerated in this sketch.)

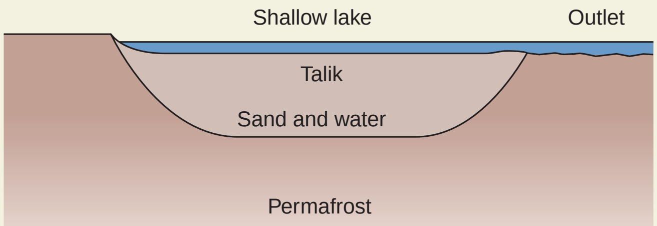
13.26 Pingo formation

▼ **How a pingo forms** A *pingo* is formed when a tundra lake in sandy alluvium is drained. The unfrozen ground under the lake, called a *talik*, slowly freezes and expands, pushing up a mound of sand and water.

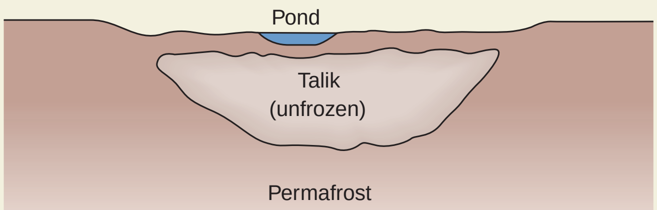
▶ This is Ibyuk pingo, on the Mackenzie River delta, Northwest Territories, Canada. It began to form about 1200 years ago in a drained lakebed. Later, coastline retreat flooded the former lake basin, and today it is connected to Kugmallit Bay of the Beaufort Sea.



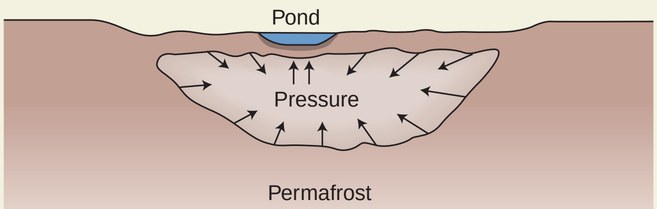
Shallow lake A shallow lake in sandy alluvium is underlain by a talik.



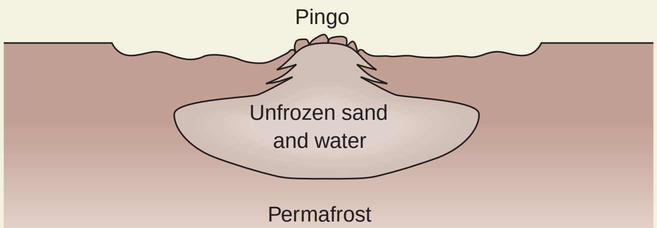
Draining Over time, the lake drains and grows shallower, perhaps because its outlet has eroded and become larger.



Freezing Eventually, the lake shrinks to a small pond. The water in the unfrozen talik, consisting of saturated sand, begins to freeze as the insulating lake above shrinks and disappears.



Pressure As the talik shrinks and the new ice expands, the remaining ground water becomes pressurized.



Dome The pressure on the talik pushes water upward at a weak point in the permafrost layer, forming a dome of ice and sediment. As permafrost slowly engulfs the talik, the pingo grows.

13.27 Thermokarst lake

This *thermokarst lake*, in the boreal forest near May, Yukon.

The lakes expand by thawing the permafrost at their margins, and soon a terrain of shallow lakes and bogs, called *thermokarst*, develops (Figure 13.27).

Clearing of natural surface layers can induce rapid thawing of ice masses in permafrost, leading to thermal erosion and the growth of shallow thermokarst lakes.

To avoid creating thermal erosion and thermokarst terrain, buildings on permafrost are placed on piles with an air space below or, alternatively, on a thick insulating pad of coarse gravel. Steam and hot-water lines are placed above ground to prevent thawing of the permafrost layer.

PATTERNED GROUND AND SOLIFLUCTION

Areas that contain coarse-textured regolith, consisting of rock fragments in a wide range of sizes, can give rise to some very beautiful and distinctive features. The annual cycle of thawing and freezing sorts the coarsest fragments—pebbles and cobbles—from finer particles by moving them horizontally and vertically. This sorting produces rings of coarse fragments. The rings are linked in a network, forming systems of *stone polygons* or *stone nets* (Figure 13.28). On steep slopes, soil creep elongates the polygons in the downslope direction, turning them into parallel stone stripes. Stone polygons and ice-wedge polygons are examples of **patterned ground**.

Patterned ground includes circles, polygons, or nets of stones. They are formed as freeze–thaw cycles in the active layer push coarser fragments upward and to the side.

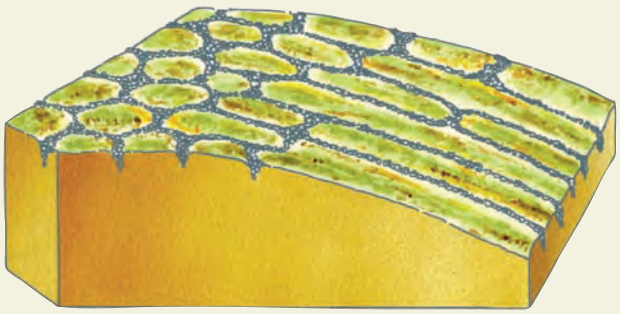
Solifluction is a special variety of earthflow in arctic permafrost tundra regions. It occurs in late summer, when the ice-rich layer at the bottom of the active layer thaws to form a plastic mud. Moving almost imperceptibly on the plastic layer, the saturated soil is deformed into solifluction terraces and solifluction lobes that give the tundra slope a stepped appearance (Figure 13.29).

ALPINE TUNDRA

Most of the periglacial processes and forms we've discussed for the low arctic tundra are also found in

13.28 Patterned ground

◀ **Stone rings** *Sorted circles* of gravel form a network of stone rings on this nearly flat land surface. The circles in the foreground are 3 to 4 m (10 to 13 ft) across. The gravel ridges are 20 to 30 cm (8 to 12 in.) high. Broggerhalvoya, western Spitsbergen, latitude 78° N.



▶ **Stone stripes** This diagram shows how stone rings can be drawn out downslope into *stone stripes*.

the high *alpine tundra* throughout high mountains of the middle and high latitudes (Figure 13.30). Here, steep mountainsides with large exposures of hard bedrock were strongly abraded by glacial ice. Patterned ground and solifluction terraces occupy relatively small valley floors where slopes are low and finer sediment tends to accumulate.

CLIMATE CHANGE IN THE ARCTIC

Climate change is expected to raise temperatures and bring more precipitation to much of the North American arctic region. Substantial warming has already occurred. Climate scientists predict that by the end of the century arctic temperatures will have risen by 4°C to 8°C (7.2°F to 14.4°F), and annual precipitation will increase by as much as 20 percent. What impact will this have on arctic and boreal environments?

Global warming will bring widespread permafrost thawing to the arctic. Populations and patterns of mammals, sea birds, and fish will be disturbed. The boreal forest will move northward.

First, the warm temperatures and increased precipitation will deepen the active layer over broad areas of permafrost. This will create more thermokarst terrain, as ice-rich layers of permafrost melt and subside. Roads and pipelines will

13.29 Solifluction

Solifluction has created this landscape of soil mounds in the Richardson Mountains, Northwest Territories, Canada. Bulging masses of water-saturated regolith have slowly moved downslope, overriding the permafrost below, while carrying their covers of plants and soil.

13.30 Alpine tundra

Treeless tundra is found at high elevations, often with permafrost. These hikers are enjoying the views of the Selkirk Mountains in the Canadian Rockies (National Geographic Image Collection).

be disrupted. The winter hunting season will become shorter, and the populations of mammals, fish, and sea birds will fluctuate, making it harder for native people to maintain their way of life.

The boreal forest will migrate poleward, carrying along the border between continuous and discontinuous permafrost as increased snowfall warms the ground under new forest. Discontinuous permafrost will be reduced at the southern boundary, and the isolated permafrost to the south will largely disappear. Warmer soil temperatures will increase the decay of soil organic matter, releasing CO_2 and further boosting the warming. Forest productivity will decline from summer drought stress, increased disease and insect damage, and more frequent burns. In short, the arctic environment seems set for major changes.

GEODISCOVERIES **Web Quiz**
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

In this chapter, we have examined the processes of weathering and mass wasting. In the weathering process, rock near the surface is broken up into smaller fragments and often altered in chemical composition. In mass wasting, weathered rock and soil move downhill in slow to sudden mass movements.

Note that the landforms of mass wasting are produced by gravity acting directly on soil and regolith. Gravity also powers another landform-producing agent—running water—which we take up in the next two chapters. The first deals with water in the hydrologic cycle, in soil, and in streams. The second deals specifically with how streams and rivers erode regolith and deposit sediment to create landforms.

GEODISCOVERIES **Web Links**
Examine gravestone weathering, tour earthflows and landslides, and view the periglacial environment, all by visiting the web links for this chapter.

IN REVIEW WEATHERING AND MASS WASTING

- The *Madison Slide* is an impressive example of mass wasting. An earthquake triggered a huge avalanche that blocked the Madison River, creating a new lake.
- **Weathering** is the action of processes that cause rock near the surface to disintegrate and decompose into **regolith**.
- **Physical weathering** produces regolith from solid rock by breaking *bedrock* into pieces.
- *Frost action* breaks rock apart by the repeated growth and melting of ice crystals in rock fractures and *joints*, as well as between individual mineral grains. In mountainous regions of frequent hard frost, fields of angular blocks accumulate as *rock seas* or *rock glaciers*. Cliffs shed rock fragments by frost action to form *talus* and *talus slopes*.
- *Salt-crystal growth* in dry climates breaks individual grains of rock free, and creates landforms such as niches and arches. It can also damage brick and concrete.
- *Unloading* of the weight of overlying rock layers can cause some types of rock to expand and break loose into thick shells, producing *exfoliation domes*.
- Daily temperature cycles in arid environments are thought to cause rock breakup. Wedging by plant roots also forces rock masses apart.
- **Chemical weathering** results from mineral alteration. Igneous and metamorphic rocks can decay to great depths through *hydrolysis* and *oxidation*, producing a regolith that is often rich in clay minerals.
- *Carbonic acid action*, created by solution of carbon dioxide in water, dissolves limestone. Acid precipitation weathers building stones and architectural decorations. In warm, humid climates, basaltic lavas also weather by acid action.
- **Mass wasting** is the spontaneous downhill motion of soil, regolith, or rock under gravity.
- Mass wasting occurs on slopes. Most slopes are mantled with regolith, which lies atop unweathered **bedrock**. *Colluvium* and *alluvium* are two types of transported regolith.
- **Soil creep** is a process of mass wasting in which regolith moves down slopes almost imperceptibly under the influence of gravity.
- In an **earthflow**, water-saturated soil or regolith slowly flows downhill.
- A **mudflow** is much swifter than an earthflow. It follows stream courses, becoming thicker as it descends and picks up sediment. A watery mudflow with debris ranging from fine particles to boulders to tree trunks and limbs is called a *debris flood* or *debris flow*.
- A **landslide** is a rapid sliding of large masses of bedrock, sometimes triggered by an earthquake. *Rockslides* and *bedrock slumps* are forms of landslides.
- Human activities can lead to *induced mass wasting*—mass movement of soil and regolith by oversteeping or undercutting slopes or by building unstable piles of regolith.

- *Scarification* includes excavation and relocation of regolith to extract mineral resources. Strip mining is an example.
- The **periglacial** environment of the tundra is dominated by the freezing and thawing of water.
- Ground and bedrock with temperatures below the freezing point is called **permafrost**. Water in permafrost is *ground ice*.
- *Continuous permafrost* and *subsea permafrost* occur at the highest latitudes, flanked by a band of *discontinuous permafrost*.
- The ***active layer*** overlies permafrost and thaws each year during the warm season. It contains the roots of plants and the water and nutrients needed to support them.
- **Ice wedges** form when water fills cracks in the active layer caused by shrinkage due to extreme winter cold. Ice wedges occur in systems of *ice-wedge polygons*. *Ice lenses* form at the base of the active layer.
- Ground doesn't freeze under lakes or rivers, so these water bodies are underlain by *taliks*—pockets of unfrozen ground with temperatures near 0°C.
- *Pingos* are distinctive domed hills of ice that form when shallow lakes are drained and permafrost invades the water-rich talik below, creating pressure as the water freezes and expands. The pressurized water breaks through the permafrost and wells upward to freeze near the surface.
- Disturbance of the surface layer in permafrost terrain by human activity can induce *thermal erosion* and the formation of *thermokarst*. Structures, roads, and pipelines must be constructed so as not to thaw ice-rich permafrost.
- **Patterned ground** includes circles, polygons, and nets that cover large areas of tundra and are produced by freeze–thaw action.
- **Solifluction** (soil flowage) occurs in late summer, when the bottom of the active layer thaws, releasing water that lubricates downhill movement of the active layer.
- *Alpine tundra* shows many of the same landforms and processes of arctic tundra, but is restricted to higher elevations where mean annual ground temperatures are below freezing.
- Climate warming will thaw vast areas of permafrost, producing extensive regions of *thermokarst lakes* and subsiding terrain. The boreal forest will migrate poleward. Soil organic matter will decay more rapidly, releasing more CO_2. Forest productivity will decline.

KEY TERMS

weathering, p. 442
physical weathering, p. 442
chemical weathering, p. 442
regolith, p. 442
mass wasting, p. 448
bedrock, p. 448
soil creep, p. 448
earthflow, p. 448
mudflow, p. 451
landslide, p. 451
periglacial, p. 455
permafrost, p. 456
active layer, p. 456
patterned ground, p. 460
solifluction, p. 460

REVIEW QUESTIONS

1. Describe the Madison Slide and the events that took place directly after it.
2. What is meant by the term *weathering*? What types of weathering are recognized? What is *regolith*?
3. How does frost action break up rock? Use the term *joint* in your answer. Provide some examples of landforms produced by frost action.
4. How does salt-crystal growth break up rock? Use the term *capillary action* in your answer. Provide some examples of landforms produced by salt-crystal growth.
5. What is an *exfoliation dome*, and how does it arise? Refer to Figure 13.6 in your answer.
6. Name three types of chemical weathering. Describe how limestone is affected by chemical weathering.
7. Define *mass wasting*. What factors can be used to distinguish different types of mass movements?
8. What is *soil creep*, and how does it arise?
9. What is an *earthflow*? What features distinguish it as a landform?
10. Contrast earthflows and mudflows, providing an example of each.
11. Define the term *landslide*. How does a landslide differ from an earthflow?
12. Define and describe induced mass wasting. Provide some examples.
13. Explain the term *scarification*. Provide an example of an activity that produces scarification.
14. What is meant by the term *periglacial*?
15. Define and describe permafrost and some of its features, including *ground ice*, *active layer*, and *permafrost table*.
16. Identify the zones of permafrost and describe their general location.
17. Describe the formation of an ice wedge.

18. What is a *talik*? How does the size of a talik under a lake depend on the width of the lake?
19. What is a *pingo*? How does it form?
20. Define *thermal erosion* and describe the formation of *thermokarst*.
21. What techniques are used to safely build structures, roads, and pipelines in permafrost terrains?
22. What is meant by the term *patterned ground*? How is it formed?
23. What is *solifluction*? How and when does it occur?
24. How will global climate warming affect boreal and arctic regions?

VISUALIZING EXERCISES

1. Define the terms *regolith*, *bedrock*, *sediment*, and *alluvium*. Sketch a cross section through a part of the landscape showing these features and label them on the sketch.
2. Copy or trace Figure 13.10. Then identify and plot on the diagram the mass movement associated with each of the following locations: Turtle Mountain, Palos Verdes Hills, Madison River, Santa Tecla, and Herculaneum.
3. Diagram the formation of a pingo, adding explanatory text as needed to document the process.

ESSAY QUESTIONS

1. A landscape includes a range of lofty mountains elevated above a dry desert plain. Describe the processes of weathering and mass wasting that might be found on this landscape and identify their location.
2. Identify and describe the unique processes of mass wasting that characterize arctic environments. Explain how permafrost plays a central role. How has human activity affected the arctic environment in the past and what impact is predicted for the future?
3. Imagine yourself as the newly appointed director of public safety and disaster planning for your state or province. One of your first jobs is to identify locations where human populations are threatened by potential disasters, including those of mass wasting. Where would you look for mass wasting hazards and why? In preparing your answer, you may want to consult maps of your state or province.

Chapter 14
Fresh Water of the Continents

Arising high in the mountains of Patagonia, the Leona River is fed by high mountain glaciers, giving it a striking milky-blue color. The glacial meltwater is rich in freshly ground rock particles that scatter skylight from below the water surface. Since water scatters blue light preferentially, the water looks milky blue.

The braided pattern of flow, with channels dividing and re-forming around low islands of fresh sediment, is typical of rivers carrying large volumes of sediment. The sediment builds up in the bed of the channel until the bed is higher than the surrounding deposits, and the river then spills out to the side, creating a new channel. This process produces the many abandoned channels visible in the photo.

Patagonia's glaciers are part of an ice cap on the Southern Andes that feeds the glaciers of Chile, to the west, and Argentina, to the east. The ice cap includes 47 large glaciers, including several large tidewater glaciers that reach the Pacific. Like many other glaciers worldwide, they are shrinking because of climate warming. According to a recent study by NASA, the melting of the Patagonia ice fields now accounts for nearly 10 percent of global sea-level rise.

Leona River, Santa Cruz Province, Argentina

Fresh Water of the Continents

The Earth's fresh water is a scarce resource, whether it is in the flowing water of streams and rivers, the still waters of lakes, or deep under the land in ground water. How does rainfall feed streams, rivers, and lakes? How does it recharge ground water to feed wells? What is a flood? What are the effects of urbanization on the behavior of streams and rivers? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

The Aral Sea

East of the Caspian Sea, astride the former Soviet republics of Kazakhstan and Uzbekistan, lies an immense saline lake—the *Aral Sea*. Fed by meltwaters of high glaciers and snowfields in the lofty Hindu Kush, Pamir, and Tien Shan Ranges, the lake endured through thousands of years as an oasis for terrestrial and aquatic wildlife deep in the heart of the central Asian desert.

But in the last 40 years, the Aral Sea, once larger than Lake Huron, has shrunk to a shadow of its former extent (Figure 14.1). The volume of its waters has decreased by more than two-thirds, and its salinity has increased from 1 percent to over 3 percent, making it more salty than sea water. Twenty of the 24 fish species native to the lake have disappeared. Its catch of commercial fish, which once supplied 10 percent of the total for the Soviet Union, has dwindled to zero. The deltas of the Amu Darya and Syr Darya rivers, which enter the south and east sides of the lake, were islands of great ecological diversity, teeming with fingerling fishes, birds, and their predators. Now only about half of the species of nesting birds remain. Many species of aquatic plants, shrubs, and grasses have vanished. Commercial hunting and trapping have almost ceased.

What caused this ecological catastrophe? The answer is simple—the lake's water supply was cut off. As an inland lake with no outlet, the Aral Sea receives water from the Amu Darya and Syr Darya, as well as a small amount from direct precipitation, but it loses water by evaporation. Its gains balanced its losses, and, although these gains and losses varied from year to year, the area, depth, and volume of the lake remained nearly constant until about 1960.

In the late 1950s the Soviet government embarked on the first phases of a vast irrigation program, using water from the Amu Darya and Syr Darya for cotton cropping on the region's desert plain. The diversion of water soon became significant as more and more land came under irrigation. As a result, the inflow fell to nearly zero by the early 1980s. The surface level of the Aral was sharply lowered and its area reduced. The sea became divided into two separate parts.

As the lake's shoreline receded, the exposed lakebed became encrusted with salts (Figure 14.2). The once-flourishing fishing port of Muynak became a ghost town, 50 km (30 mi) from the new lake shoreline. Strong winds now blow salt particles and mineral dusts in great clouds southwestward over the irrigated cotton fields and westward over grazing pastures. These salts—particularly the sodium chloride and sodium sulfate components—are toxic to plants. The salt dust permanently poisons the soil and can only be flushed away with more irrigation water.

However, a portion of this vast ecological ruin is now in rehabilitation. The flow of the Syr Darya reaching the lake is sufficient to maintain the smaller northern section of the lake, now called the Small Sea, in a productive state. A dike some 13 km (8 mi) now separates the Small Sea from its larger brother, the Big Sea. The dike traps the inflowing waters of the Syr Darya and by 2006 had raised the level of the Small Sea from 30 m (98 ft) to 38 m (125 ft), with 42 m (138 ft) considered the level of viability.

In 2006, commercial fishing returned to the Small Sea. A new fish hatchery is under construction, with a target of producing 10,000 tons of sturgeon, carp, and flounder each year. This is about half the former yield of the whole Aral Sea. The local population, which was decimated as their livelihood faded away, is now coming back, with some villages doubling their populations within a few years. The increased water surface area has stimulated increased rainfall downwind of the sea, helping local agriculture.

But what of the Big Sea? Unfortunately, its prospects are dim. At a salinity level of more than 85 parts per thousand (more than twice as salty as ocean water), the last of its native fish species are dying. Still, there is some hope for the Big Sea's fishermen. When the salinity reaches 110 parts per thousand, conditions will be favorable for brine shrimp. These tiny creatures are used as food for young fishes raised in fish farms worldwide and can provide a valuable cash crop. However, there will be no respite from the toxic dust storms of salt and pesticide residues that sweep over the region downwind from the Big Sea.

The Aral Sea has been reduced in volume and increased in salinity as its inflow has been diverted to irrigation. Only a small portion, the Small Sea, now survives.

14.1 The Aral Sea shrinks

This pair of satellite images shows the Aral Sea in 1976 and 2006. More than two-thirds of the sea's volume has been lost in the last 40 years.

14.2 Aral Sea gallery

▲ **Blowing dust** Vast expanses of lake bottom, left high and dry by the shrinking of the Aral Sea, provide a source for wind-blown dust, here displayed along a road in the village of Kyzylkum.

▲ **Graveyard of ships** As the Aral Sea shrank, it left behind the hulks of abandoned fishing vessels, now useless without fish.

▼ **Salinization** Accumulation of salts in agricultural soils accompanies the shrinking of the Aral Sea. Salty wind-blown dust and saline ground water drawn to the surface concentrate salt in the top layer of soil.

The Hydrologic Cycle Revisited

Water is essential to life. Nearly all organisms require constant access to water or at least a water-rich environment for survival (Figure 14.3). Humans are no exception. We need a constant supply of fresh water from precipitation over the lands. Some of this water is stored in soils, regolith, and pores in bedrock. And a small amount of water flows as fresh water in streams and rivers. In this chapter, we will focus on water at the land surface and water lying within the ground.

Fresh water on the continents in surface and subsurface water makes up only about 3 percent of the hydrosphere's total water. This fresh water is mostly locked into ice sheets and mountain glaciers. Ground water can be found at almost every location on land that receives rainfall, but only accounts for a little more than half of 1 percent of global water. This small fraction is still many times larger than the amount of fresh water in lakes, streams, and rivers, which only amount to about three-hundredths of 1 percent of the total water. Fresh surface water varies widely across the globe, and many arid regions do not have permanent streams or rivers.

PATHS OF PRECIPITATION

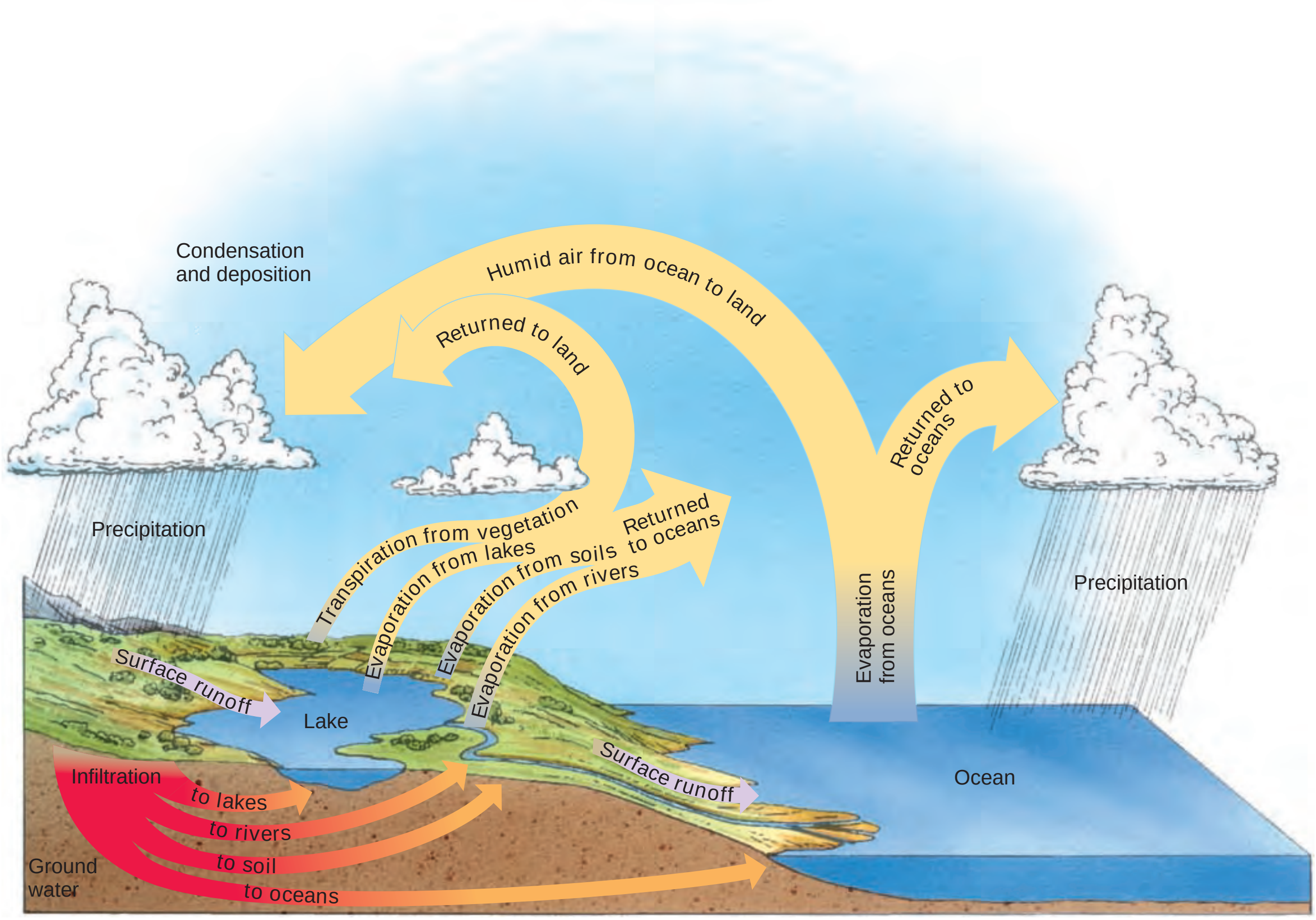
Figure 14.4 shows the flow paths of water between ocean, land, and atmosphere. The study of these flows is part of the science of *hydrology*, which is the study of water as a complex but unified system on the Earth. In this chapter, we will trace the part of the hydrologic cycle that includes both the surface and subsurface pathways of water flow. This part arises from precipitation over land.

Land precipitation either runs off or infiltrates into the soil. As runoff, it flows into streams. As infiltration, it returns to the air through evapotranspiration or percolates downward to become ground water.

As shown in Figure 14.5, there are three pathways for land precipitation. First, water can sink into the soil in the process of **infiltration**, remaining in the *soil-water belt* or passing through into

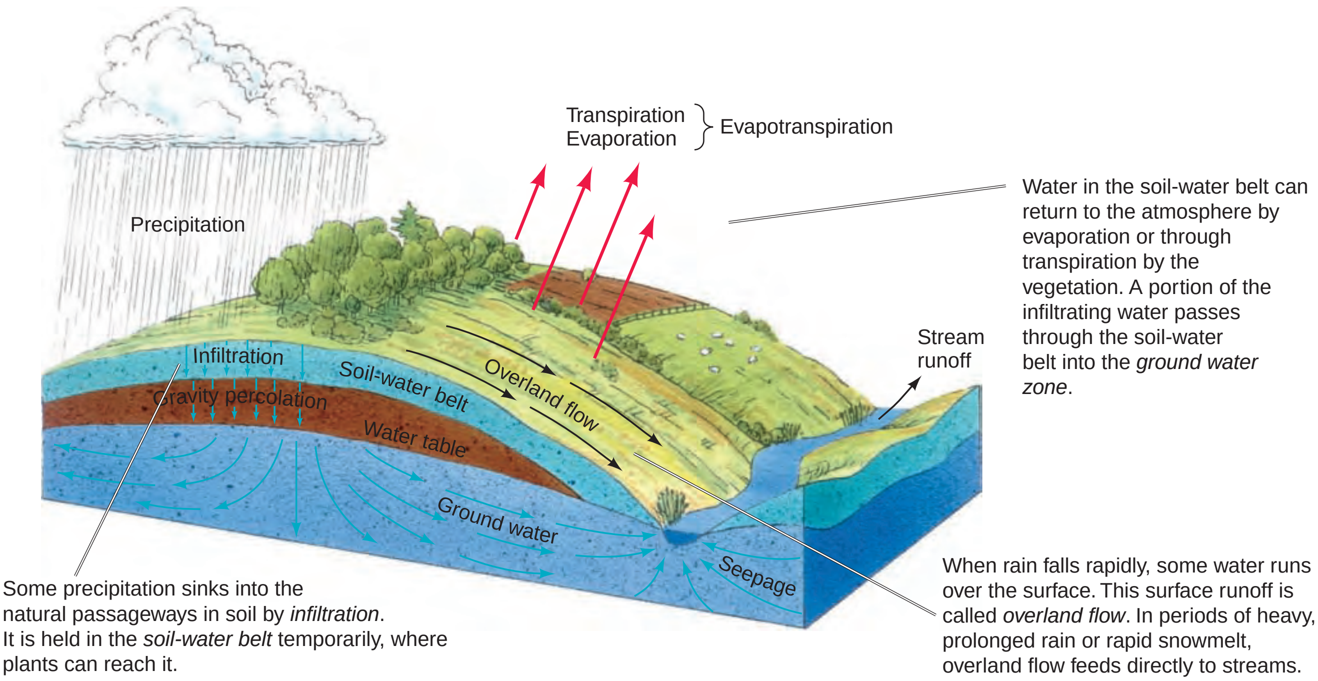
14.3 Fresh water

Humans require abundant amounts of fresh water. Rivers and streams are important sources of water for human uses (National Geographic Image Collection).



14.4 The hydrologic cycle

The hydrologic cycle traces the paths of water as it moves from oceans through the atmosphere to land and returns to the ocean once more.



14.5 Paths of precipitation

the zone of ground water below. Second, the water can return to the atmosphere through *evapotranspiration*. Third, water can form surface **runoff** that flows directly downslope and into streams. This **overland flow** moves surface particles from hills to valleys, helping to shape landforms. By supplying water to streams and rivers, runoff also allows rivers to carve out canyons and gorges and to carry sediment to the ocean.

GEODISCOVERIES Ground Water

Watch an animation of the hydrologic cycle and trace the path of ground water as it infiltrates the soil, percolates to the water table, and flows to streams.

Ground Water

Water from precipitation can flow through the soil-water belt under the force of gravity. We call this flow *percolation*. Eventually, the percolating water reaches ground water. **Ground water** is the part of the subsurface water that fully saturates the pore spaces in bedrock, regolith, or soil (Figure 14.6). The top of the *saturated zone* is marked by the **water table**. Above the water table is the *unsaturated zone* in which water does not fully saturate the pores. This zone also includes the soil-water belt.

Ground water moves slowly along deep flow paths and eventually emerges by seepage into streams, ponds, lakes, and marshes (Figure 14.7). In these places the land surface dips below the water table.

THE WATER TABLE

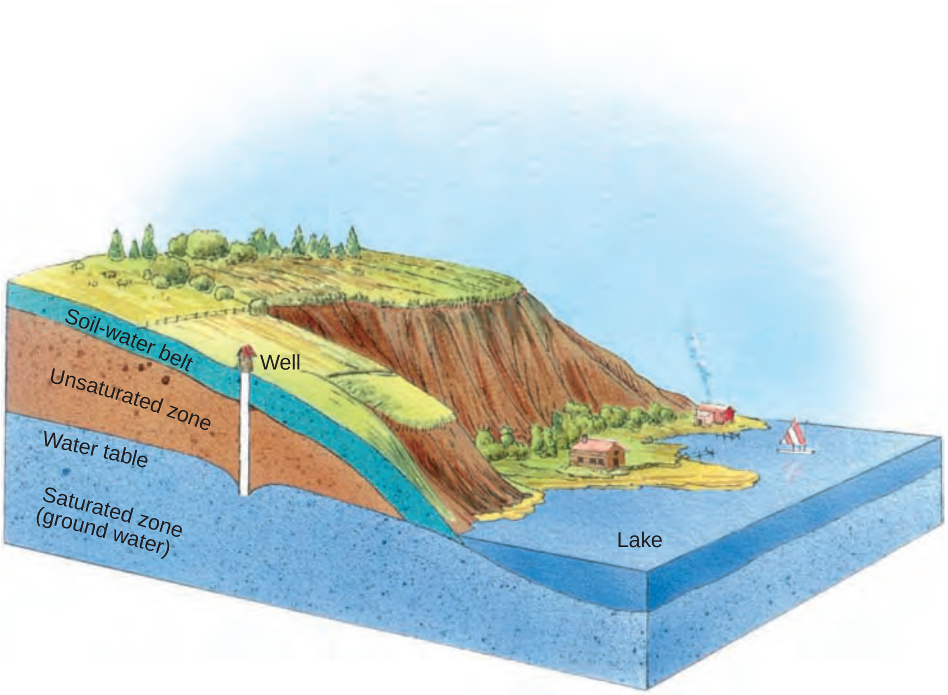
The water table can be mapped in detail, if there are many wells in an area, by plotting the water height in each well (Figure 14.8). Water percolating down through the unsaturated zone tends to raise the water table, while seepage into lakes, streams, and marshes draws off ground water and tends to lower its level. When there's a large amount of precipitation, the water table rises under hilltops or divide areas. During droughts, the water table falls.

These differences in water table level are built up and maintained because ground water moves with extreme slowness through the fine chinks and pores of bedrock and regolith. Over time, the water table level tends to remain stable, and the flow of water released to streams and lakes balances the flow of water percolating down into the water table.

The water table marks the top of the saturated zone of ground water. It is highest under hilltops and divides, and it slopes to intersect the surface at lakes, marshes, and streams.

AQUIFERS

Clean, well-sorted sand—in beaches, dunes, or in stream deposits, for example—can hold an amount of ground water equal to about one-third of its bulk volume. So,



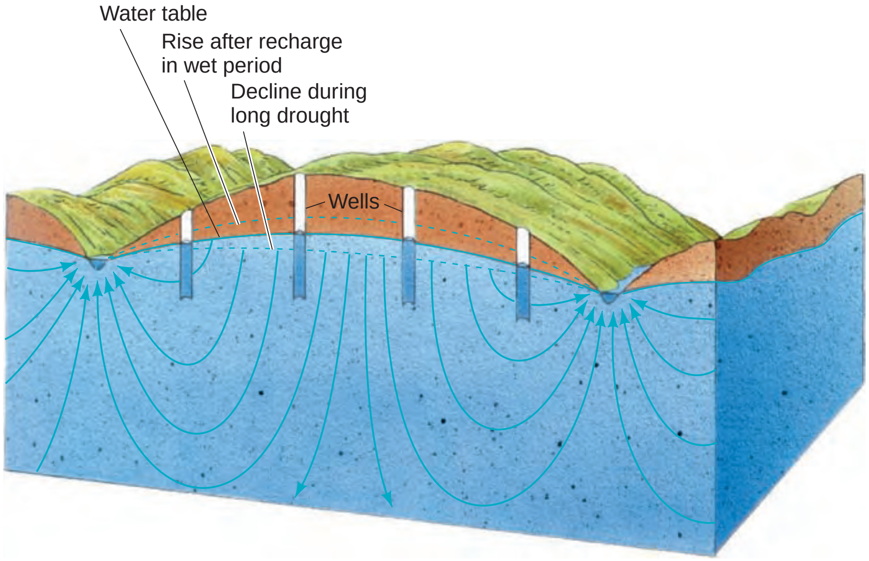
14.6 Zones of subsurface water

Water in the soil-water belt is available to plants. Water in the *unsaturated zone* percolates downward to the *saturated zone* of ground water, where all pores and spaces are filled with water.

14.7 Surface waters

▲ **Streams** Steams and rivers carry runoff from the land surface, but in moist climates they are also fed by ground water. This fly fisherman is testing the waters in a stream near Coyhaique, Chile (National Geographic Image Collection).

▼ **Ponds** Ponds and lakes are fed by ground water, so their levels are determined by the water table. This pond is in Baxter State Park, Maine (National Geographic Image Collection).



14.8 Ground water and the water table

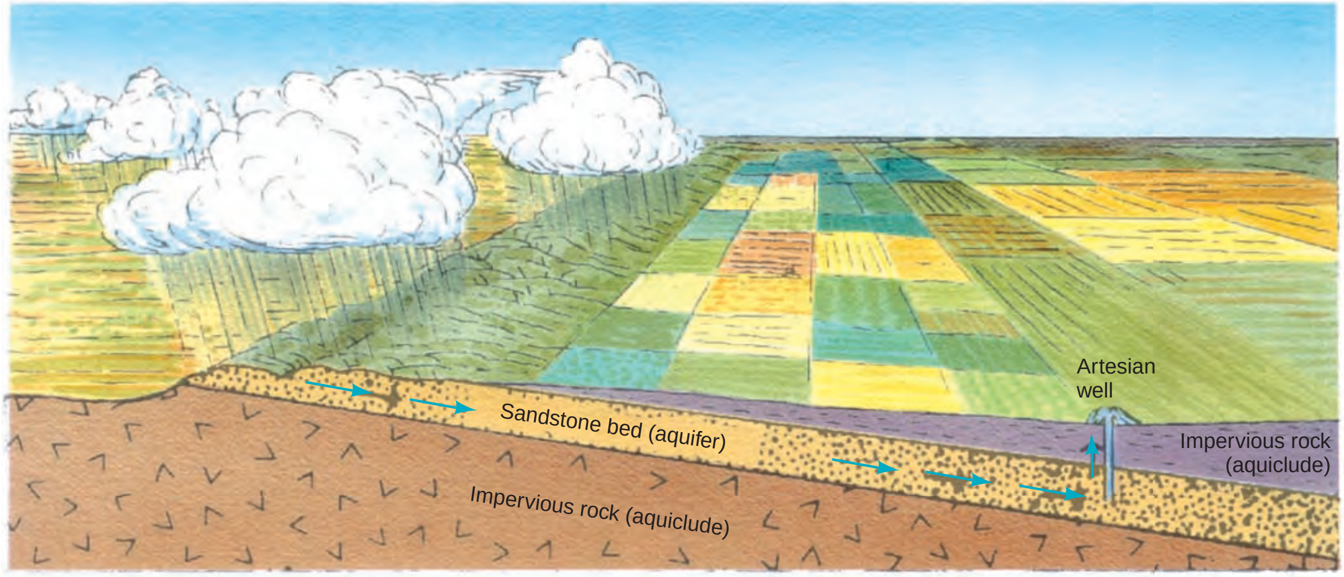
This figure shows paths of ground water flow. It takes a long time for water to flow along the deeper paths, but flow near the surface is much faster. The most rapid flow is close to the stream, where the arrows converge.

sedimentary layers often control the storage and movement of ground water. Such layers are called **aquifers**. A bed of sand or sandstone is often a good aquifer. Clay and shale beds, by contrast, are relatively impermeable and are known as *aquicludes*.

Figure 14.9 shows ground water flowing in an aquifer that is sandwiched between two aquicludes. Because it can't easily penetrate into the aquicludes, this ground water is under pressure, so it flows freely from a well. This type of self-flowing well is an *artesian well*.

LIMESTONE SOLUTION BY GROUND WATER

Carbonic acid—a weak acid produced from carbon dioxide dissolved in water—slowly erodes limestone at the surface in moist climates. Similarly, limestone below



14.9 Artesian well

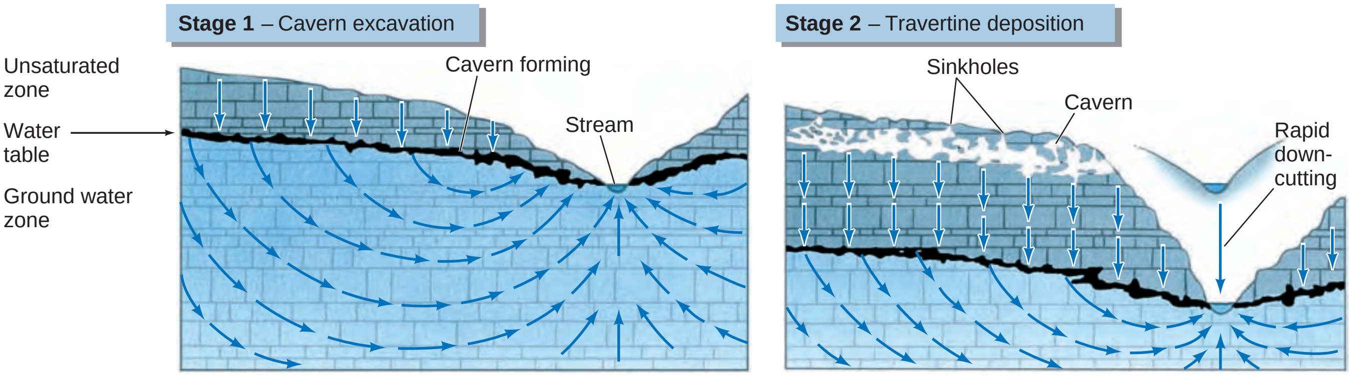
A porous sandstone layer (*aquifer*) is sandwiched between two impervious rock layers (*aquicludes*). Precipitation provides water that saturates the sandstone layer. Since the elevation of the well that taps the aquifer is below that of the range of hills feeding the aquifer, pressure forces water to rise in the well.

the surface can be dissolved by ground water slowly flowing in the saturated zone, forming deep underground *limestone caverns*. Mammoth Cave in Kentucky and Carlsbad Caverns in New Mexico are examples of famous and spectacular caverns formed by solution. Figure 14.10 describes how caverns develop.

Sinkholes are surface depressions in a region of cavernous limestone (Figure 14.11). Some sinkholes are filled with soil washed from nearby hillsides, whereas others are steep-sided, deep holes. They develop where the limestone is more susceptible to solution weathering, or where an underground cavern near the surface has collapsed.

Landscapes where there are numerous sinkholes and no small surface streams are called **karst**. Figure 14.12 shows how a karst landscape develops. Important regions of karst or karst-like

Carbonic acid action dissolves limestone, producing caverns. Cavern collapse creates sinkholes and a karst landscape.



▲ **Stage 1** Carbonic acid action is concentrated in the saturated zone just below the water table. Limestone dissolves at the top of the ground water zone, creating tortuous tubes and tunnels, great open chambers, and tall chimneys below the ground. Subterranean streams can flow in the lowermost tunnels.

▲ **Stage 2** In a later stage, the stream has deepened its valley, making the water table level drop. The previously formed cavern system now lies in the unsaturated zone. As water flows through the caverns, it deposits carbonate matter, known as travertine, on exposed rock surfaces in the caverns. Travertine encrustations take many beautiful forms–stalactites (hanging rods), stalagmites (upward-pointing rods), columns, and drip curtains.

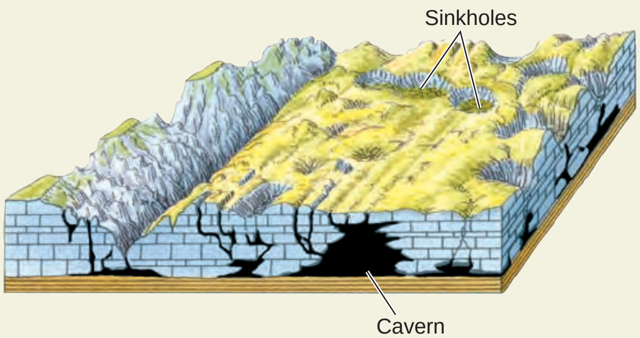
14.10 Cavern development

14.11 Sinkholes

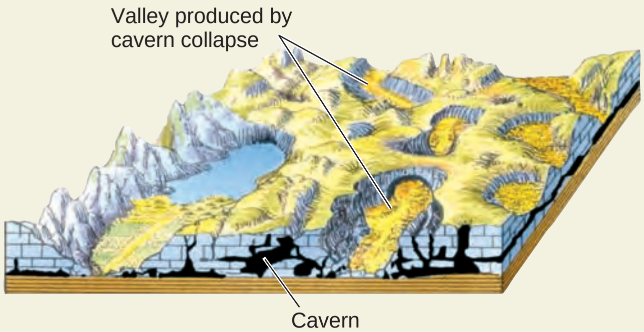
Sinkholes in limestone are created by solution. These sinkholes are near Roswell, New Mexico.

EYE ON THE LANDSCAPE **What else would the geographer see?** The large amount of bare rock visible in many large patches (A) suggests that the limestone is so pure that it leaves little or no residual material behind as it dissolves. Also, look at the vegetation ringing the sinkholes (B). The plants are probably drawing on ground water adjacent to the sinkhole.

14.12 Evolution of a karst landscape



▲ Over time, rainwater dissolves limestone, producing caverns and sinkholes. In warm, humid climates, solution of pure limestone can form towers (left side of diagrams).



▲ Eventually, the caverns collapse, leaving open, flat-floored valleys. Surface streams flow on shale beds beneath the limestone. Some parts of the flat-floored valleys can be cultivated.

topography are the Mammoth Cave region of Kentucky, the Yucatan Peninsula, the Dalmatian coastal area of Croatia, and parts of Cuba and Puerto Rico. The karst landscapes of southern China and west Malaysia are dominated by steep-sided, conical limestone hills or towers (Figure 14.13).

GROUND WATER MANAGEMENT PROBLEMS

Rapid withdrawal of ground water has had a serious impact on the environment in many places. Vast numbers of wells use powerful pumps to draw huge volumes of ground water to the surface—greatly altering nature's balance of ground water discharge and recharge. The yield of a single drilled well ranges from as low as a few hundred liters or gallons per day in a domestic well to many millions of liters or gallons per day for a large industrial or irrigation well (Figure 14.14).

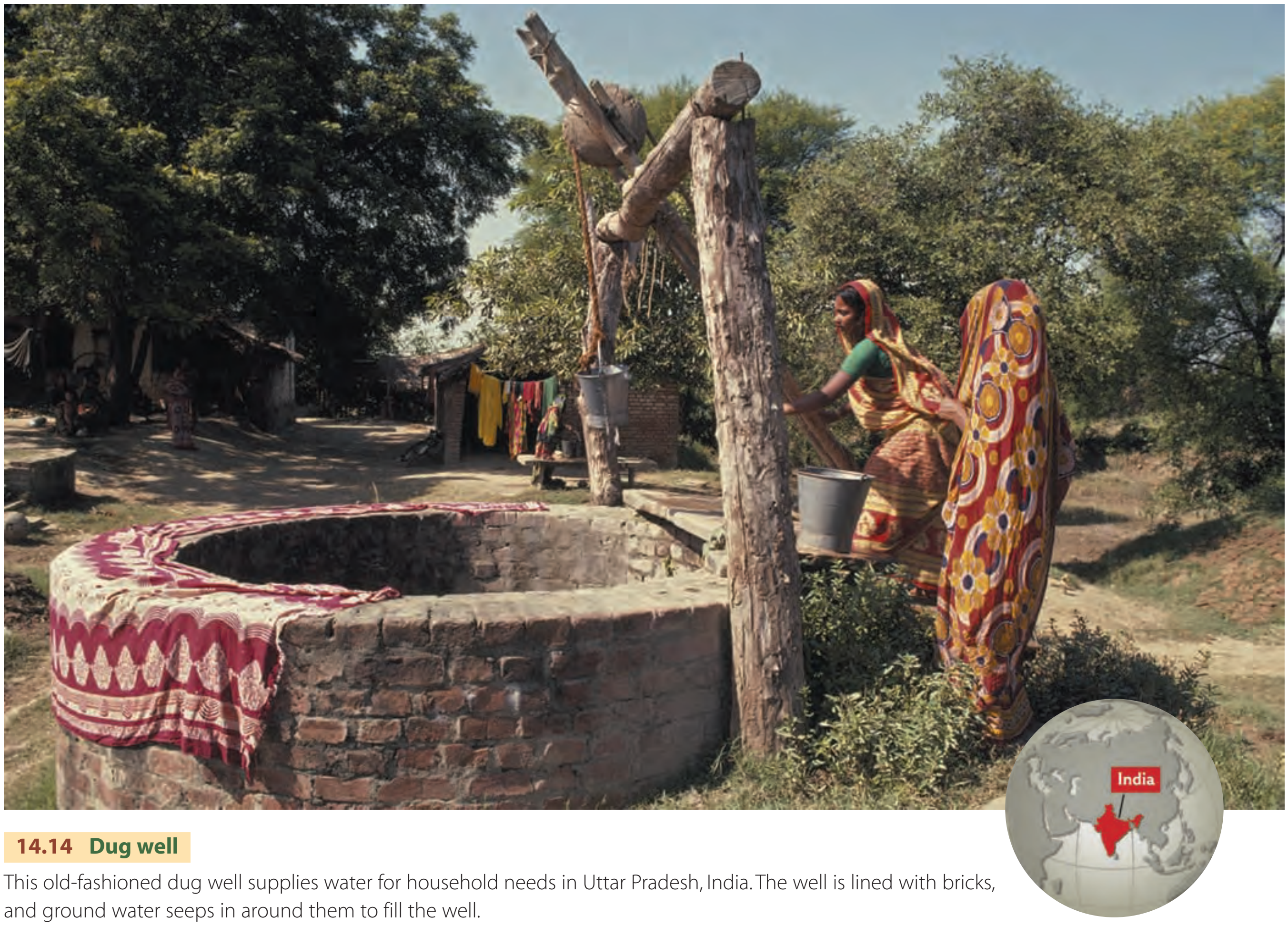
As water is pumped from a well, the level of water in the well drops. At the same time, the surrounding water table is lowered in the shape of a downward-pointing cone, which is called the *cone of depression* (Figure 14.15). The difference in height between the cone tip and the original water table is known as the *drawdown*. Where many wells are in operation, their intersecting cones will lower the water table. The water table is often depleted far faster than it is recharged by water infiltrating downward to the saturated zone. As a result, we are exhausting a natural resource that is not renewable except over very long periods of time.

An important environmental effect of excessive ground water withdrawal is *subsidence* of the ground surface. Venice, Italy, provides a dramatic example of this side effect. Venice was built in the eleventh century on low-lying islands in a coastal lagoon, sheltered from the ocean by a barrier beach. Underlying the area are some 1000 m (about 3300 ft) of sand, gravel, clay, and silt layers, with some layers of peat. Compaction of these soft layers has been going on gradually for centuries under the heavy load of city buildings. However, ground

14.13 Tower karst

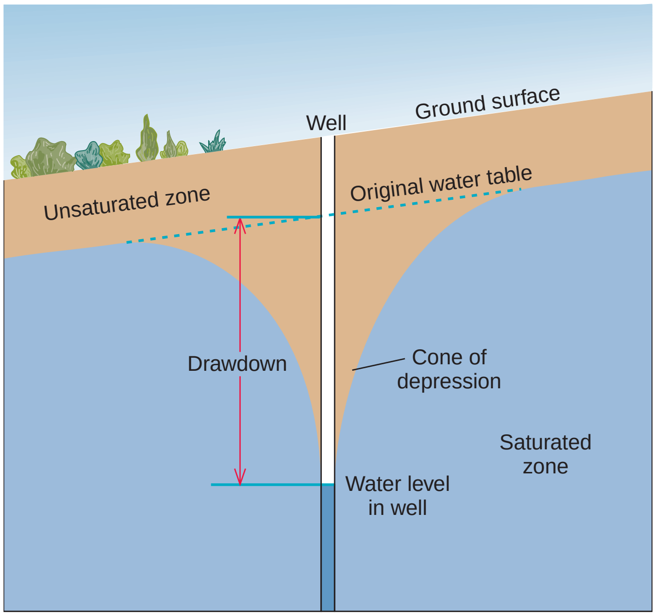
White limestone is exposed in the nearly vertical sides of these towers. Near Guilin (Kweilin), Guangxi Province, southern China.

EYE ON THE LANDSCAPE **What else would the geographer see?** Solution weathering of certain types of bedrock in warm and wet environments can produce a landscape of steep, vertical slopes. Compare these towers (A), formed by solution of limestone, with the fins and grooves of Kauai in Figure 13.9, formed by solution of basaltic lava. Note also the flooded fields (B). They are probably rice paddies in the spring, just before planting with young rice stalks.)



14.14 Dug well

This old-fashioned dug well supplies water for household needs in Uttar Pradesh, India. The well is lined with bricks, and ground water seeps in around them to fill the well.



14.15 Drawdown in a pumped well

As the well draws water, the water table is depressed in a cone shape centered on the well. This *cone of depression* may extend out as far as 15 km (9.3 mi) or more from a well where heavy pumping is continued.

water withdrawal, which has been greatly accelerated in recent decades, has aggravated the condition.

Many ancient buildings in Venice now rest at lower levels and have suffered severe damage as a result of flooding during winter storms on the adjacent Adriatic Sea (Figure 14.16). The problem of flooding during storms is aggravated by the fact that many of the canals of Venice still receive raw sewage, so that the floodwater is contaminated.

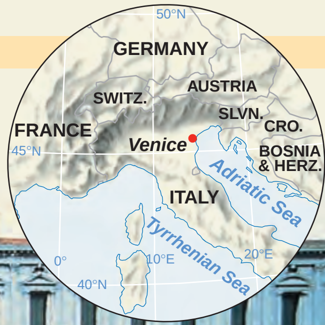
Most of the subsidence was caused by withdrawals of large amounts of ground water from nearby industrial wells, which has now stopped. At present, the rate of subsidence is only about 1 mm per year. However, the threat of flooding and damage to churches and other buildings of great historical value remains. Other cities that have suffered significant land subsidence include Bangkok and Mexico City.

Another major environmental problem is the

Wells draw down the water table at a point, creating a cone of depression. As many wells exploit an aquifer, their cones of depression merge to create a general lowering of the water table.

14.16 Flooding in Venice

Land subsidence has subjected Venice to episodes of flooding by waters of the Adriatic Sea. Here, high water has flooded the Piazza San Marco and an outdoor café.



contamination of wells by pollutants. One common source of these pollutants is the *sanitary landfill*, in which layers of waste are continually buried, usually by sand or clay available on the landfill site (Figure 14.17). This waste is situated in the unsaturated zone, where it reacts with rainwater that infiltrates the ground surface. Modern landfills are often designed with an impervious layer at the bottom, but if this layer fails, infiltrating water picks up a wide variety of chemical compounds from the waste and carries them down to the water table.

> **Sanitary landfills can release pollutants and toxic compounds that infiltrate to the water table, causing ground water contamination that renders adjacent well waters unfit for consumption.**

Salt water can also contaminate the water in coastal wells. Fresh water is less dense than salt water, so a layer of salt water from the ocean can lie below a coastal aquifer. When the aquifer is depleted, the level of salt water rises and eventually reaches the well from below, making the well unusable.

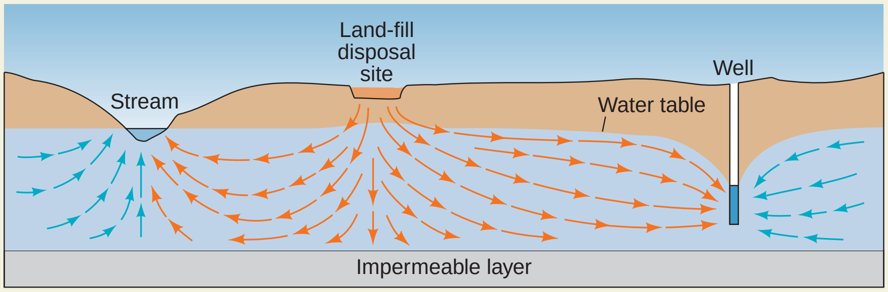
Surface Water

OVERLAND FLOW AND STREAMFLOW

Runoff that flows down the land slopes in broadly distributed sheets is called *overland flow*. This is different from *streamflow*, in which the water runs along a narrow channel between banks. Overland flow can take several forms. Where the soil or rock surface is smooth, the flow may be a continuous thin film, called *sheet flow* (Figure 14.18). If the ground is rough or pitted, overland flow may be made up of a series of tiny rivulets connecting one water-filled hollow with another. On a grass-covered slope, overland flow is divided into countless tiny threads of water, passing around the stems. Even in a heavy and prolonged rain, you might not notice overland flow in

14.17 Ground water contamination

▶ **Sanitary landfill** Rainwater percolating though a landfill, like this one on the eastern shore of Maryland, can pick up contaminants and carry them to the water table, where they can reappear in streams, lakes, or marshes (National Geographic Image Collection).



◀ **Movement of polluted ground water** Polluted water, leached from a waste disposal site, moves toward a supply well (right) and a stream (left).

14.18 Sheet flow

Following a downpour, a thin sheet of water flows across this semiarid grassland near Holbrook, Arizona.

progress on a sloping lawn. On heavily forested slopes, overland flow may be entirely concealed beneath a thick mat of decaying leaves.

Overland flow eventually creates streamflow. We can define a **stream** as a long, narrow body of water flowing through a channel and moving to lower levels under the force of gravity. The **stream channel** is a narrow trough, shaped by the forces of flowing water. A channel may be so narrow that you can easily jump across it, or, in the case of the Mississippi River, it may be as wide as 1.5 km (about 1 mi) or more.

The water meets resistance as it flows because of friction with the channel walls. So, water close to the bed and banks moves more slowly than water in the central part of the flow (Figure 14.19). If the channel is straight and symmetrical, the line of maximum velocity is located in midstream. If the stream curves, the maximum velocity shifts toward the bank on the outside of the curve.

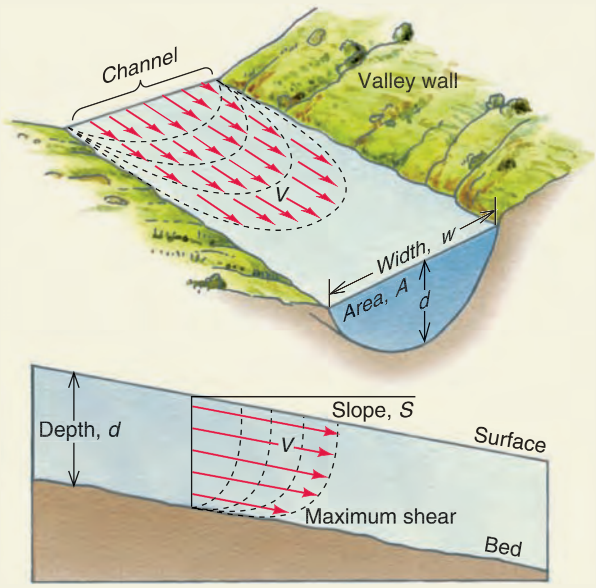
In all but the most sluggish streams, the movement of water is affected by *turbulence*. If we could follow a particular water molecule, we'd see it travel a highly irregular, corkscrew path as it is swept downstream. But if we measure the water velocity at a certain fixed point for several minutes, we'll see that the average motion is in a downstream direction.

The rate of water flow in a stream is called its **discharge**, which is measured in cubic meters (cubic feet) per second. Discharge is determined by the product of the stream's cross section and the mean velocity of the water (Figure 14.19). When the gradient, or slope, of the stream channel is steep, the force of gravity will act more strongly so the water will flow faster. When the slope is gentler, the flow will be slower.

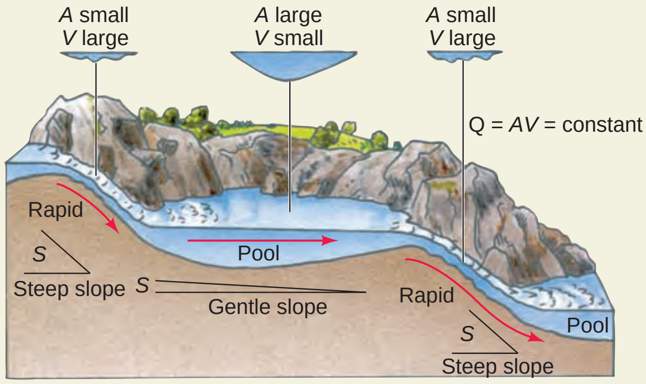
In stretches of *rapids*, where the stream flows

The discharge of a stream measures its volume rate of flow. It is the product of the mean velocity and the cross-sectional area.

14.19 Characteristics of streamflow



▲ Friction slows flowing water near the banks and bed of the stream, so the velocity of flow is greatest in the middle and at the top of the stream.



▲ This figure shows how average velocity (*V*), cross-sectional area (*A*), and slope (*S*) change between pools and rapids. The cross-sectional area and average velocity of a stream can change within a short distance, but the volume of water per unit time passing through a cross section of the stream at that location—known as the stream *discharge (Q)*—remains constant.

swiftly, the stream channel will be shallow and narrow. In *pools*, where the stream flows more slowly, the stream channel will be wider and deeper to maintain the same discharge. Sequences of pools and rapids can be found along streams of all sizes.

Figure 14.20 shows the relative discharge of major rivers of the United States. The mighty Mississippi with its tributaries dwarfs all other North American rivers. The Columbia River, draining a large segment of the Rocky Mountains in southwestern Canada and the northwestern United States, and the Great Lakes, discharging through the St. Lawrence River, also have large discharges.

The discharge of major rivers increases downstream. That's a natural consequence of the way streams and rivers combine to deliver runoff and sediment to the oceans. The general rule is the larger the cross-sectional area of the stream, the lower the gradient. Great rivers, such as the Mississippi and Amazon, have gradients so low that they can be described as "flat." For example, the water surface of the lower Mississippi River falls in elevation about 3 cm for each kilometer of downstream distance (1.9 in. per mi).

DRAINAGE SYSTEMS

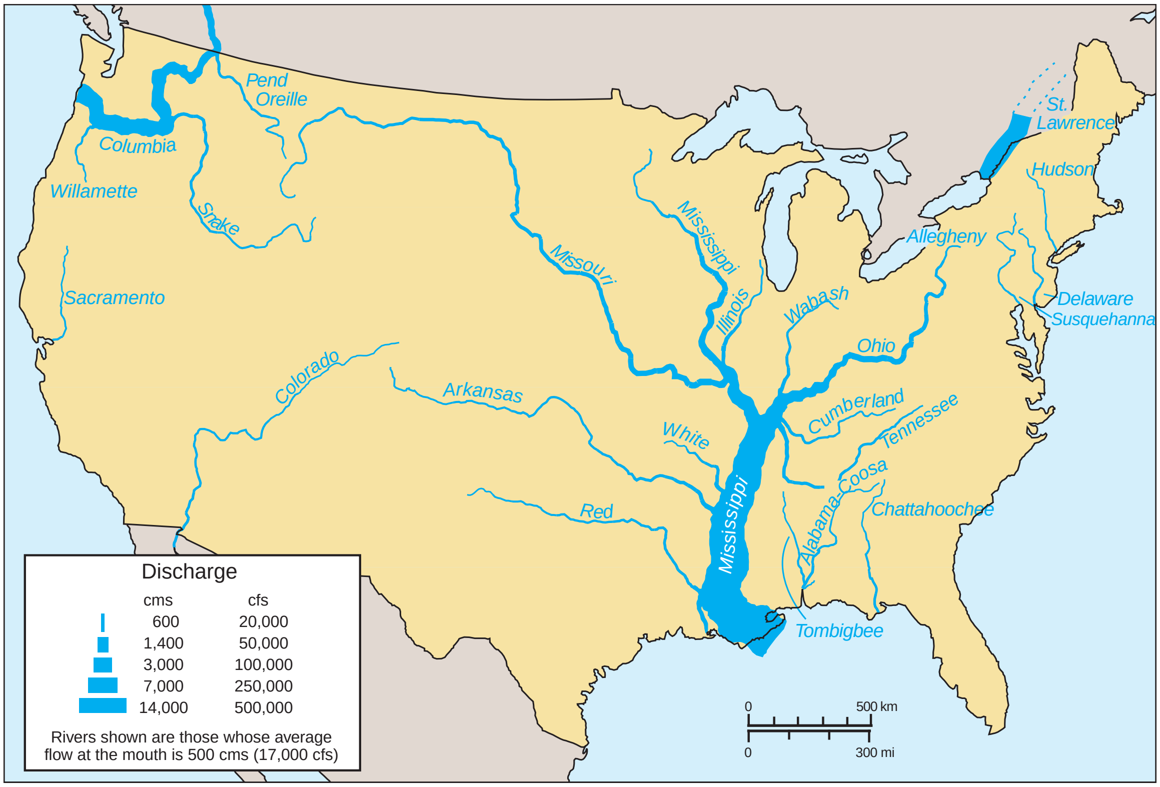
As runoff moves to lower and lower levels and eventually to the sea, it becomes organized into a branched network of stream channels. This network and the sloping ground surfaces next to the channels that contribute overland flow to the streams are together called a **drainage system**. The *drainage divides* mark the boundary between slopes that contribute water to different streams or drainage systems. The entire system is bounded by an outer drainage divide that outlines a more-or-less pear-shaped **drainage basin** or *watershed* (Figure 14.21). Drainage systems funnel overland flow into streams and smaller streams into larger ones.

A drainage basin, or watershed, consists of a branched network of stream channels and adjacent slopes that feed the channels. It is bounded by a drainage divide.

Streamflow and Floods

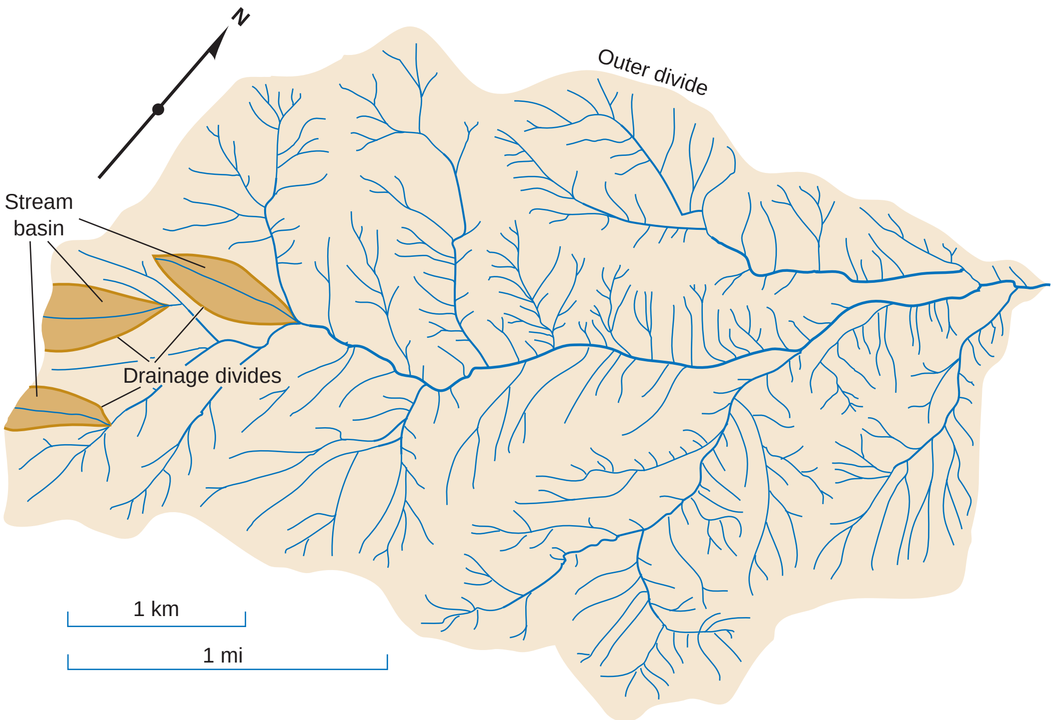
Stream discharge increases after heavy rainfall or snowmelt. But there is a delay in this increase because it takes time for the water to move into stream channels. The length of this delay depends, among other factors, on the size of the drainage basin feeding the stream. Larger drainage basins show a longer delay.

It's easiest to look at the relationship between stream discharge and precipitation on a *hydrograph*, which plots



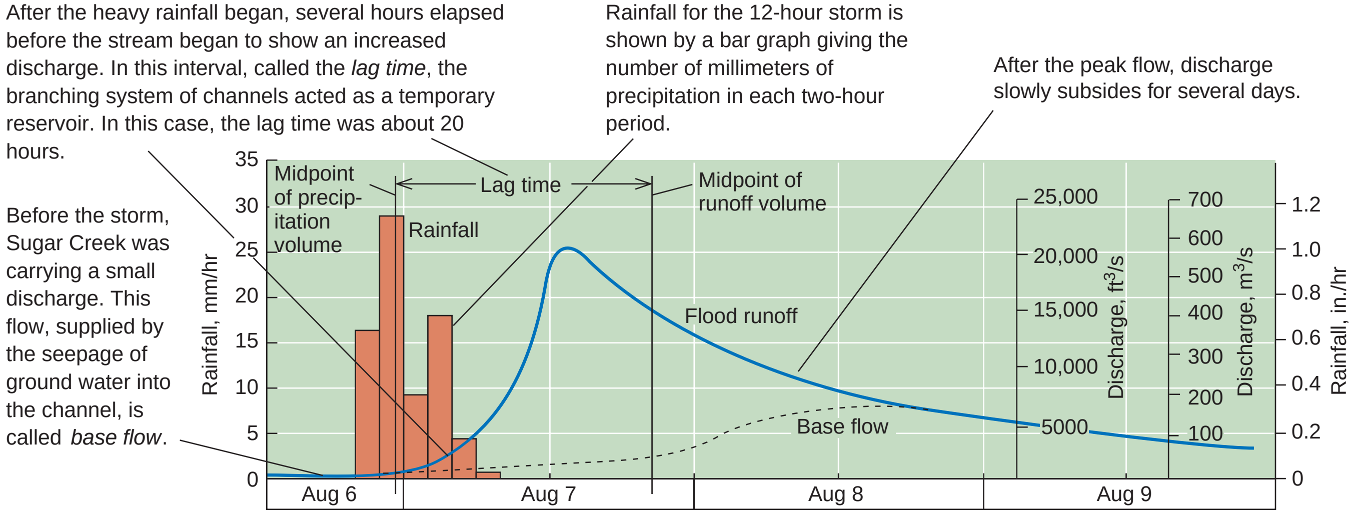
14.20 River discharge

This schematic map shows the relative magnitude of the discharge of U.S. rivers. Width of the river as drawn is proportional to mean annual discharge.



14.21 Channel network of a stream

Smaller and larger streams merge in a network or *drainage system* that carries runoff downstream. Each small tributary has its own small *drainage basin*, bounded by *drainage divides*. An outer drainage divide marks the stream's watershed at any point on the stream.



14.22 Sugar Creek hydrograph

The graph shows the discharge of Sugar Creek (smooth line), the main stream of the drainage basin, during a four-day period that included a heavy rainstorm. The average total rainfall over the watershed of Sugar Creek was about 150 mm (6 in.). About half of this amount passed down the stream within three days' time. Some rainfall was held in the soil as soil water, some evaporated, and some infiltrated to the water table to be held in long-term storage as ground water.

the discharge of a stream with time at a particular stream gauge. Figure 14.22 is a hydrograph for a drainage basin of about 800 km² (300 mi²) in Ohio, with a moist continental climate. Comparing the timing of the midpoints of rainfall volume and the runoff volume, we see that the *lag time* for this hydrograph is about 20 hours. In general, larger streams have longer lag times.

In humid climates, where the water table is high and normally intersects the important stream channels, the hydrographs of larger streams clearly show the effects of two sources of water–*base flow* and overland flow. Figure 14.23 is a hydrograph of the Chattahoochee River in Georgia, a fairly large river draining a watershed of 8700 km² (3350 mi²), much of it in the southern Appalachian Mountains.

A hydrograph plots streamflow with time. Peaks in the hydrograph occur after rainfall events. Between rains, streamflow falls to base flow, which is fed by ground water seepage into the stream's channels.

URBANIZATION AND STREAMFLOW

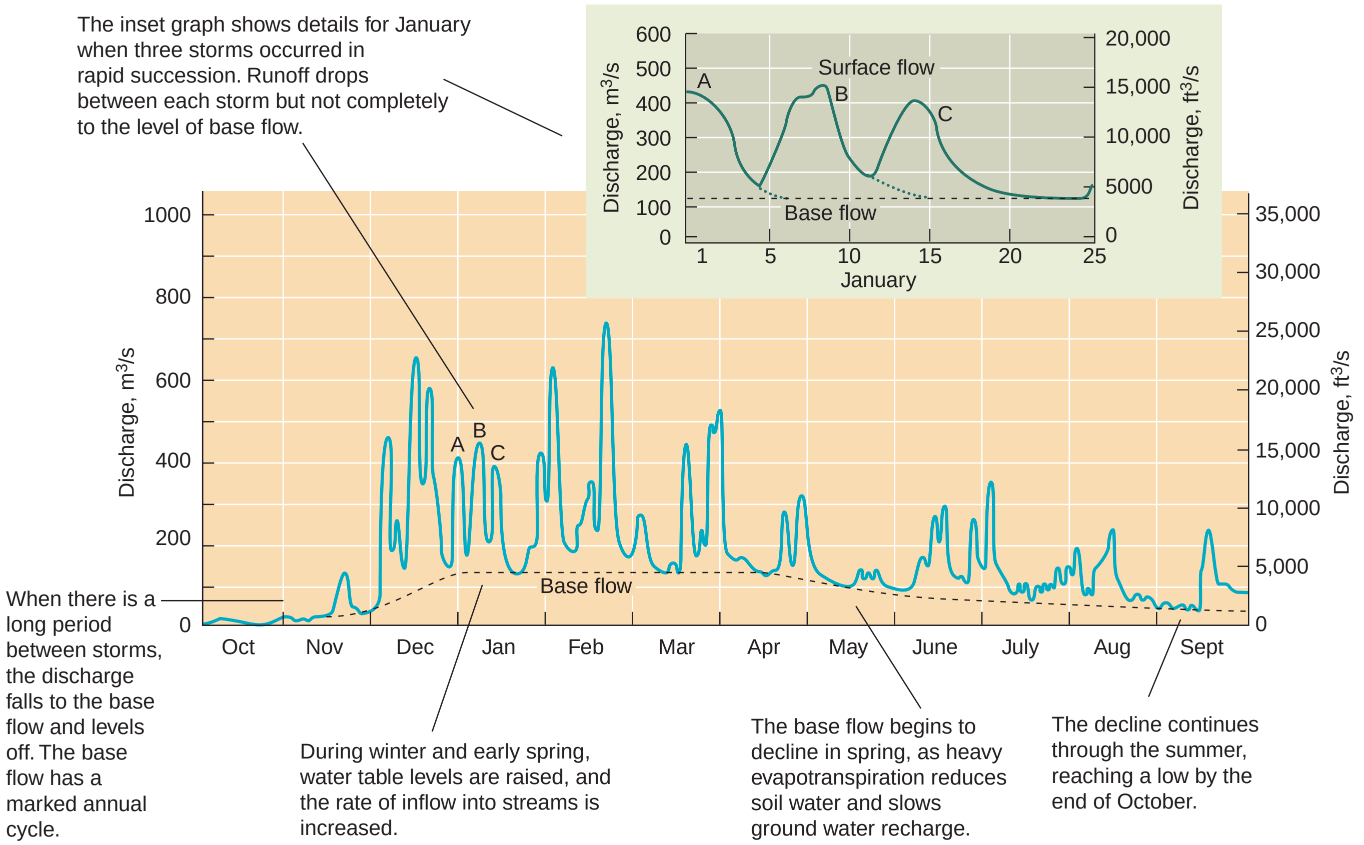
The growth of cities and suburbs affects the flow of small streams in two ways. First, it is far more difficult for water to infiltrate the ground, which is increasingly covered in buildings, driveways, walks, pavements, and parking lots (Figure 14.24). In a closely built-up residential area, 80 percent of the surface may be impervious to water. This in turn increases overland flow, making flooding more common during heavy storms for small watersheds lying largely within the urbanized area. It's also harder to recharge the ground water beneath. The reduction in ground water decreases the base flow to channels in the same area. So, in dry periods, stream discharges will tend to be lower in urban areas, while in wet periods, the chance and amount of flooding rise.

A second change caused by urbanization comes from the introduction of *storm sewers.* This system of large underground pipes quickly carries storm runoff from paved areas directly to stream channels for discharge. This shortens the time it takes runoff to travel to channels, while the proportion of runoff is increased by the expansion in impervious surfaces. Together, these changes reduce the lag time of urban streams and increase their peak discharge levels. Many rapidly expanding suburban communities are finding that low-lying, formerly flood-free, residential areas now experience periodic flooding as a result of urbanization.

RIVER FLOODS

When the discharge of a river cannot be accommodated within its normal channel, the water spreads over the adjoining ground, causing a **flood**. Often the flooded area is cropland or forest, but sometimes it is occupied by houses, factories, or transportation corridors (Figure 14.25).

Most rivers of humid climates have a **floodplain**—a low area bordering the channel on one or both sides (Figure 14.26). Annual inundation is considered to be a flood, even though it is expected and it doesn't prevent crop cultivation after the flood has subsided. Annual



14.23 Chattahoochee River hydrograph

This hydrograph shows the fluctuating discharge of the Chattahoochee River, Georgia, through a typical year. The sharp, abrupt fluctuations in discharge are produced by overland flow after rainfall periods lasting one to three days.

14.24 Urban waterflow

Impervious surfaces like this street in Bangkok increase runoff and hasten the flow of water into streams and rivers draining urban environments (National Geographic Image Collection).

14.25 River flooding

▼ **Harper's Ferry** Historic town centers are often close to rivers and subjected to river flooding. Harper's Ferry, West Virginia, is at the junction of the Potomac and Shenandoah rivers (National Geographic Image Collection).

▼ **Sainte Genevieve** Large rivers, like the Mississippi, can flood extensive areas far from their banks. Pictured here is a home in Sainte Genevieve, Missouri, surrounded by sandbags in the great Mississippi flood of 1993 (National Geographic Image Collection).

14.26 Limpopo River floodplain

During flooding, large rivers overflow their banks and fill their floodplains with water. Deposition of silt and fine sediment over time produces a wide plain of flat ground. This example is in the Maputo Elephant Reserve, Mozambique (National Geographic Image Collection).

flooding doesn't interfere with the growth of dense forests, which are widely distributed over low, marshy floodplains in all humid regions of the world. The National Weather Service designates a particular water surface level as the *flood stage* for a particular river at a given place. If water rises above this critical level, the floodplain will be inundated. Once in 30 to 50 years on average, we see cases in which even higher discharges cause rare and disastrous floods that inundate ground well above the floodplain.

> **A flood occurs when a river rises to leave its bed and cover adjacent lands, which are called the floodplain. The height of the river at that time and place is called the flood stage.**

Flash floods are characteristic of streams draining small watersheds with steep slopes. These streams have short lag times of only an hour or two, so when there's intense rainfall the stream quickly rises to a high level. The flood arrives as a swiftly moving wall of turbulent water, sweeping away buildings and vehicles in its path. In arid western watersheds, great quantities of coarse rock debris are swept into the main channel and travel with the floodwater, producing debris floods. In forested landscapes, tree limbs and trunks, soil, rocks, and boulders are swept downstream in the floodwaters. Flash floods often occur too quickly to warn people, so they can cause significant loss of life.

The National Weather Service operates a River and Flood Forecasting Service through offices located at strategic points along major river systems of the United States. When a flood threatens, forecasters analyze precipitation patterns and the progress of high waters moving downstream. They develop specific flood forecasts after examining the flood history of the rivers and streams concerned. The forecasts are then delivered to communities that might be affected.

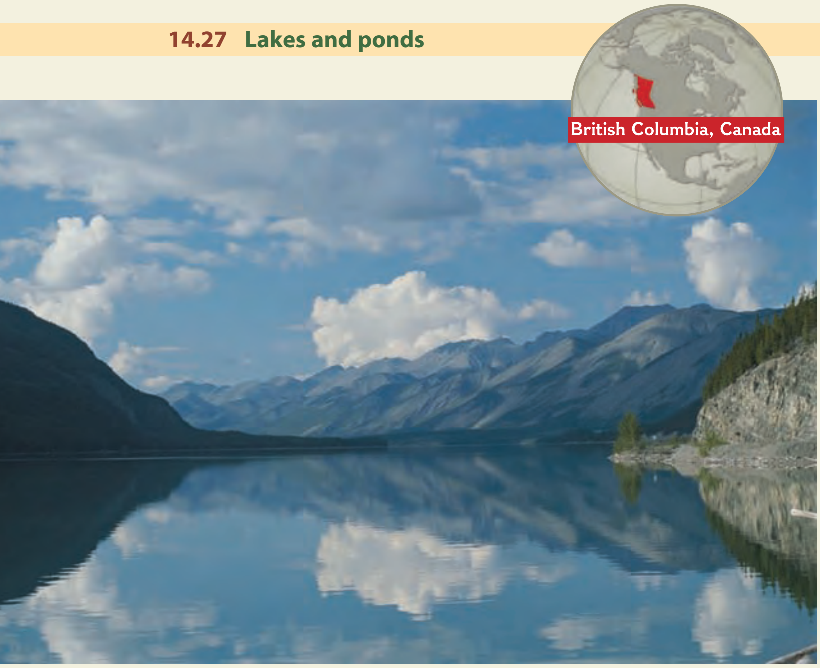
GEODISCOVERIES Surface Water
Take a journey down the Rhine River through the heart of Europe, starting high in the Alps and ending at the Atlantic coast of The Netherlands. A video.

Lakes

A **lake** is a body of standing water with an upper surface that is exposed to the atmosphere and does not have an appreciable gradient. Ponds, marshes, and swamps with standing water can all be included under the definition of a lake (Figure 14.27). Lakes receive water from streams, overland flow, and ground water, and so they form part of drainage systems. Many lakes lose water at an outlet, where water drains over a dam—natural or constructed—to become an outflowing stream. Lakes also lose water by evaporation. Lakes, like streams, are landscape features but are not usually considered to be landforms.

Lakes are quite important as sources of fresh water and food, such as fish. They can also be used to generate hydroelectric power, using dams (Figure 14.28). And, of course, lakes and ponds are sites of natural beauty. Lake basins, like stream channels, are true landforms, created by a number of geologic processes and ranging widely in size. For example, the tectonic process of crustal faulting creates large, deep lakes. Lava flows often form a dam in a river valley, causing water to back up as a lake. Landslides can also suddenly create lakes.

14.27 Lakes and ponds



▲ **Lake** Lakes are usually larger and deeper than ponds. Many lakes are artificial, dammed to provide water supplies or hydroelectric power. Muncho Lake, British Columbia (National Geographic Image Collection).

▲ **Pond** The shallow waters of this pond in Nicolet National Forest, Wisconsin, support an almost continuous cover of grasses and sedges (National Geographic Image Collection).

Where there aren't enough natural lakes, we create them by placing dams across the stream channels. Many regions that once had almost no lakes now have many. Some are small ponds built to serve ranches and farms, while others cover hundreds of square kilometers. In some areas, the number of artificial lakes is large enough to have significant effects on the region's hydrologic cycle.

On a geologic time scale, lakes are short-lived features. Lakes disappear by one of two processes, or a combination of both. First, lakes that have stream outlets will be gradually drained as the outlets are eroded to lower levels. Even when the outlet lies above strong bedrock, erosion will still occur slowly over time. Second, inorganic sediment carried by streams enters the lake and builds up, along with organic matter produced by plants and animals within the lake. Eventually, the lake fills, forming a boggy wetland with little or no free water surface. Many former freshwater ponds have become partially or entirely filled by organic matter from the growth and decay of water-loving plants.

Lakes can also disappear when the climate changes. If precipitation is reduced, or temperatures and net radiation increase, evaporation can exceed input and the lake will dry up. Many former lakes of the southwestern United States that flourished during the Ice Age have now shrunk greatly or have disappeared entirely.

Lakes serve as vital reservoirs of fresh water on the land. They are formed in many different ways but are generally short-lived over geologic time.

The water level of lakes and ponds in moist climates closely coincides with the surrounding water table (Figure 14.29). The water surface is maintained at this level as ground water seeps into the lake and as precipitation runs off.

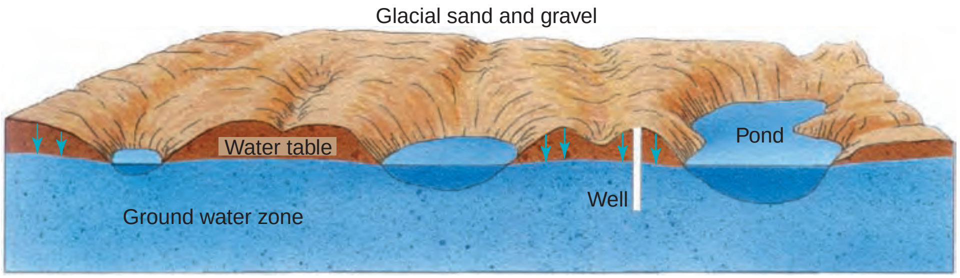
THE GREAT LAKES

The *Great Lakes*—Superior, Huron, Michigan, Erie, and Ontario—along with their smaller bays and connecting lakes form a vast network of inland waters in the heart of North America (Figure 14.30). They contain 23,000 km^3 (5500 mi^3) of water—about 18 percent of all the fresh, surface water on Earth. Only the polar ice caps and Lake Baikal in Siberia have a larger volume. Of the Great Lakes, Lake Superior is by far the largest. In fact, the volume of the other Great Lakes combined would not fill its basin. The Great Lakes watershed contains a population of about 33 million people—22.8 million Americans and 9.2 million Canadians. The lakes are an essential resource for drinking water, fishing, agriculture, manufacturing, transportation, and power generation.

The Great Lakes are largely the legacy of Ice Age glaciation, formed in a low interior basin of old, largely sedimentary rock. During at least four major periods in the last two million years, ice sheets advanced over this

14.28 Hydroelectric dam

Mountain rivers are often dammed for hydropower because of their narrow canyons and steep slopes. Pictured is the Picote Dam on the Douro River, Portugal (National Geographic Image Collection).

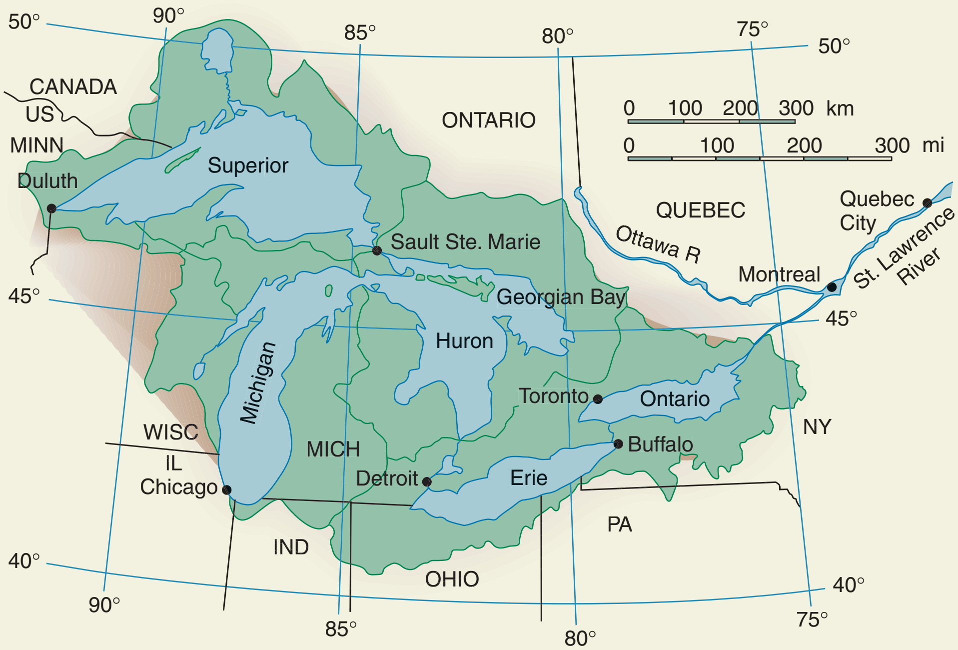


14.29 Freshwater ponds

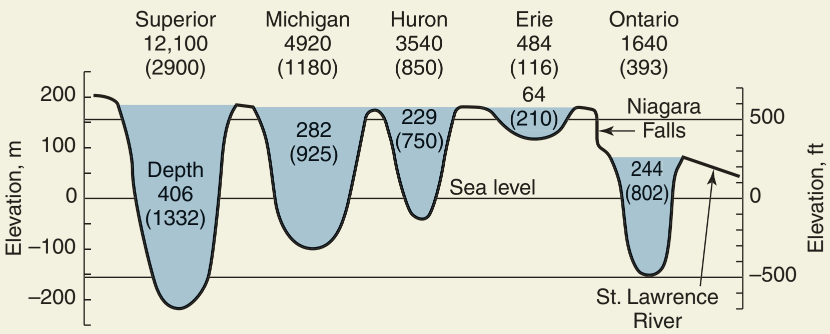
A sketch of freshwater ponds in sandy glacial deposits on Cape Cod, Massachusetts. The water level of the ponds is close to the level of the water table.

14.30 The Great Lakes

▼ **The Great Lakes and their watersheds** The Great Lakes constitute a vast water resource lying astride the boundary between Canada and the United States.



▶ **Volumes, elevations, and depths of the five Great Lakes** Volumes are shown below the name of each lake in km³ (mi³). Depths are shown in m (ft).



basin, scouring the rocks and lowering the surface by as much as 500 m (1600 ft) below the surrounding terrain. As the continental ice sheets of the last glacial advance retreated, water filled these depressions, creating lakes dammed by glacial deposits and melting ice. With the final melting of the ice and a slow, gentle uplift of the terrain, the lakes eventually acquired their present shapes and configurations.

Because of their position close to centers of population and agricultural development, the Great Lakes have suffered significant water pollution. Lake Erie, with the smallest water volume and its heavily developed coastal region, was hard hit in the 1960s and 1970s. Persistent organic compounds have also been a source of concern. These include organic substances largely of industrial origin that are long-lasting, highly mobile in the aquatic system, and toxic in very small amounts. Many of these compounds accumulate up the food chain as predators consume contaminated prey. In 1987 an American and Canadian commission identified 43 "Areas of Concern," with 28 in the United States and 15 in Canada. Remedial action plans were proposed and implemented, and many of the sites have experienced much improvement.

The Great Lakes are a vast North American water resource, although they have suffered somewhat from water pollution.

SALINE LAKES AND SALT FLATS

In arid regions, we find lakes with no surface outlet. In these lakes, the average rate of evaporation balances the average rate of stream inflow. When the rate of inflow increases, the lake level rises and the lake's surface area increases, allowing more evaporation—striking a new balance. Similarly, if the region becomes more arid, reducing input and increasing evaporation, the water will fall to a lower level.

Salt often builds up in these lakes. Streams bring dissolved solids into the lake, and since evaporation removes only pure water, the salts remain behind. The *salinity*, or "saltiness," of the water slowly increases. Eventually, the salinity level reaches a point where salts are precipitated as solids (Figure 14.31).

Sometimes the surfaces of such lakes lie below sea level. An example is the Dead Sea, with a surface elevation of −396 m (−1299 ft) (Figure 14.32). The largest of all lakes, the Caspian Sea, has a surface elevation of −25 m (−82 ft). Both of these large lakes are saline. Another saline inland lake is the Aral Sea (Figures 14.1, 14.2).

In some cases the lake is missing. In regions of high evapotranspiration and low precipitation, we find shallow empty basins covered with salt deposits instead of lakes. These are called *salt flats* or dry lakes (Figure 14.33). On rare occasions, these flats are covered by a shallow layer of water, brought by flooding streams.

DESERT IRRIGATION

Desert irrigation is as old as civilization itself. Two of the earliest civilizations—Egypt and Mesopotamia—relied heavily on irrigation with large supplies of water from nondesert sources. For Egypt and Mesopotamia, the water sources of ancient times were the rivers that cross the desert but derive their flow from regions that have a water surplus. These are referred to as *exotic rivers* because their flows are derived from an outside region.

Salinization and waterlogging are undesirable side effects of long-continued irrigation. Arid regions watered by exotic rivers are most affected.

14.31 Salt encrustations

These salt encrustations at the edge of Great Salt Lake, Utah, were formed when the lake level dropped during a dry period.

14.32 Dead Sea

Swimmers in the Dead Sea float easily on the dense, salty water (National Geographic Image Collection).

14.33 Bonneville Salt Flats

Salt flats are dry lake bottoms covered with mineral salts and sediments. One of the most famous is the Bonneville Salt Flats, which has a very uniform and smooth surface and is used as a speedway for high-speed race cars (National Geographic Image Collection).

Irrigation systems in arid lands can suffer from two undesirable side effects: salinization and waterlogging of the soil (Figure 14.34). *Salinization* occurs when salts build up in the soil to levels that inhibit plant growth. This happens when an irrigated area loses large amounts of soil water through evapotranspiration. Salts contained in the irrigation water remain in the soil and increase to high concentrations.

Salinization can be prevented or cured by flushing the soil salts downward to lower levels by the use of more water. This remedy requires greater water use than for crop growth alone. In addition, new drainage systems must be installed to dispose of the excess salt water.

Waterlogging occurs when irrigation with large volumes of water causes a rise in the water table, bringing the zone of saturation close to the surface. Most food crops

14.34 Salinization

Salinization from long-continued irrigation has turned these once-productive fields into a barren expanse of salty earth in the Indus Valley, Sindh Province, Pakistan. Agricultural areas of major salinization include the Indus River valley in Pakistan, the Euphrates valley in Syria, the Nile delta of Egypt, and the wheat belt of western Australia. In the United States, extensive regions of heavily salinized agriculture are found in the San Joaquin and Imperial valleys of California.

cannot grow in perpetually saturated soils. When the water table rises to the point at which upward movement under capillary action can bring water to the surface, evaporation is increased and salinization is intensified.

Surface Water as a Natural Resource

Fresh surface water is a basic natural resource essential to human agricultural and industrial activities (Figure 14.35). Runoff held in reservoirs behind dams provides water supplies for great urban centers, such as New York City and Los Angeles, as well as irrigation water for agriculture. We can also generate hydroelectric power from surface water where the gradient of a river is steep. If the gradient is gentle, we can travel along surface water.

But our heavily industrialized society requires enormous supplies of fresh water to sustain it, and demand is increasing. Urban dwellers consume 150 to 400 l (50 to 100 gal) of water per person per day in their homes. We use large quantities of water in air conditioning units and power plants, and much of this water is obtained from surface water.

Unlike ground water, which represents a large water storage body, fresh surface water in the liquid state is stored only in small quantities. (The Great Lakes system is an exception.) About 20 times as much ground water is available globally than water held in freshwater lakes. And water in streams is about one one-hundredth of that in lakes. We build dams to help store runoff that would otherwise escape to the sea. But even if the reservoir is full, we can still only use as much water as is naturally supplied by inflowing rivers in the long run.

Human society is heavily dependent on fresh surface water for irrigation, drinking water, and industrial usage. However, fresh water is a limited resource.

POLLUTION OF SURFACE WATER

Streams, lakes, bogs, and marshes provide specialized habitats for plants and animals. These habitats are particularly sensitive to changes in the water balance and in water chemistry. Our industrial society not only makes radical changes to the flow of water by constructing dams, irrigation systems, and canals, but it also pollutes and contaminates our surface waters with a large variety of wastes.

14.35 Clean catch

We rely on clean water for food, recreation, and countless other uses. This Alaskan fisherman is displaying a silver salmon, freshly caught on Kodiak Island, Alaska.

14.36 Water pollution

Acid mine drainage is a major problem in areas of strip mining (National Geographic Image Collection).

There are many different sources of water pollutants. Some industrial plants dispose of toxic metals and organic compounds directly into streams and lakes. Many communities still discharge untreated or partly treated sewage wastes into surface waters. In urban and suburban areas, deicing salt and lawn conditioners (lime and fertilizers) enter and pollute streams and lakes, and also contaminate ground water. In agricultural regions, fertilizers and livestock wastes are important pollutants. Mining and processing of mineral deposits also pollute water. Surface water can even be contaminated by radioactive substances released from nuclear power and processing plants.

Many chemical compounds dissolve in water by forming *ions*—charged forms of molecules or atoms. Among the common chemical pollutants of both surface water and ground water are sulfate, chloride, sodium, nitrate, phosphate, and calcium ions. Sulfate ions enter runoff from both polluted urban air and sewage. Chloride and sodium ions come from polluted air and from deicing salts used on highways. Fertilizers and sewage also contribute nitrate and phosphate ions. Nitrates can be highly toxic in large concentrations and are difficult and expensive to remove.

Phosphate and nitrate are plant nutrients and can encourage algae and other aquatic plants to grow to excessive amounts in streams and lakes. In lakes, this process is known as *eutrophication* and is often described as the "aging" of a lake. Nutrients stimulate plant growth, producing a large supply of dead organic matter in the lake. Microorganisms break down this organic matter but require oxygen in the process. But oxygen is normally present only in low concentrations because it dissolves only slightly in water. The microorganisms use up oxygen to the point where other organisms, including desirable types of fish, cannot survive. After a few years of nutrient pollution, the lake takes on the characteristics of a shallow pond that has been slowly filled with sediment and organic matter over thousands of years.

Acid mine drainage is a particularly important form of chemical pollution of surface water in parts of Appalachia, where abandoned coal mines and strip-mine workings are concentrated (Figure 14.36). Ground water emerges from abandoned mines as soil water percolates through strip-mine waste banks. This water contains sulfuric acid and various salts of metals, particularly of iron. In sufficient concentrations, the acid from these sources is lethal to certain species of fish and has at times caused massive fish kills.

Plants and animals have also been killed by toxic metals, including mercury, pesticides, and a host of other industrial chemicals introduced into streams and lakes. Sewage introduces live bacteria and viruses—classed as biological pollutants—that can harm humans and animals alike. Another form of pollution is *thermal pollution*, which is created when heat, generated from fuel combustion and from the conversion of nuclear fuel to electricity, is discharged into the environment. Heated water put into streams, estuaries, and lakes can have drastic effects on local aquatic life. The impact can be quite large in a small area.

Water pollutants include various types of common ions and salts, as well as heavy metals, organic compounds, and acids. Excessive plant nutrients in runoff feeding lakes can lead to eutrophication.

GEODISCOVERIES **Web Quiz**

Take a quick quiz on the key concepts of this chapter.

A Look Ahead

This chapter has focused on processes of water flow, both within the ground and on the Earth's surface. These processes respond to the local and regional balance of the hydrologic cycle that provides precipitation on the land. The pattern of streams on the landscape acts as an efficient system to collect and carry runoff to the sea or to inland basins. However, this cannot happen unless the gradients of slopes and streams are adjusted so that water keeps flowing downhill. This means that the landscape is shaped and organized into landforms that are an essential part of the drainage system. The shaping of landforms within the drainage system occurs as running water erodes the landscape, which is the subject of the next chapter.

GEODISCOVERIES **Web Links**
Explore caves around the world, including the famous cave paintings of Lascaux in France. Learn more about the causes and effects of floods.

IN REVIEW FRESH WATER OF THE CONTINENTS

- The Aral Sea shrank substantially because its inflow was diverted for upstream irrigation. A small northern portion, the Small Sea, is now being rehabilitated.
- The fresh water of the lands accounts for only a small fraction of the Earth's water.
- Precipitation over land follows three paths: to the atmosphere as *evapotranspiration*, to ground water through **infiltration**, and to streams and rivers as **runoff**.
- **Ground water** occupies the pore spaces in rock and regolith. The **water table** marks the upper surface of the *saturated zone* of ground water, where pores are completely full of water.
- Ground water moves in slow paths deep underground, recharging rivers, streams, ponds, and lakes by upward seepage and thus contributing to runoff.
- The water table rises under divides and dips down to the surface of lakes and rivers.
- Porous rock layers, such as sandstone, are good **aquifers**. Impervious layers, such as shale, are *aquicludes* that block the flow of ground water.
- Solution of limestone by ground water can produce *limestone caverns* and create *sinkholes*. A landscape of sinkholes lacking streams is called *karst*.
- Wells draw down the water table and create a *cone of depression*. Large wells can easily lower the water table more quickly than it can be recharged.
- Land subsidence can occur when water is pumped out of aquifers. Venice is an example.
- Ground water contamination can occur when precipitation percolates through contaminated soils or waste materials. Coastal wells can experience saltwater contamination from excessive withdrawals of fresh water.
- Runoff includes *overland flow*, moving as a sheet across the land surface, and *streamflow* in **streams** and rivers, which is confined to a *channel*.
- In a stream channel, water moves most rapidly near the center. Streamflow is turbulent and experiences friction at the bed and banks.
- The **discharge** of a stream measures the flow rate of water moving past a given location. Rapids have a steeper slope, smaller cross-sectional area, and higher flow velocity than pools.
- Discharge increases downstream as tributary streams add more runoff. Large rivers have very low gradients.
- Rivers and streams are organized into a **drainage system** that moves runoff from slopes into channels and from smaller channels into larger ones.
- The *hydrograph* plots the discharge of a stream at a location through time. After a storm, the midpoint of storm discharge differs from the midpoint of precipitation by a *lag time*.
- Annual hydrographs of streams from humid regions show an annual cycle of *base flow* with superimposed discharge peaks from individual rainfall events.
- Because urban surfaces are largely impervious, urban streams have short lag times and higher peak discharges.
- **Floods** occur when discharge increases and water spreads over the *floodplain*, inundating low fields and forests near the channel. High discharges can bring damaging high waters to developed areas.
- *Flash floods* occur in small, steep watersheds and can be highly destructive. Water and debris descends rapidly along the channel, damaging structures and developments.
- **Lakes** are sources of fresh water, recreation, and hydroelectric power. Lakes shrink and disappear as their outlet is eroded and they fill with sediment.
- The *Great Lakes* are an enormous resource of fresh water for North America. But water pollution is a constant concern because of development along lake shores.
- Where lakes occur in inland basins, they are often saline. Some large saline inland lakes are below sea level. When climate changes, such lakes can dry up, creating *salt flats*.
- Irrigation is the diversion of fresh water from streams and rivers to supply the water needs of crops. In desert regions, where irrigation is most needed, *salinization* and *waterlogging* can occur, reducing productivity and eventually creating unusable land.
- Ground water and surface water are essential natural resources, and civilization depends on abundant supplies of fresh water for many uses. The amount of fresh water stored in streams, rivers, and lakes is small compared to the amount of ground water.
- Water pollution arises from many sources, including industrial sites, sewage treatment plants, agricultural

activities, mining, and processing of mineral deposits. Sulfate, nitrate, phosphate, chloride, sodium, and calcium ions are frequent contaminants.

- *Acid mine drainage* coupled with toxic metals, pesticides, and industrial chemicals are important hazards.

KEY TERMS

infiltration, p. 470
runoff, p. 472
overland flow, p. 472
ground water, p. 472
water table, p. 472
aquifer, p. 473
karst, p. 474
stream, p. 479
stream channel, p. 479
discharge, p. 479
drainage system, p. 480
drainage basin, p. 480
flood, p. 482
floodplain, p. 482
lake, p. 485

REVIEW QUESTIONS

1. What has happened to the Aral Sea in the last 40 years and why? What are its future prospects?
2. What happens to precipitation falling on land? What processes are involved? Use the terms *infiltration, runoff,* and *overland flow* in your answer.
3. How are caverns formed in limestone? Describe the key features of a karst landscape.
4. How do wells affect the water table? What happens when pumping exceeds recharge?
5. How is ground water contaminated? Describe how a well might become contaminated by a nearby landfill dump.
6. Why has land subsidence occurred in Venice? What are the effects?
7. Define discharge (of a stream) and the two quantities that determine it. How does discharge vary in a downstream direction? How does gradient vary in a downstream direction?
8. What is a *drainage system*? How are slopes and streams arranged in a drainage basin? Use the term *drainage divide* in your answer.
9. What are the effects of urbanization on streamflow? Describe why they occur.
10. Define the term *flood*. What is a *floodplain*? What is a *flash flood*?
11. How are lakes defined? What are some of their characteristics? How do lakes disappear?
12. Why are the Great Lakes important? What water quality problems have the Great Lakes experienced?
13. Where do saline lakes occur? Why are they salty? Provide some examples of saline lakes.
14. Describe some of the problems that can arise in long-continued irrigation of desert areas.
15. Discuss surface water as an important natural resource.
16. Identify common surface water pollutants and their sources.

VISUALIZING EXERCISES

1. Sketch a cross section through the land surface showing the position of the water table and indicating flow directions of subsurface water motion with arrows. Include the flow paths of ground water. Be sure to provide a stream in your diagram. Label the saturated and unsaturated zones.
2. Why does water rise in an artesian well? Illustrate with a sketched cross-sectional diagram showing the aquifer, aquicludes, and the well.
3. Sketch a hydrograph for a small stream showing both discharge and precipitation. Draw a second curve showing how the discharge would look if the stream were larger.

ESSAY QUESTIONS

1. A thundershower causes heavy rain to fall in a small region near the headwaters of a major river system. Describe the flow paths of that water as it returns to the atmosphere and ocean. What human activities influence the flows? in what ways?
2. Imagine yourself a recently elected mayor of a small city located on the banks of a large river. What issues might you be concerned with that involve the river? In developing your answer, choose and specify some characteristics for this city—such as its population, its industries, its sewage systems, and the present uses of the river for water supply or recreation.

Chapter 15
Landforms Made by Running Water

Laden with red-brown sediment, the Río Uruguay is joined by a sluggish tributary covered with green aquatic plants or algae.

The Río Uruguay here gets its color from the red soils of the Misiones Province of Argentina. As we learned in the chapter opener photo for Chapter 10, this province includes an upland plateau of ancient basalt flows that are particularly rich in iron oxides. The iron oxides lend their color—a rusty red—to the ancient Ultisols of the region, which are washed into the river by soil erosion.

Flowing south, the Río Uruguay deposits its sediment load in the Río de la Plata estuary at Buenos Aires, about 900 km (620 mi) downstream. The river and its mighty sister, the Paraná, provide 27 million m^3 (2 billion ft^3) of silt each year to the estuary, which is the widest in the world—about 200 km (125 mi) wide at its mouth. This rate of sedimentation, caused by erosion of agricultural lands and development, is many times larger than the presettlement rate and has produced problems of water quality and ecosystem degradation.

Junction of Río Uruguay and a tributary, Misiones Province, Argentina.

Landforms Made by Running Water

Most of the landforms we see around us are formed by running water as it erodes, transports, and deposits sediment. How do slopes erode, and what happens to eroded particles? How do streams build their beds and erode their banks? What causes streams to form floodplains and to meander? Why are fluvial processes so active in dry and desert climates? These are some of the questions we will answer in this chapter.

Slope Erosion

Most of the world's land surface has been sculpted by running water. Waves, glacial ice, and wind also carve out landforms, but for physical geographers, running water is the most important. That's because landforms made by glacial ice, wind, and waves are restricted to certain areas on the globe. We'll look at some of these other landform-creating agents in later chapters, but in this chapter we will concentrate on **fluvial landforms** (Figure 15.1).

Fluvial landforms are made by **fluvial processes**, which include *overland flow* and *streamflow*. Flowing as a sheet across the land, running water picks up particles and moves them downslope. When rainfall is heavy, streams and rivers swell, lifting large volumes of sediment and carrying them downstream. Weathering and the slower forms of mass wasting, such as soil creep, operate hand in hand with overland flow, supplying the rock and

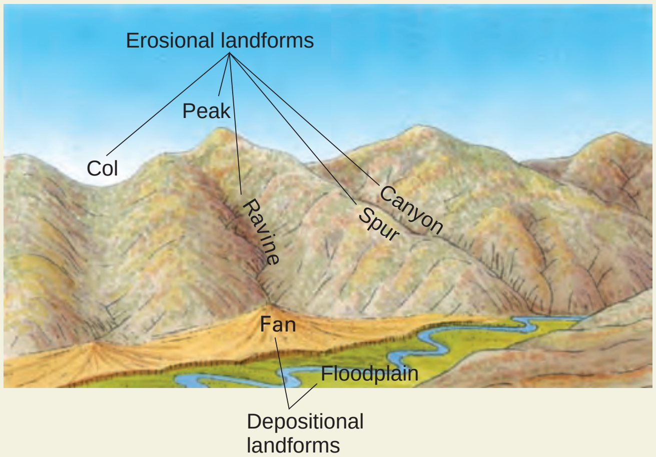
Fluvial landforms are shaped by the fluvial processes of overland flow and streamflow. Wherever rain falls, these processes act to create erosional and depositional landforms.

15.1 Grand Canyon

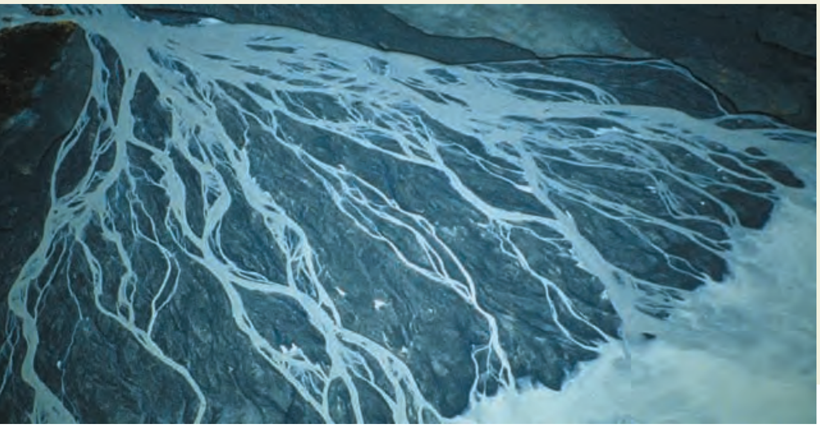
Arizona's Grand Canyon, carved by the Colorado River and its tributaries into a plateau of flat-lying sedimentary rocks, provides a spectacular example of fluvial landforms (National Geographic Image Collection).

15.2 Erosional and depositional landforms

▼ **Erosional and depositional landforms** The *ravine, canyon, peak, spur,* and *col* are erosional landforms. The *fan,* built of rock fragments below the mouth of the ravine, is a depositional landform. The *floodplain,* built of material transported by a stream, is also a depositional landform.



▲ **Ravine** This narrow valley, located in a biosphere reserve on the Kamchatka Peninsula, is an example of an *erosional landform* (National Geographic Image Collection).



◀ **Alluvial fan** An alluvial fan in Wrangell Saint Elias National Park, Alaska, is a *depositional landform* (National Geographic Image Collection).

mineral fragments that are carried into stream systems. In this way, running water erodes mountains and hills, carves valleys, and deposits sediment.

There are two major groups of landforms—erosional landforms and depositional landforms (Figure 15.2). As a crustal block is uplifted by plate tectonic activity, it is attacked by running water. Valleys form as rock is eroded away by fluvial agents. The ridges, hills, or mountain summits that we see between valleys are the surviving parts of the crustal block that have not yet been carved by running water. The landforms shaped by the progressive removal of bedrock are **erosional landforms**. Fragments of soil, regolith, and bedrock removed from the parent rock mass are transported and deposited elsewhere, making an entirely different set of surface features—the **depositional landforms**.

Fluvial action starts on the uplands as *soil erosion.* Overland flow picks up particles of mineral matter ranging in size from fine colloidal clay to coarse sand or even gravel. The size of particles removed depends on how fast the flow moves and how tightly plant rootlets and leaves hold down the soil. The water also carries dissolved mineral ions.

This process happens everywhere precipitation falls. Under stable natural conditions in a humid climate, the erosion rate is slow enough to allow soil to develop normally. Each year a small amount of soil is washed away, while a small amount of solid rock material is turned into regolith and soil. This stable equilibrium is called the *geologic norm*.

ACCELERATED SOIL EROSION

In contrast to this natural balance, human activities can produce *accelerated erosion*. Destroying vegetation and clearing land for cultivation sets the stage for a series of drastic changes. With no foliage to intercept rain and no ground cover from fallen leaves and stems, raindrops fall directly on the mineral soil. In these cases, soil is removed much faster than it can be formed, exposing the uppermost soil horizons. Some natural events, such as forest fires, can also speed up soil erosion.

When falling raindrops hit bare soil, their force causes a geyser-like splashing in which soil particles are lifted and then dropped into new positions. This is called *splash erosion* (Figure 15.3). A torrential rainstorm can disturb as much as 225 metric tons of soil per hectare (about 100 U.S. tons per acre). On a sloping ground surface, splash erosion shifts the soil slowly downhill. The soil surface also becomes much less able to absorb water. This important effect occurs because the natural soil openings become sealed by particles shifted by raindrop splash. Since water cannot infiltrate the soil as easily, a much greater depth of overland flow can be triggered from a smaller amount of rain. This intensifies the rate of soil erosion.

Destroying vegetation also reduces the resistance of the ground surface to erosion by overland flow. On a slope covered by grass sod, even a deep layer of overland flow causes little soil erosion. This is because the grass stems are tough and elastic, creating friction with the moving water and taking up the water's energy to erode. Without a cover, the water can easily dislodge soil grains, sweeping them downslope.

Soil erosion occurs when overland flow moves soil particles downslope. Erosion is greatest on bare slopes of fine particles, carving rills and gullies. A vegetation cover greatly reduces soil erosion.

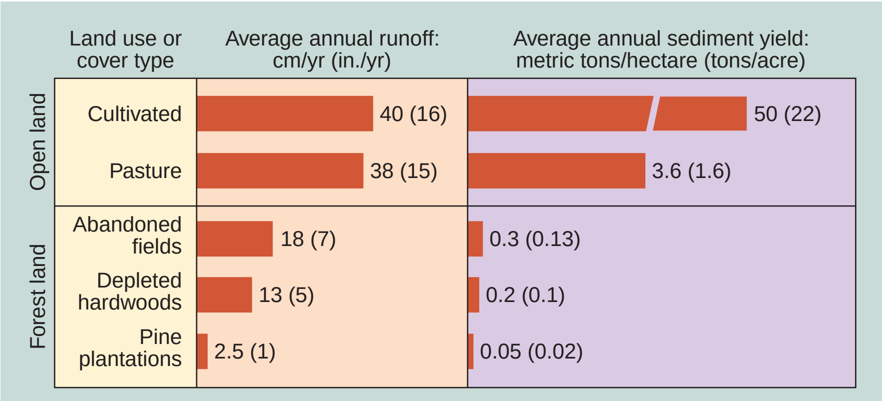
How does erosion from vegetated land compare with erosion from open land? To compare erosion rates, we use *sediment yield*—a technical term for the rate of sediment removal in metric tons per hectare per year (tons per acre per year). As shown in Figure 15.4, both surface runoff and sediment yield are much lower for vegetated surfaces. In fact, sediment yield from cultivated land undergoing accelerated erosion is over 10 times greater than that of pasture and about a thousand times greater than that of a pine plantation.

Accelerated soil erosion is a big problem in cultivated regions with a substantial water surplus. We don't see much erosion immediately after forest or prairie grasslands are removed and the soil is plowed for cultivation. But once rain splash erosion has broken down soil aggregates and sealed the larger openings, making it harder for water to infiltrate, overland flow removes the soil in thin, uniform layers. This process is called *sheet erosion*. Because of seasonal cultivation, the effects of sheet erosion are often little noticed until the upper layers of the soil are removed or greatly thinned.

Where land slopes are steep, runoff from torrential rains is even more destructive. *Rill erosion* scores many closely spaced channels into the soil and regolith. If these rills are not destroyed by soil tillage, they can join together to make still larger channels. These deepen

15.3 Soil erosion by rain splash

A large raindrop lands on a wet soil surface, producing a miniature crater (right). Grains of clay and silt are thrown into the air, and the soil surface is disturbed.



15.4 Runoff and sediment yield

This bar graph shows that both runoff and sediment yield are much greater for open land than for land covered by shrubs and forest. Values are for upland surfaces in northern Mississippi. Here, climate, soil, and topography are fairly uniform.

15.5 Gullies

These *gullies* on Santa Rosa Island, in Channel Islands National Park near Santa Barbara, California, were formed following the clearing of natural vegetation for grazing.

rapidly, turning into *gullies*—steep-walled, canyon-like trenches whose upper ends grow progressively upslope (Figure 15.5). Ultimately, accelerated soil erosion creates a rugged, barren topography.

Soil particles picked up by overland flow are carried downslope. Eventually, they reach the base of the slope, stopping where the surface slope becomes more gentle and meets the valley bottom. As we saw in Chapter 13 (see Figure 13.11), these particles accumulate in a thickening layer known as **colluvium**. Because this deposit is built by overland flow, it is distributed in sheets, making it difficult to notice unless it eventually buries fence posts or tree trunks.

Any sediment that isn't deposited as colluvium is carried by overland flow until it reaches a stream. Once in the stream, it is carried farther downvalley where it can build up as **alluvium** in layers on the valley floor. Alluvium can bury fertile floodplain soil under infertile, sandy layers. Coarse alluvium chokes the channels of small streams, making the water flood over the valley bottoms.

SLOPE EROSION IN SEMIARID AND ARID ENVIRONMENTS

So far, we've been talking about slope erosion in moist climates where there are natural forests or dense prairie grasslands. Conditions are quite different in a midlatitude semiarid climate with summer drought. Here, the natural plant cover is short-grass prairie (steppe). It is sparse and provides a rather poor ground cover of plant litter, but the grass cover is normally strong enough to slow the pace of erosion.

We also see these conditions in the tropical savanna grasslands. But in these semiarid environments, the natural equilibrium is highly sensitive and can easily be upset. Fires or grazing herds of domesticated animals that reduce the plant cover can easily trigger rapid erosion. These sensitive, marginal environments don't rapidly recover from accelerated erosion once it begins.

Erosion at a very high rate by overland flow is actually a natural process in certain locations in semiarid

15.6 Badlands

Clay beds form *badlands* at Zabriskie Point, Death Valley National Monument, California.

and arid lands. Here, the erosion produces badlands. *Badlands* are underlain by clay formations, which are easily eroded by overland flow. Erosion rates are too fast to permit plants to take hold, and no soil can develop. A maze of small stream channels is developed, and ground slopes are very steep (Figure 15.6).

The Work of Streams and Stream Gradation

Streams carry out three closely related activities—*stream erosion*, *stream transportation*, and *stream deposition*. Mineral materials, from bedrock or regolith, are removed from the floor and sides of the stream channel by erosion. The particles are suspended in the stream by turbulent water motion or are dissolved and held in solution. The transported particles are finally deposited on the streambed and floodplain, or on the floor of a standing body of water into which the stream empties, where they build up. Erosion, transportation, and deposition are simply three phases of a single activity.

STREAM EROSION

Streams erode in various ways, depending on the nature of the channel materials and the tools with which the current is armed. The flowing water drags on the bed and banks and also forces particles to hit the bed and banks. These actions easily erode alluvial materials, such as gravel, sand, silt, and clay. This form of erosion is called *hydraulic action*, and it can excavate enormous quantities in a short time when river flow is high. As the banks are undermined, large masses of alluvium slump into the river, where the particles are quickly separated and become part of the stream's load.

Where rock fragments carried by the swift current strike against bedrock channel walls, they knock off chips of rock. The larger, stronger fragments become rounded as they travel. As cobbles and boulders roll over the streambed, they crush and grind the smaller grains, producing a wide assortment of grain sizes. This process of mechanical wear is called *abrasion*. In bedrock that's too strong to be eroded by simple hydraulic action, abrasion is the main method of erosion. A striking example of abrasion is the erosion of a *pothole* (Figure 15.7).

Finally, chemical weathering removes rock from the stream channel. This is called *corrosion*. We see corrosion in limestone, in particular, which develops cupped and fluted surfaces.

Streams erode their beds and banks by hydraulic action, abrasion, and corrosion. Abrasion by stones on a bedrock river bed can create deep depressions known as potholes.

STREAM TRANSPORTATION

The solid matter carried by a stream is the **stream load**. Figure 15.8 illustrates how stream load is carried in three ways—*dissolved load, suspended load,* or *bed load*. Of the three forms, suspended load is generally the largest. A large river such as the Mississippi, for example, carries as much as 90 percent of its load in suspension.

15.7 Potholes

These *potholes* in lava bedrock were created by abrasion on the bed of a swift mountain river. The holes are produced when a shallow depression in the bedrock of a streambed acquires one or several grinding stones, which are spun around and around by the flowing water, carving a hole in the rock.

Stream capacity measures the maximum solid load of debris—including bed load and suspended load—that can be carried by a stream at a given discharge. It's given in units of tons per day passing downstream at a given location.

Stream capacity increases sharply as stream velocity rises. This is because swifter currents are more turbulent, so they can hold more sediment in suspension. The capacity to move bed load also increases with velocity because faster water drags against the bed harder. In fact, the capacity to move bed load increases according to the third to fourth power of the velocity. In other words, if a stream's velocity is doubled in times of flood, its ability to transport bed load will increase from 8 to 16 times. So, most of the conspicuous changes in a stream channel occur in a flood.

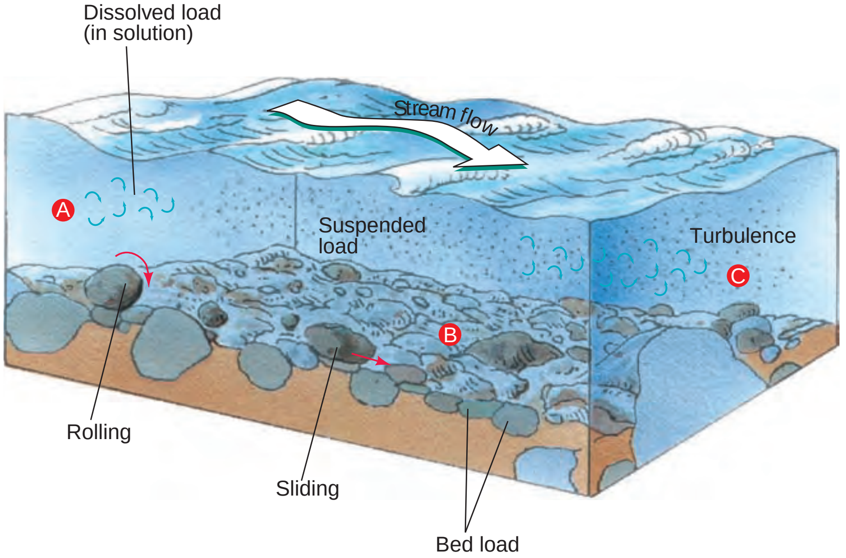
Streams carry dissolved matter, sediment in suspension, and a bed load of larger particles bumped and rolled along the bottom. A stream's capacity to carry sediment increases sharply with its velocity.

When waterflow increases, a stream flowing in a silt, sand, or gravel channel will easily widen and deepen that channel. When the flow slackens, the stream will deposit material in the bed, filling the channel again. If the stream flows in a hard bedrock channel, it won't be able to deepen the channel as quickly in response to rising waters, so it may not change much during a single flood. Such conditions exist in streams in deep canyons with steep gradients.

GEODISCOVERIES **Fluvial Geomorphology and Stream Processes Interactivity**
Use this interactivity to master the processes by which streams erode, transport, and deposit sediment, depending on stream velocity and depth.

STREAM GRADATION

Most major stream systems have gone through thousands of years of runoff, erosion, and deposition. Over time, the gradients of different parts of the stream adjust so that they just carry the average load of sediment that they receive from slopes and inflowing channels. A stream in this condition is called a **graded stream** (Figure 15.9). How does this come about?



15.8 Sediment load

Streams carry their load as *dissolved, suspended,* and *bed load.*

A Dissolved matter is transported invisibly in the form of chemical ions. All streams carry some dissolved ions created by mineral alteration.

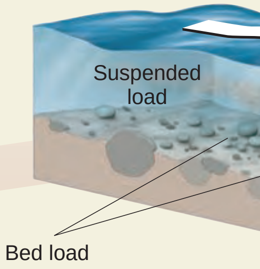
B Sand, gravel, and larger particles move as bed load, rolling or sliding close to the channel floor.

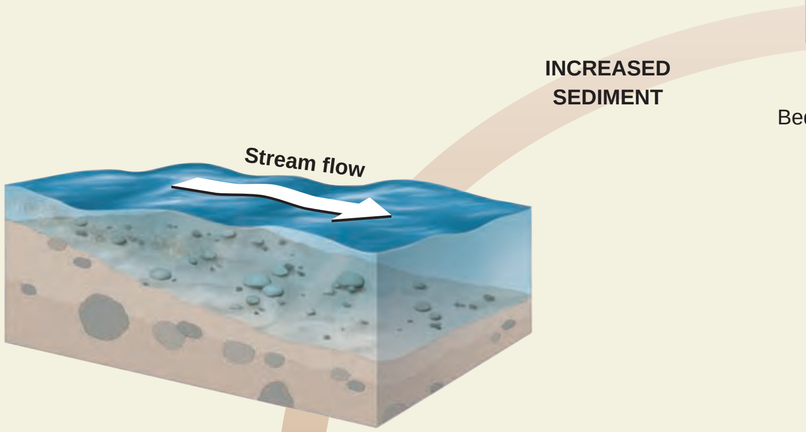
C Clay and silt are carried in *suspension*—that is, they are held within the water by turbulent eddies in the stream.

15.9 Graded streams

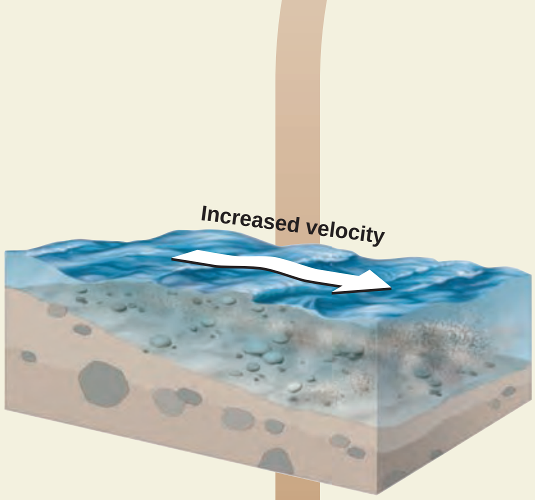
Every stream channel adjusts to the amount of sediment supplied to it at each segment. This graphic shows how a stream segment responds to either an increase (left) or a decrease (right) in the amount of sediment it receives. In both cases, the stream channel reaches equilibrium. Over time, the gradients of different parts of the stream adjust in this way, so they carry the average load of sediment they receive from slopes and inflowing channels. A stream in equilibrium condition is called a *graded stream*.

▶ **Stream channel** A stream channel carries sediment that has been supplied by runoff from a stream basin and from flow.



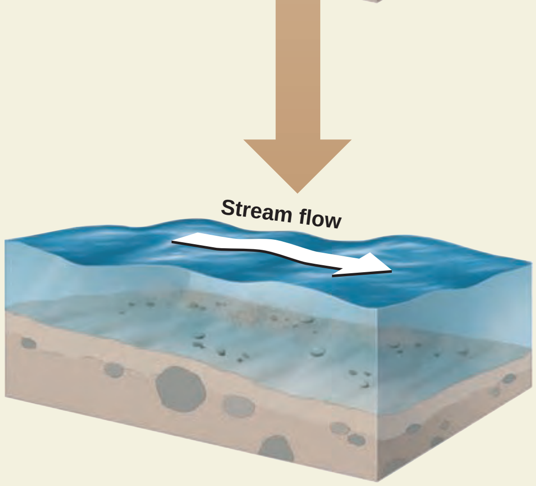


▶ **Increased sediment** If more sediment accumulates each year in the stream channel than can be carried away, the channel surface builds up, which increases the stream's slope.

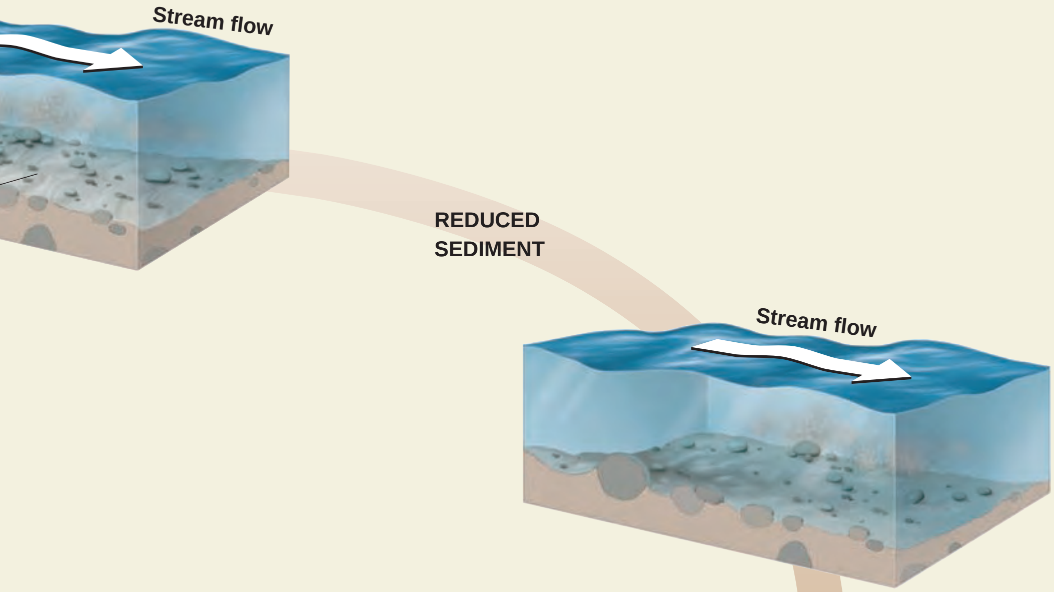


▶ **Increased velocity** With increased slope comes increased stream velocity and a greater capacity to carry sediment.

▲ **A graded stream carrying coarse sediment** Riley Creek, near the entrance to Denali National Park, Alaska, has a steep slope adjusted to carrying cobbles and larger stones, which are visible on stream banks and on the gravel bar.

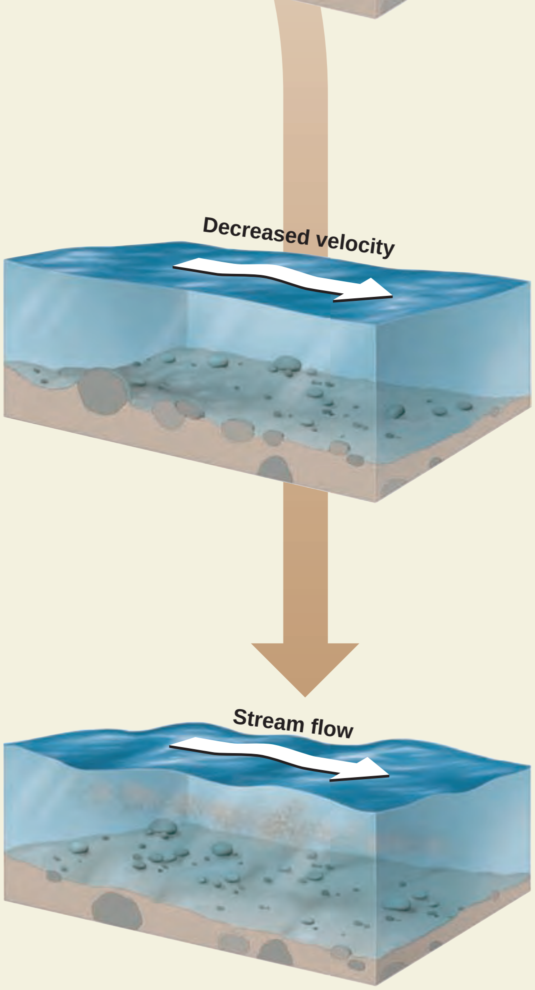


▶ **Equilibrium** Eventually, the slope will stabilize so that the stream just carries away the sediment that it receives.



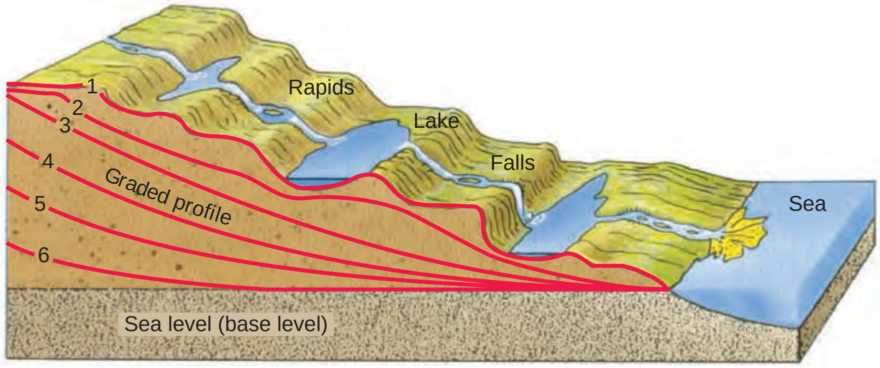
◀ **Reduced sediment** If the sediment flow to the stream is reduced, the stream will gradually erode its channel downward, reducing its slope.

▲ **A graded stream carrying fine sediment** The Avon River, located in southern England, has a shallow slope adjusted to carrying sand and silt, which can be readily seen on the riverbanks.



◀ **Decreased velocity** Reducing its slope also reduces the stream's velocity and therefore its capacity to carry sediment.

◀ **Equilibrium** Eventually, the slope will stabilize so that the stream just carries away the sediment that it receives.



15.10 Stream gradation

Schematic diagram of *gradation* of a stream. Originally, the channel consists of a succession of lakes, falls, and rapids (profile 1). As time passes, the landscape is slowly eroded by fluvial action (profile 2). Each stream segment adjusts to its own average load, and the stream profile is smoothed out into a uniform curve (profile 3). The profile has now been graded. From that time forward, this *graded profile* is steadily lowered in elevation toward the *base level* (profiles 4 through 6).

Visualize a small stream basin in which runoff and overland flow carry sediment to a stream channel. If more sediment accumulates each year in the stream channel than can be carried away, the surface of the channel will be built up and the slope of the stream will increase. But with increased slope comes increased stream velocity and increased ability to carry sediment. Eventually, the slope will reach a point at which the stream just carries away the sediment that it receives. If sediment flow to the stream is reduced, the stream will gradually erode its channel downward. This will reduce its slope and also reduce its ability to carry sediment until it can only carry the reduced amount it receives from the hillslopes.

Since every stream channel experiences this process, eventually the whole stream will tend toward a state in which the slopes of all its segments form a coordinated network that just carries the sediment load contributed by the drainage basin. A stream in this equilibrium condition is referred to as a *graded stream*.

Figure 15.10 shows how a graded stream might develop on a landscape that is rapidly uplifted, perhaps by a series of fault steps or blocks, or possibly uncovered after erosion by continental glaciers. The side of the block shows a series of *stream profiles*—plots of elevation of the stream with distance from the sea. At first, the stream is ungraded, with large fluctuations in the slope profile. As the stream cuts down, steeper areas are eroded more rapidly, smoothing the profile. Soon the stream has a *graded profile*, and the slope of each part is just sufficient to carry the average annual load of water and sediment produced by its drainage basin.

Over time, a stream develops a graded profile in which the gradient is just sufficient to carry the average annual load of water and sediment produced by its drainage basin.

LANDSCAPE EVOLUTION OF A GRADED STREAM

Figure 15.11 shows how the stream gradation process over a landscape creates a **floodplain** and **alluvial meanders** over time. At first, downcutting produces canyons and gorges. With time, the stream becomes graded and begins to build a floodplain. The river moves freely from one side of the valley to the other in alluvial meanders that sweep down the valley. As the floodplain widens, the river attacks and undermines the adjacent valley wall less frequently. Weathering, mass wasting, and overland flow then act to reduce the steepness of the valley-side slopes. Eventually, a landscape of open valleys with soil-covered slopes forms, protected by a dense plant cover. It takes tens of millions of years for a stream to reach a graded condition and erode a broad valley.

GEODISCOVERIES **The Graded Stream**

This animation demonstrates how rivers maintain a graded profile. Also watch how rivers widen their channels and deepen their beds during floods.

STREAM ORDER

In a channel network, the gradient and channel form varies from the smaller, steeper streams at the headwaters of the network to the broad and gently sloping river channels found farther downstream. One way to study how the properties of streams change systematically is to organize them by *stream order* (Figure 15.12). The smallest tributaries are first-order streams, which receive overland flow from within their first-order basin. When two first-order streams join, the result is a second-order stream and so forth. As you might well imagine, many stream properties are related to stream order, including slope, drainage area, and discharge.

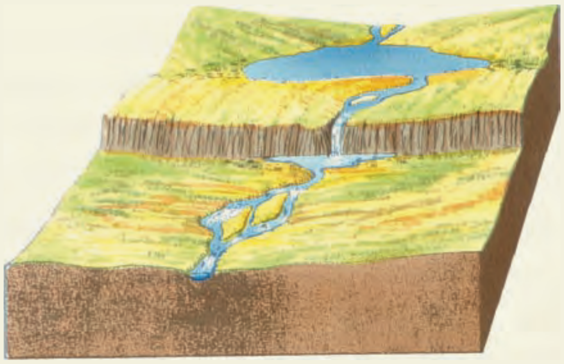
Fluvial Landscapes

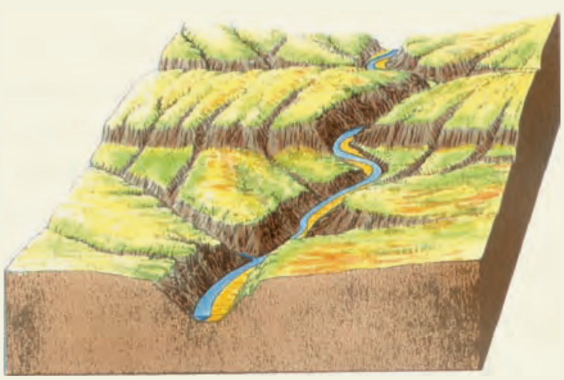
GREAT WATERFALLS

Large *waterfalls* are comparatively rare the world over, since the stream gradation process drains lakes and removes falls and rapids. But when tectonic activity fractures and dislocates crustal blocks, erosion may be hard pressed to keep up. As a result, we see great waterfalls on several large rivers in the African Rift Valley region.

15.11 Evolution of a graded stream and its valley

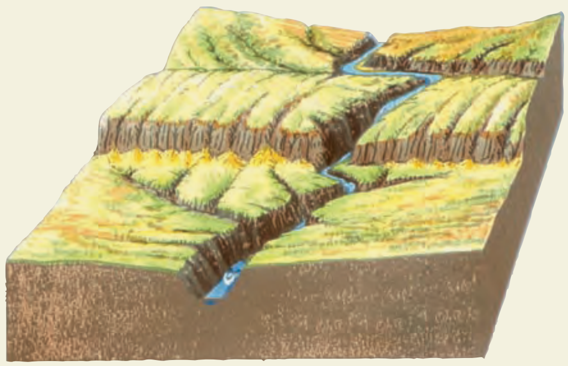
▼ The ungraded stream is made of waterfalls, rapids, and lakes and ponds. The flow is faster at the waterfalls and rapids, so abrasion of bedrock is intense, cutting back the falls and trenching the rapids. At the same time, the ponds and lakes are filled with sediment. In time, the lakes disappear and the falls are transformed into rapids.



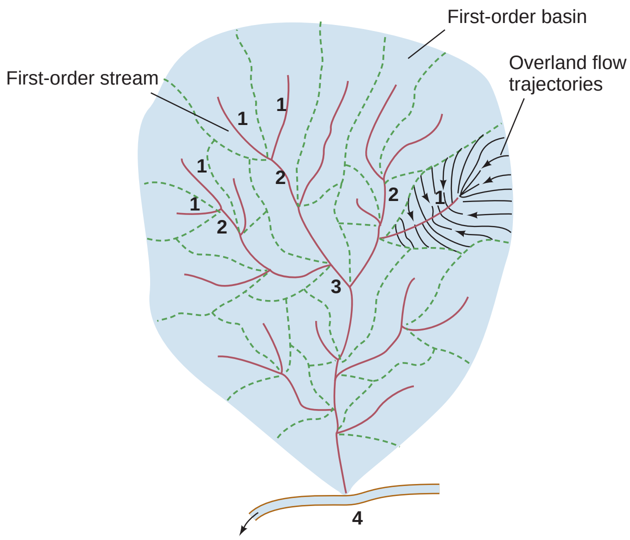


▲ Once the stream is graded, *floodplains* develop. The river begins to wander sideward, cutting into the side slopes, creating a curving path. Alluvium accumulates on the inside of each bend.

▼ The rapids are eroded until their gradient is closer to the stream's average gradient. At the same time, the main stream branches into higher parts of the original land mass, carving out many new small drainage basins.



▲ As cutting continues, the floodplain strips widen, and the channel develops sweeping bends, or *alluvial meanders*. The floodplain becomes a continuous belt of flat land between valley walls. In a humid climate, the landscape will eventually become a network of broad valleys and gentle side slopes.



15.12 Stream order

Schematic diagram of a third-order drainage basin showing both the stream channel system and the drainage divide network.

FOCUS ON REMOTE SENSING

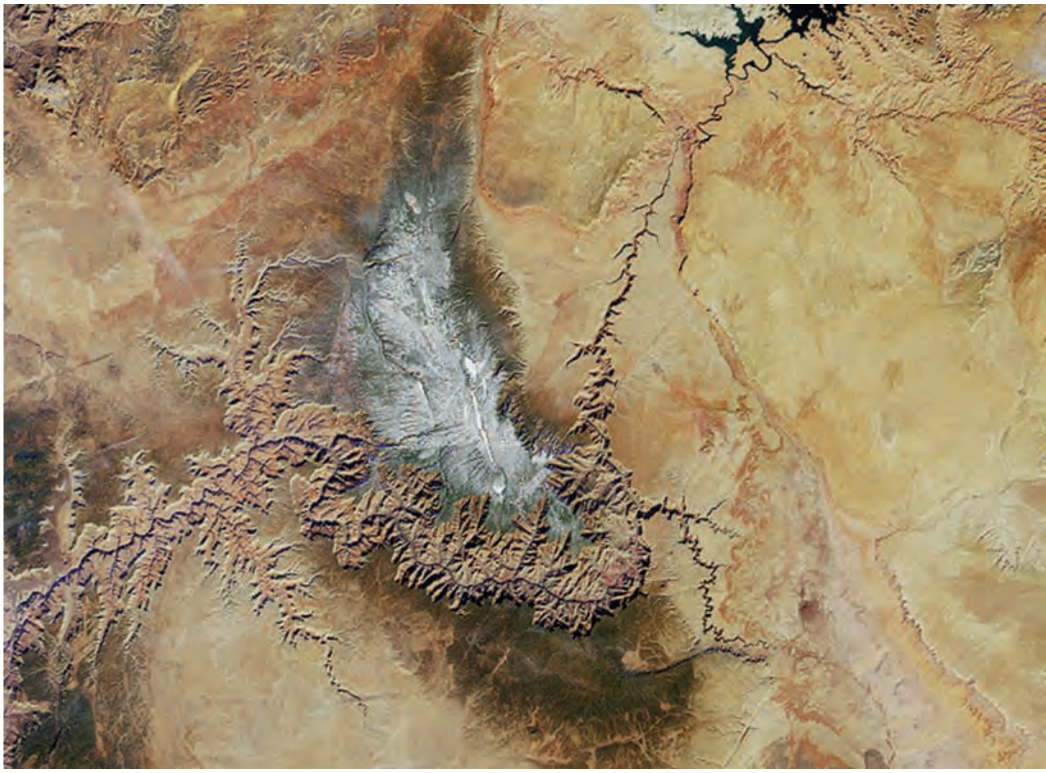
Canyons from Space

Deep canyons, carved by powerful rivers crossing high terrain, are among the most dramatic features of the landscape. The Grand Canyon of the Colorado River is among the most famous in the world, spanning a length of about 450 km (about 280 mi) with vertical drops up to about 1500 m (about 5000 ft). Figure 15.13A, in true color, was acquired by NASA's MISR imager on December 31, 2000. Trace the path of the Colorado from Lake Powell, at the upper right, through narrow Marble Canyon, until the canyon broadens to the southeast of the snow-covered Kaibab Plateau. Here the Grand Canyon begins, revealing a dissected landscape between the two canyon rims as the river curves around the plateau. The canyon continues as the river flows westward to the edge of the frame.

Figure 15.13B, an image acquired by the ASTER instrument on May 12, 2000, is a computer-generated perspective view of the Grand Canyon looking north up Bright Angel Canyon from the South Rim. In this false color image, vegetation appears green and water appears blue, but rocks are not shown in their true colors.

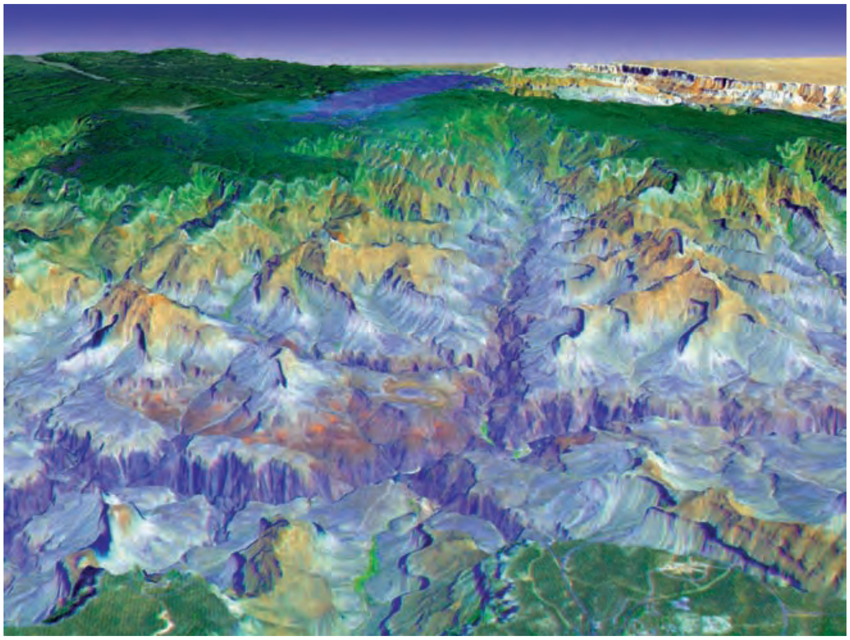
Another MISR image (Figure 15.13C) shows the coast of southern Peru in the Arequipa region. Here the Pacific coast runs nearly east-west. The coastline is obscured by low clouds and fog at the bottom of the picture. Note the two vast canyons reaching from the sea upward into the Andean Plateau. They are the canyons of the Rio Ocoña (left) and Rio Camaná (right). The canyon of the middle branch of the Rio Ocoña (Rio Cotahuasi) reaches a depth of 3354 m (11,001 ft) below the plateau, which is more than twice as deep as the Grand Canyon. The white patch between the two canyon systems is the snow-covered Nevado Coropuna, at 6425 m (21,074 ft) elevation.

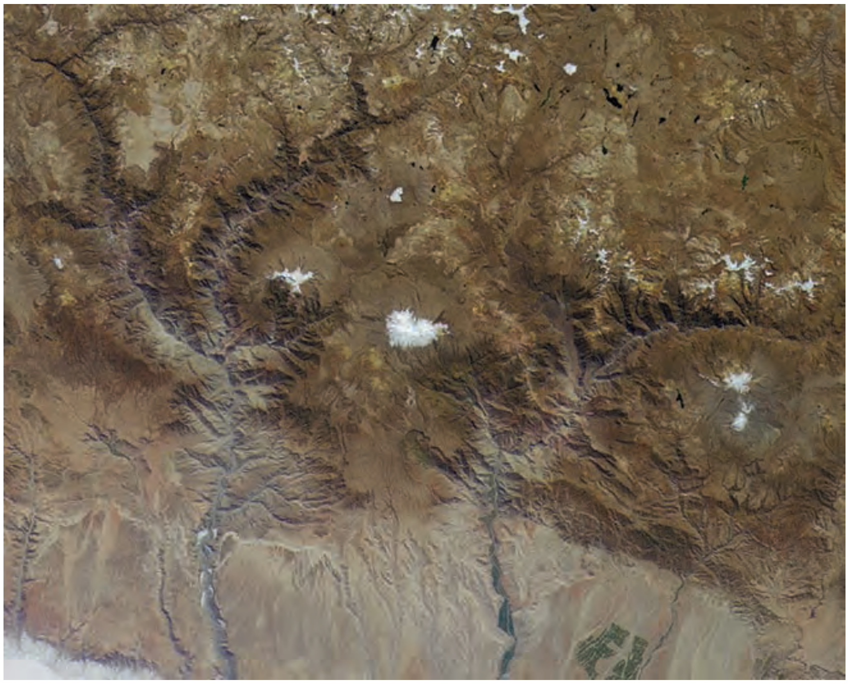
15.13 A canyon gallery



▲ Grand Canyon, Arizona, imaged by MISR (A)

▼ Grand Canyon perspective view from ASTER (B)

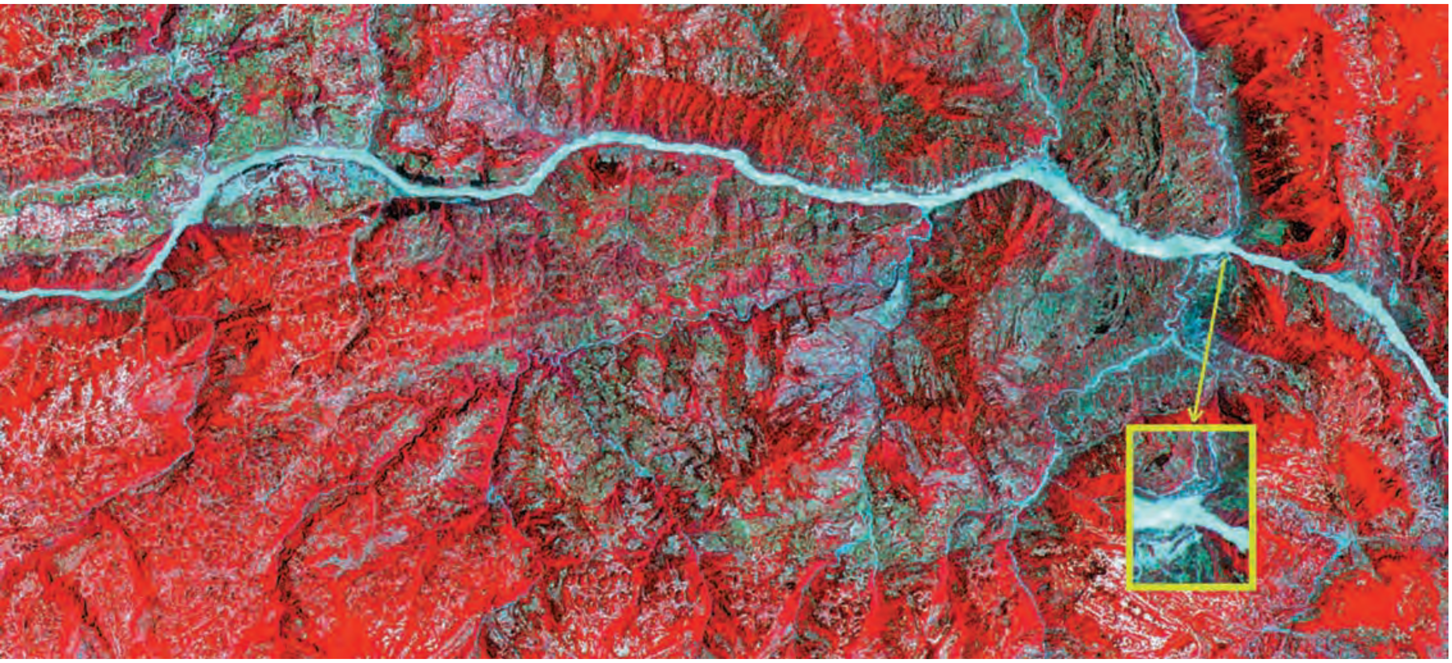




▲ Canyons of the Andes as seen by MISR (C)

Figure 15.13D is another ASTER scene, a color-infrared image of the Yangtze River canyon in the Three Gorges region of the provinces of Hubei and Sichuan, China. Although not a candidate for the deepest canyon, it is among the most scenic, with steep limestone cliffs and forest-covered slopes separating clusters of quaint villages where tributaries meet the main channel. The inset image shows the Three Gorges Dam under construction. The dam, which was completed in 2008, created a reservoir that will be 175 m (574 ft) deep and about 600 km (about 375 mi) long. The dam provides vast amounts of hydroelectric power and sharply reduces extreme flooding of the Yangtze.

▼ Three Gorges region of the Yangtze River imaged by ASTER (D)



15.14 Victoria Falls

Located on the Zambezi River at the border of Zimbabwe and Zambia in southern Africa, Victoria Falls is one of the world's scenic wonders.

EYE ON THE LANDSCAPE **What else would the geographer see?** A fault has shattered and broken rock layers, creating a zone of weakness that has been eroded by the Zambezi River to form the gorge of Victoria Falls (A). Note the resistant rock layer that keeps the waterfall vertical (B). Native vegetation here is thorntree-tall grass savanna, which is visible in the near distance (C).

One of these is Victoria Falls, on the Zambezi River, shown in Figure 15.14.

Another class of large waterfalls involves new river channels resulting from glacial activity in the Ice Age. Large moving ice sheets eroded and deposited sediment, creating lakes and shifting river courses in northern continental regions. Niagara Falls is a prime example (Figure 15.15). The outlet from Lake Erie into Lake Ontario, the Niagara River, runs over a gently inclined layer of limestone, beneath which lies easily eroded shale. The river has gradually eroded the edge of the limestone layer, producing a steep gorge marked by Niagara Falls at its head. The Niagara Power project uses the falls' 52-m (171-ft) drop to generate hydroelectric power. Water is withdrawn upstream from the falls and is carried in tunnels to generating plants located about 6 km (4 mi) downstream from the falls.

GEODISCOVERIES **Waterfalls**
See some of the world's waterfalls in action, from Niagara Falls to the spectacular Iguazu Falls of Argentina. A video.

AGGRADATION AND ALLUVIAL TERRACES

Graded streams are delicately adjusted to their supply of water and rock waste from upstream sources. So they are highly sensitive to any changes in those inputs. Changes in climate or vegetation cover affect the discharge and stream load at downstream points, and these changes in turn require channel readjustments. One such change is the buildup of alluvium in valley floors.

15.15 Niagara Falls

This panoramic image shows the Niagara River as it plunges over the Canadian (Horseshoe) Falls (foreground, right) and the American Falls (left center). The river, which connects Lake Erie to Lake Ontario, provides water for domestic and industrial uses as well as hydroelectric power (National Geographic Image Collection).

Picture a stream transporting sediment. What happens if the bed load increases beyond the transporting capacity of the stream? The coarse sediment will start to accumulate along the section of channel where the excess load was introduced. These deposits of sand, gravel, and pebbles will raise the elevation of the streambed, a process called **aggradation**. As more bed materials accumulate, the stream channel gradient steepens and the flow speeds up. This velocity increase makes it easier for the stream to drag bed materials downstream, spreading them over the channel floor at more and more distant downstream sections. In this way, sediment introduced at the head of a stream will gradually spread along the whole length of the stream.

> **Accelerated soil erosion and glacial activity can increase the amount of sediment brought to a river system, causing aggradation and the development of braided streams and river segments.**

Aggradation changes the channel cross section from a narrow and deep form to a wide and shallow one. The new sediment deposits encourage the flow to divide into multiple threads, which rejoin and subdivide repeatedly to create a *braided stream* (Figure 15.16). The coarse channel deposits spread across the former floodplain, burying fine-textured alluvium under the coarse material.

What causes stream load to increase, creating aggradation? One cause is accelerated soil erosion. Other causes are related to major changes in global climate, such as the onset of an ice age of glaciers that provide meltwater and sediment at their ends.

When stream load decreases, the braiding channel disappears. The stream begins to pick up sediment from the bed and banks and deepen its channel. The result is the formation of *meanders* and *alluvial terraces*, shown in Figure 15.17. The case shown could represent any one of a large number of valleys in New England or the Midwest.

Alluvial terraces attract human settlement because—unlike valley-bottom floodplains—they aren't subject to annual flooding, and they are easier to cultivate than hillslopes, which can be steep and rocky. Terraces are easily tilled and make prime agricultural land. Towns, roads, and railroads are also easily laid out on the flat ground of a terrace.

> **Alluvial terraces form when an aggrading river loses its sediment input and begins degrading its bed, leaving terraces behind as it cuts deeper into its sediment-filled valley.**

GEODISCOVERIES Meanders

View this animation to see how a meandering river erodes its banks at the outside of bends and deposits sediment on the inside of bends.

ALLUVIAL RIVERS AND THEIR FLOODPLAINS

Now let's examine the floodplain of a graded river. As time passes, the floodplain is widened, so that broad areas of floodplain lie on both sides of the river channel. Civil engineers have given the name **alluvial river**

15.16 Braided stream

The braided channel of the Chitina River, Wrangell Mountains, Alaska, shows many distinct channels separating and converging on a floodplain filled with glacial debris.

to a large river of very low channel gradient. It flows on a thick floodplain of alluvium constructed by the river itself in earlier stages of its activity. An alluvial river in a humid environment normally experiences overbank floods each year or two (Figure 15.18).

Figure 15.19 illustrates the typical landforms of an alluvial river and its floodplain, including *bluffs*, *ox-bow lakes*, *natural levees*, and *backswamps*. Bluffs are cut when meanders excavate older terraces or preexisting materials. Ox-bow lakes remain when meanders are cut off. When the floodplain is inundated, sand and silt are deposited in a zone next to the channel, creating *natural levees*. These flanks of high ground along the channel are normally the sites of towns and villages.

An alluvial river, with its low gradient and broad floodplain, creates characteristic landforms, including bluffs, meanders, cutoffs, ox-bow lakes, and natural levees.

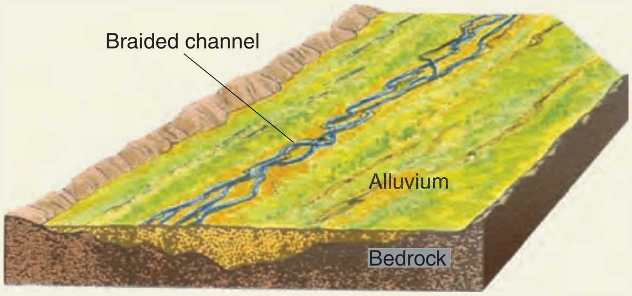
Between the levees and the bluffs is lower ground, called the backswamp, which is subject to frequent flooding. It is best suited to agriculture, as regular overbank flooding of the backswamp provides a new layer of silt and infuses the soil with dissolved minerals. The resupply of nutrients helps floodplain soils retain their remarkable fertility, even though they may be located in regions of rainfall surplus from which these nutrients are normally leached away.

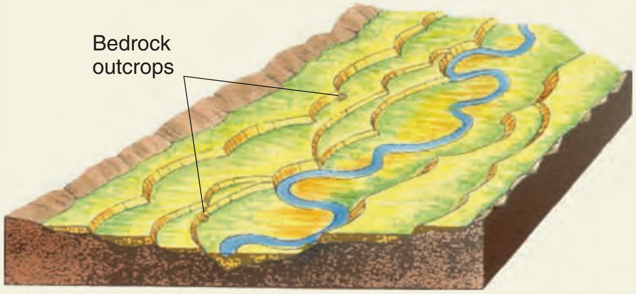
ENTRENCHED MEANDERS

What happens when a broadly meandering river is uplifted by rapid tectonic activity (Figure 15.20)? The uplift increases the river's gradient, and in turn, its velocity, so

15.17 Alluvial terrace formation

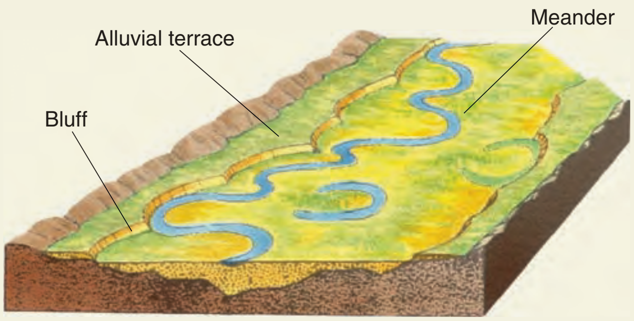
▼ Suppose that the bed load of an aggrading stream is cut off, for example, because the ice sheets providing rock debris have disappeared. In addition, reforestation covers the neighboring slopes, stopping coarse mineral particles from entering the stream through overland flow. The stream is now below its transporting capacity.





▲ This leaves step-like alluvial surfaces on both sides of the valley. The treads of these steps are called *alluvial terraces.*

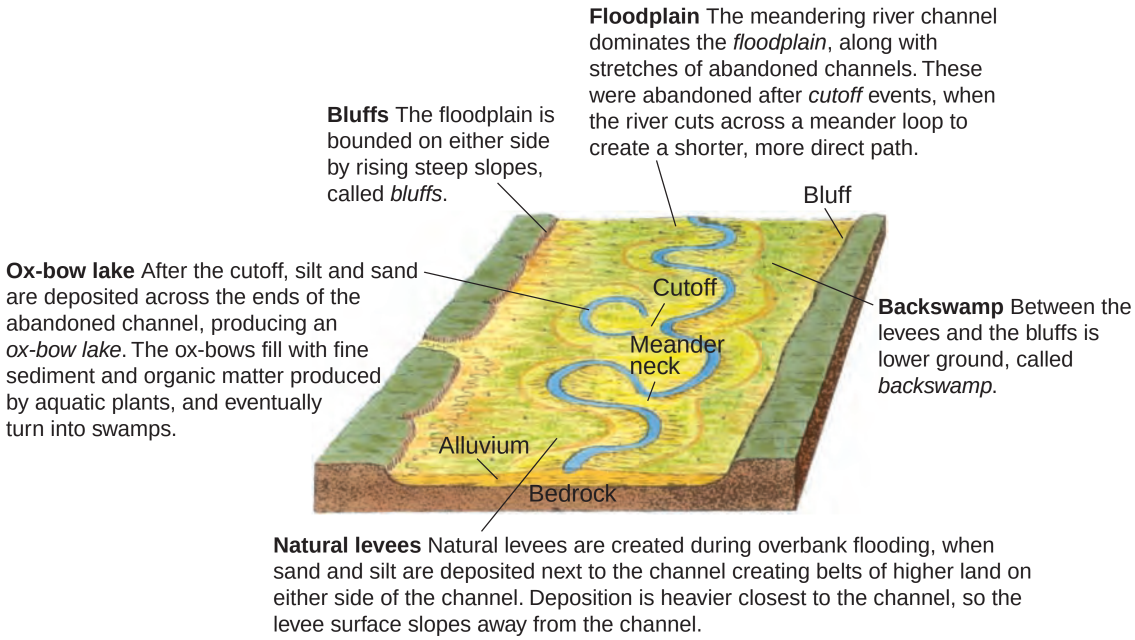
▼ In response, the channel becomes both deeper and narrower and starts to meander. The stream's meander bends grow as it excavates alluvium and carries it downstream. Not all the alluvium can be removed because the channel encounters hard bedrock in many places, preventing further cutting.



▲ These terraces line the Rakaia River gorge on the South Island of New Zealand. The flat terrace surface in the foreground is used as pasture for sheep. Two higher terrace levels can be seen on the left.

15.18 Overbank flooding

Every few years, a free-flowing alluvial river will leave its banks, flooding the lowlands that surround it. This aerial view shows the Hatchie River, Tennessee, in flood. Floodwaters have invaded the riverside forest as well as the field in the foreground (National Geographic Image Collection).



15.19 Floodplain landforms of an alluvial river

that it cuts downward into the bedrock below. This forms a steep-walled *inner gorge*. On either side of the gorge there will be the former floodplain, now a flat terrace high above river level. Any river deposits left on the terrace are rapidly stripped off by runoff because floods no longer reach the terraces to restore eroded sediment.

The meanders become impressed into the bedrock, passing on their meandering pattern to the inner gorge. We call these sinuous bends *entrenched meanders* to distinguish them from the floodplain meanders of an alluvial river. Although entrenched meanders are not free to shift about as floodplain meanders do, they can slowly enlarge, producing cutoffs that can leave a high, round hill separated from the valley wall by the deep abandoned river channel and the shortened river course. As you might guess, such hills formed ideal natural fortifications. Many European fortresses of the Middle Ages were built on such cutoff meander spurs. Occasionally, if the bedrock includes a strong, massive sandstone formation, the meander cutoff can leave a *natural bridge* formed by the narrow meander neck.

Where rapid uplift causes meandering rivers to cut deeply into bedrock, entrenched meanders are formed.

FLUVIAL PROCESSES IN AN ARID CLIMATE

Desert regions look strikingly different from humid regions in both vegetation and landforms. Obviously, the lower precipitation makes the difference. Vegetation is sparse or absent, and land surfaces are mantled with mineral material—sand, gravel, rock fragments, or bedrock itself.

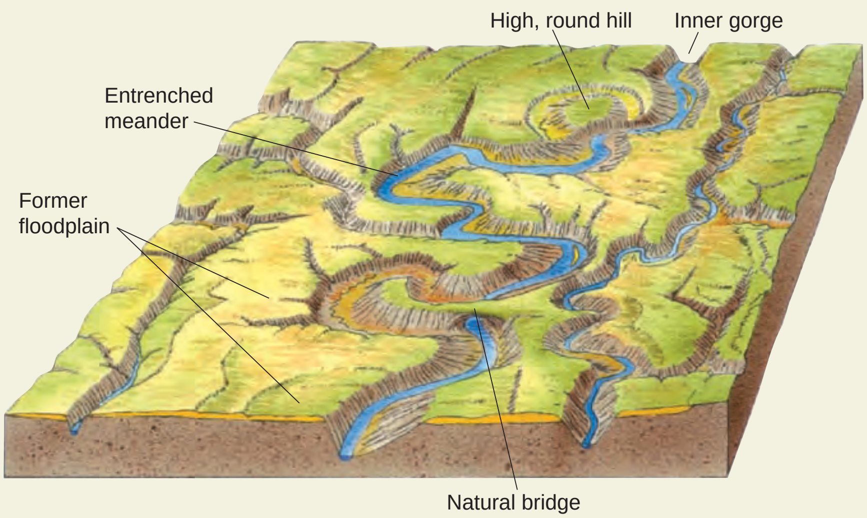
Although deserts have low precipitation, rain falls in dry climates as well as in moist, and most landforms of desert regions are formed by running water. A particular locality in a dry desert may experience heavy rain only once in several years. But when rain does fall, stream channels carry water and perform important work as agents of erosion, transportation, and deposition.

Fluvial processes are especially effective in shaping desert landforms because of the sparse vegetation cover. The few small plants that survive offer little or no protection to soil or bedrock. Without a thick vegetative cover to protect the ground and hold back the swift downslope flow of water, large quantities of coarse rock debris are swept into the streams. A dry channel is transformed in a few minutes into a *flash flood* of muddy water heavily charged with rock fragments (Figure 15.21).

Although rain is infrequent in desert environments, running water shapes desert landforms with great effectiveness because of the lack of vegetation cover.

Water enters and leaves a stream channel differently in arid climates than in humid climates (Figure 15.22). In a humid region, the high water table slopes toward a stream channel, and ground water seeps into the streambed, producing permanent (perennial) streams. In arid regions, the water table lies far below the channel floor. Where a stream flows across a plain of gravel and sand, water is lost from the channel by seepage. As a result, aggradation occurs and braided channels are common. Streams of desert regions are often short and end in alluvial deposits or on the floors of shallow, dry lakes.

15.20 Entrenched meanders



◀ **Diagram of entrenched meanders** Uplift of a meandering stream has produced *entrenched meanders*. One meander neck has been cut through, forming a *natural bridge*.

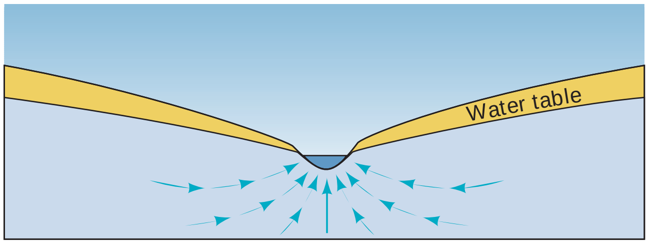
▲ **Goosenecks** The Goosenecks of the San Juan River in Utah are deeply entrenched river meanders in horizontal sedimentary rock layers. The canyon, carved from sandstones and limestones, is about 370 m (1399 ft) deep.

◀ **Cutoff entrenched meander** Here in the Massif Central of France, the gorge of the Vis River contains a cutoff entrenched meander called the Cirque de Navacelles. The circular pattern of grassy fields marks the former floodplain of the river, which surrounds a low hill that is the remains of the meander spur. The cutoff occurred at the steep end of the hill, where the river still flows today (National Geographic Image Collection).

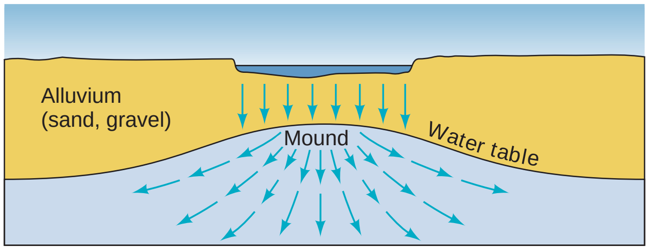
15.21 Flash flood

A *flash flood* has filled this river channel in the Sonoran Desert of Arizona with raging, turbid waters. A distant thunderstorm produced the runoff.

▼ In humid regions, a stream channel receives ground water through seepage.



▼ In arid regions, stream water seeps out of the channel and into the water table below.



15.22 Stream water flow to ground water

ALLUVIAL FANS

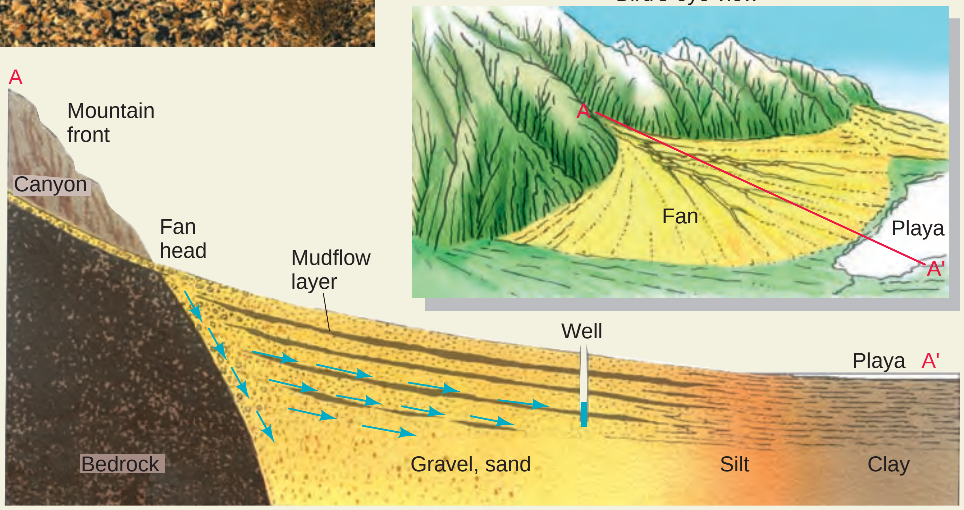
One very common landform built by braided, aggrading streams is the **alluvial fan** (Figure 15.23). This is a low cone of alluvial sands and gravels resembling an open fan. The central point of the fan lies at the mouth of a canyon or ravine. The fan is built out on an adjacent plain. Alluvial fans are of many sizes. Some desert fans are many kilometers across.

Fans are built by streams carrying heavy loads of coarse rock waste from a mountain or an upland region. The braided channel shifts constantly, but its position is firmly fixed at the canyon mouth. The lower part of the channel, below the apex, sweeps back and

15.23 Alluvial fans

◀ This vast *alluvial fan* extends out onto the floor of Death Valley. The fans are built by streams carrying rock waste from a great uplifted fault block, the Panamint Range.

Bird's-eye view



Cross section

▶ A cross section shows mudflow layers interbedded with sand layers, providing water (arrows) for a well in the fan.

forth—accounting for the fan form and the downward slope in all radial directions away from the apex.

Alluvial fans are primary sites of ground water reservoirs in the southwestern United States (Figure 15.23). In many fan areas, we have rapidly lowered the water table by pumping for irrigation. It will take an extremely long time to recharge these ground water reserves from precipitation. One serious side effect of removing too much ground water is subsidence.

Alluvial fans are common features of arid landscapes. They occur where streams discharge water and sediment from a narrow canyon or gorge onto an adjacent plain.

THE LANDSCAPE OF MOUNTAINOUS DESERTS

Where tectonic activity has recently produced block faulting in an area of continental desert, the assemblage of fluvial landforms is particularly diverse and interesting. The basin-and-range region of the western United States, which includes large parts of Nevada and Utah, southeastern California, southern Arizona, and New Mexico, is an example.

Figure 15.24 demonstrates some landscape features of these mountainous deserts. The initial uplift creates two uplifted fault blocks with a downdropped block between them. Although denudation acts on the uplifted blocks as they are being raised, we have shown them as very little modified at the time tectonic activity has ceased. At first, the faces of the fault block are extremely steep. They are scored with deep ravines, and talus blocks form cones at the bases of the blocks.

At a later stage of erosion, streams have carved the mountain blocks into a rugged landscape of deep canyons and high divides. Rock waste from these steep mountain slopes is carried from the mouths of canyons to form large alluvial fans. The fan deposits form a continuous apron extending far out into the basins.

Landforms of mountainous deserts include alluvial fans, dry lakes or playas, and pediments—rock platforms veneered with alluvium.

In the center of the desert basin is a dry lakebed, or **playa**, where fine sediments and precipitated salts produce a flat basin floor. In some playas, shallow water forms a salt lake. Figure 15.25 is an air photograph of a mountainous desert landscape showing many of these features.

A gently sloping rock surface, thinly veneered with alluvium, sometimes stretches from the mountain flank toward the playa. This surface—a *pediment*—may be an ancient low-angle fault plane; an old surface created by many years of weathering during a wetter climate; or a surface formed by retreat of the mountain front.

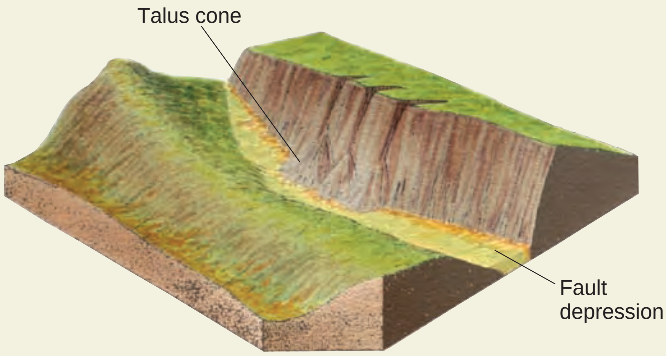
THE GEOGRAPHIC CYCLE

The Earth's fluvial landscapes are quite diverse. They range from mountain regions of steep slopes and rugged peaks to regions of gentle hills and valleys, to nearly flat plains that stretch from horizon to horizon. We can think of these constantly changing landscapes as stages of evolution in a cycle that begins with rapid uplift by plate tectonic activity and follows with long erosion by streams in a graded condition. This cycle, called the **geographic cycle**, was first described by William Morris Davis, a prominent geographer and geomorphologist of the late nineteenth and early twentieth centuries.

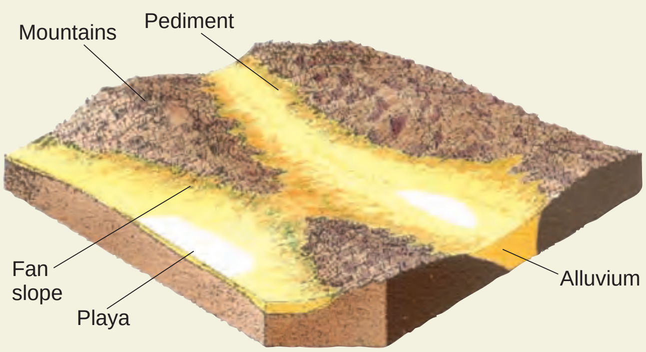
15.24 Mountainous desert landforms

Idealized diagrams of landforms of the mountainous deserts of the southwestern United States.

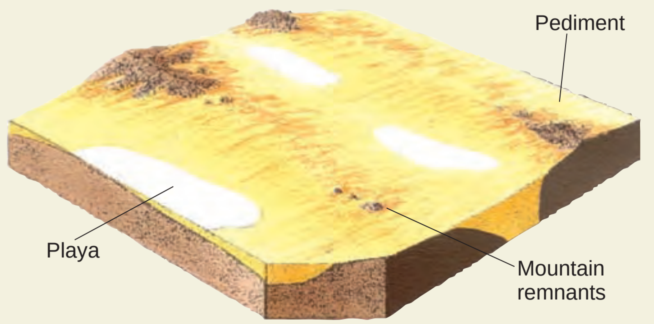
▶ Initial uplift of two blocks, with a downdropped valley between them.



◀ Stage of rapid filling of tectonic basins with debris from the high, rugged mountain blocks.



▶ Advanced stage with small mountain remnants and broad playa and fan slopes.



15.25 Desert playa

Racetrack Playa, a flat, white plain, is surrounded by alluvial fans and rugged mountains. This desert valley lies in the northern part of the Panamint Range, not far west of Death Valley, California.

Nearby uplands are rugged mountain masses dissected into canyons with steep, rocky walls.

This great uplifted fault block is the eastern face of the Inyo Mountains.

The playa occupies the floor of the central part of the basin.

A zone of coalescing alluvial fans lines the mountain front.

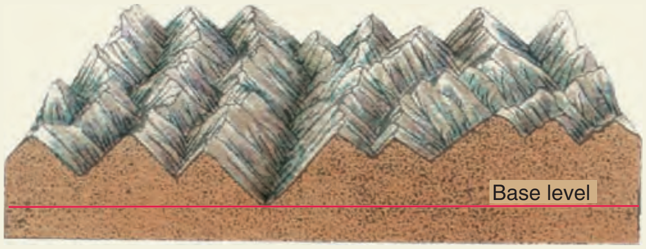
In Davis's model (Figure 15.26), the landscape begins at a *youthful stage* of steep slopes and river channels. In the *mature stage*, hills are rounded and slopes are gentler. In *old age*, the landscape is an undulating surface drained by slow and sluggish streams. With rapid uplift, *rejuvenation* occurs and the cycle begins anew.

The geographic cycle traces the fate of rivers and fluvial landforms from an initial uplift creating steep slopes and canyons to a final low, gently rolling surface called a peneplain.

EQUILIBRIUM APPROACH TO LANDFORMS

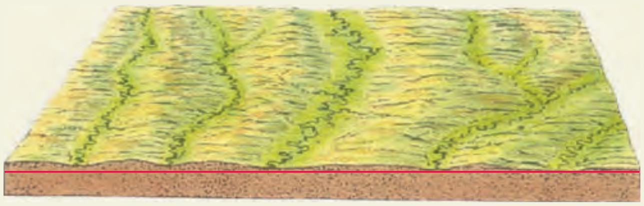
Davis's idealized geographic cycle is useful for understanding landscape evolution over very long periods of time, but it does little to explain the diversity of the features observed in real landscapes. Most geomorphologists think of landforms and landscapes in terms of *equilibrium*. This approach explains a fluvial landform as the product of forces acting on it, including both forces of uplift and denudation activities that wear down rocks.

15.26 The geographic cycle of William Morris Davis

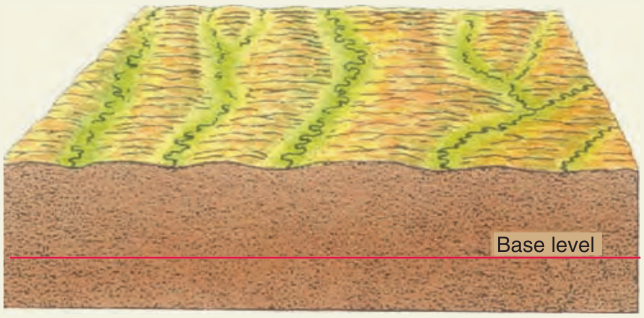


◀ **Youthful stage** A landscape has been rapidly uplifted by tectonic forces. The region is rugged and the rate of erosion is rapid. Almost all of the surface is well above the *base level*, an elevation that is just sufficient to allow streams to drain to the ocean.

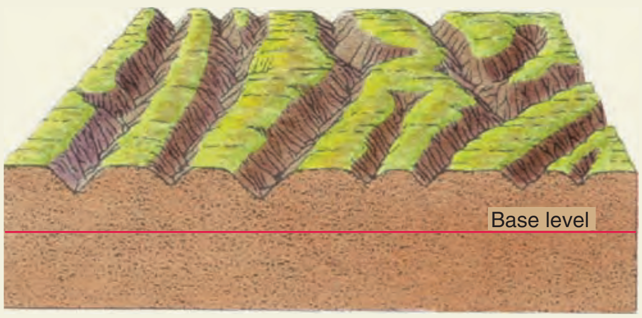
◀ **Mature stage** After a time, the main streams become graded, transporting rock debris out and eventually lowering the land surface. The sharp peaks and gorges of the youthful stage become rounded.



◀ **Old age** The gradients of streams and valley-side slopes gradually lower. The land surface approaches sea level at a slower pace. After millions of years, the land surface is reduced to a low, gently rolling surface called a *peneplain*, which is very close to the base level.



◀ **Peneplain uplift** The peneplain is now uplifted by plate tectonic activity.



◀ **Rejuvenation** Streams begin to trench the land mass and to carve deep, steep-walled valleys. Over many millions of years, the landscape will be carved into the rugged "youthful stage" shown at the top, and the cycle will begin again.

One strength of this viewpoint is that we can take into account the characteristics of the rock material. Thus, we find steep slopes and high relief where the underlying rock is strong and highly resistant to erosion. Even a "youthful" landscape may be in a long-lived equilibrium state in which hillslopes and stream gradients remain steep in order to maintain a graded condition while eroding a strong rock like massive granite.

The equilibrium approach sees fluvial landforms as reflecting a balance between processes of uplift and denudation acting on rocks of varying resistance to erosion.

Another problem with Davis's geographic cycle is that it only applies where the land surface is stable over long periods of time. But we know from our study of plate tectonics that crustal movements are frequent on the geologic time scale. Few regions of the land surface remain untouched by tectonic forces in the long run. Recall also that continental lithosphere floats on a soft asthenosphere. As layer upon layer of rock is stripped from a land mass by erosion, the land mass becomes lighter and is buoyed upward. A better model, then, is one of uplift as an ongoing process to which erosional processes are constantly adjusting rather than as a sudden event followed by denudation.

GEODISCOVERIES **Web Quiz**
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

In this chapter we have examined a number of geomorphic processes in which running water erodes, transports, and deposits sediment to create landforms. Because the landscapes of most regions on the Earth's land surface are produced by fluvial processes acting on differing rock types, running water is by far the most important agent in creating the variety of landforms that we see around us. However, three remaining agents of denudation remain—waves, wind, and glacial ice. These are the subjects of the last two chapters of our book.

GEODISCOVERIES **Web Links**
Visit this chapter's web sites to view awesome floods and dramatic waterfalls. Tour the spectacular Grand Canyon and the scenic Hudson River Valley.

IN REVIEW LANDFORMS MADE BY RUNNING WATER

- **Fluvial landforms** are made by overland flow and streamflow. Running water erodes mountains and hills, carves valleys, and deposits sediment by **fluvial processes**.
- **Erosional landforms** are shaped by the progressive removal of bedrock. **Depositional landforms** are built from the transported soil, regolith, and rock fragments provided by erosion.
- *Soil erosion* moves soil particles toward and into streams. In most natural landscapes, soil erosion and soil formation rates are more or less equal, a condition known as the *geologic norm.*
- *Accelerated soil erosion* is intensified by *splash erosion* of bare soil, which fills natural soil opening and boosts overland flow. Removing a vegetation cover also accelerates erosion.
- *Sheet erosion* on gentler slopes and *rill erosion* on steeper slopes carry soil and regolith downhill. Eventually, *gullies* can form.
- Overland flow produces sheets of sediment that accumulate as **colluvium** at the base of slopes. Transportation and deposition of sediment by streams produce **alluvium**.
- In arid and semiarid regions, *badlands* can develop on clay formations that are easily eroded by overland flow.
- The work of streams includes *stream erosion*, *stream transportation*, and *stream deposition*.
- Where stream channels are carved into soft materials, *hydraulic action* can provide large amounts of sediment. Where stream channels flow on bedrock, channels are deepened only by the abrasion of bed and banks by mineral particles, large and small.
- **Stream load** measures the total dissolved, suspended, and bed load of a stream. *Stream capacity*—the ability to carry stream load—increases greatly as velocity increases in times of flood.
- Over time, streams tend to become **graded streams**, in which their gradients are adjusted to move the average amount of water and sediment supplied to them by slopes. Lakes and waterfalls give way to a smooth, graded *stream profile*. Grade is maintained as landscapes are eroded toward *base level*.
- *Stream order* provides a way of studying streams by relative size. First-order streams are the smallest. Higher stream orders form when streams of lower but equal order merge.
- Remote sensing provides a way of viewing the world's deepest and most spectacular river canyons. The canyons of southern Peru are more than twice as deep as Arizona's Grand Canyon.

- When provided with a sudden inflow of rock material, as, for example, by glacial action, streams build up their beds by **aggradation**. When that inflow ceases, streams begin downcutting, leaving behind alluvial terraces.
- Great *waterfalls* can result from tectonic activity or recent glacial activity. In the long run, stream gradation wears away falls and rapids.
- Aggradation in response to an increased sediment load raises the elevation of a streambed and can create a *braided stream*. Aggrading streams can form *alluvial terraces*, which are ideal locations for agriculture or development.
- Large rivers with low gradients that move large quantities of sediment are termed **alluvial rivers**. The meandering of these rivers forms *bluffs*, *ox-bow lakes, natural levees*, and *backswamps*.
- When a region containing a meandering alluvial river is uplifted, *entrenched meanders* can result. A cutoff entrenched meander can form a *natural bridge*.
- With vegetation sparse or lacking in deserts, running water is very effective in producing fluvial landforms. Because desert water tables are below stream bottoms, channel flow is lost by seepage, leading to aggradation.
- Mountain streams, subject to *flash flooding*, build **alluvial fans** at the mouths of desert canyons. Water sinks into the fan deposits, creating local ground water reservoirs.
- Fine sediments and salts, carried by streams, accumulate in desert **playas**, from which water evaporates, leaving sediment and salt behind.
- Desert mountains are eventually worn down into gently sloping rock floors called *pediments*.
- The **geographic cycle** organizes fluvial landscapes according to their age in a cycle of uplift that forms mountains and subsequent erosion to nearly flat surfaces called *peneplains*.
- In the *equilibrium approach*, landforms are viewed as products of uplift and erosion acting as continuous processes on rocks of varying resistance.

KEY TERMS

fluvial landforms, p. 496
fluvial processes, p. 496
erosional landforms, p. 497
depositional landforms, p. 497
colluvium, p. 499
alluvium, p. 499
stream load, p. 500
graded stream, p. 501
floodplain, p. 504
alluvial meanders, p. 504
aggradation, p. 509
alluvial river, p. 509
alluvial fan, p. 514
playa, p. 516
geographic cycle, p. 516

REVIEW QUESTIONS

1. What are *fluvial landforms*? Identify two fluvial processes that create fluvial landforms.
2. Contrast erosional landforms and depositional landforms. Provide several examples of each.
3. Explain how accelerated soil erosion occurs. What is the role of splash erosion? How is sediment yield affected?
4. When and how does sheet erosion occur? How does it lead to rill erosion and gullying?
5. Contrast the two terms *colluvium* and *alluvium*. Where on a landscape would you look to find each one?
6. What special conditions are required for badlands to form?
7. In what ways do streams erode their beds and banks? Identify three processes of stream erosion.
8. What is *stream load*? Identify its three components. In what form do large rivers carry most of their load?
9. How is velocity related to the ability of a stream to move sediment downstream? Use the term *stream capacity* in your answer.
10. Compare Arizona's Grand Canyon to the canyons of southern Peru. Where is the Three Gorges, and why is it of interest?
11. Identify two classes of large waterfalls and provide an example of each.
12. What causes aggradation of a stream? What are the effects of aggradation?
13. What is an *entrenched meander*? How does it form?
14. Why is fluvial action so effective in arid climates, considering that rainfall is scarce? How do streams in arid climates differ from streams in moist climates?
15. Describe how an alluvial fan is formed. What natural resource is associated with alluvial fans? Explain.
16. Describe the evolution of the landscape in a mountainous desert. Use the terms *talus cone, fan slope, playa*, and *pediment* in your answer.
17. Describe the evolution of a fluvial landscape according to the geographic cycle. What is meant by rejuvenation?
18. What is the equilibrium approach to landforms? How does it differ from interpretation using the geographic cycle?

VISUALIZING EXERCISES

1. What is a *graded stream*? Sketch the profile of a graded stream and compare it with the profile of a stream draining a recently uplifted set of landforms.
2. Sketch a plan of a drainage basin and illustrate the concept of stream order.
3. Sketch the floodplain of an alluvial river. Identify key landforms on the sketch. How do they form?

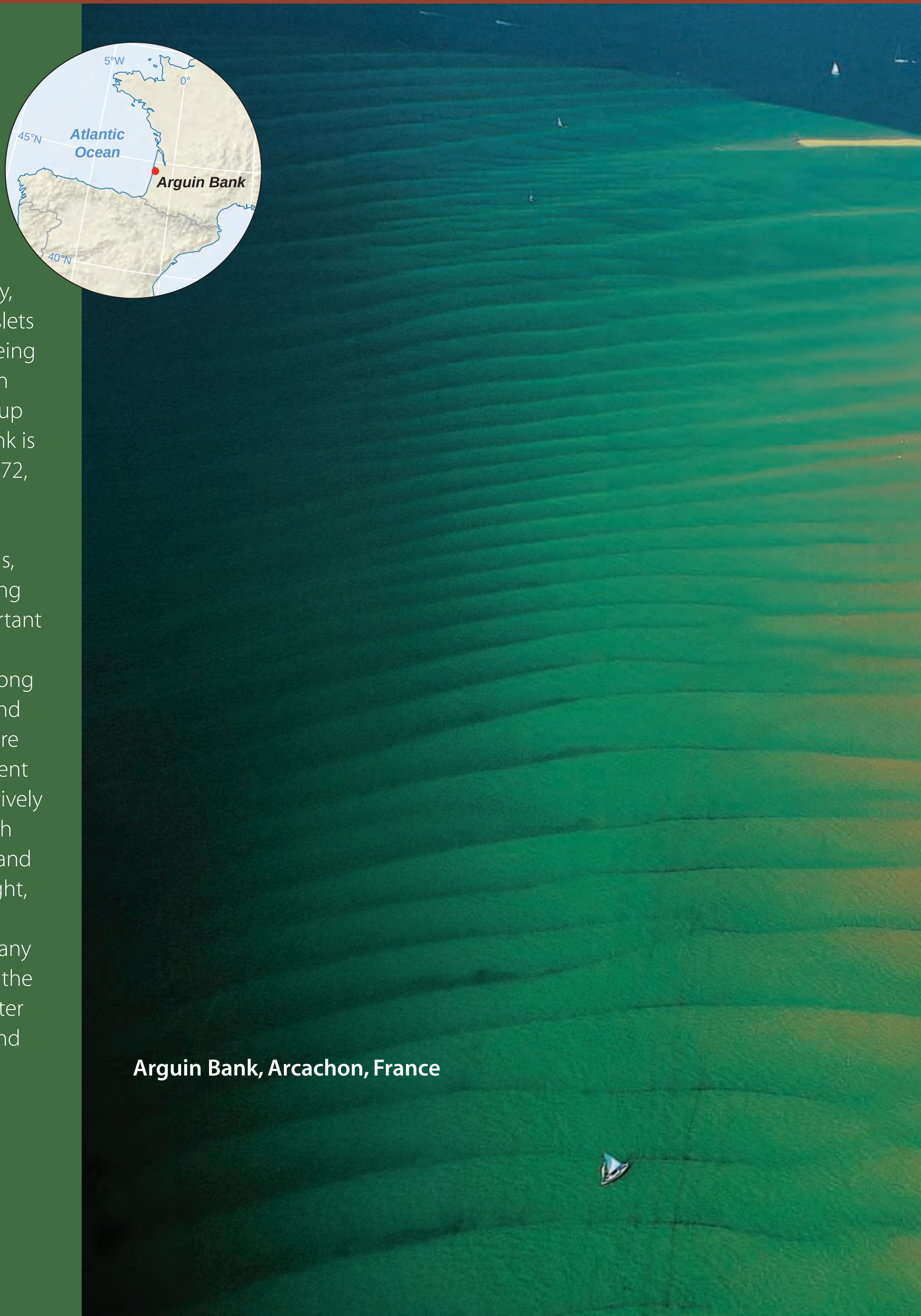
ESSAY QUESTIONS

1. A river originates high in the Rocky Mountains, crosses the high plains, flows through the agricultural regions of the Midwest, and finally reaches the sea. Describe the fluvial processes and landforms you might expect to find on a journey along the river from its headwaters to the ocean.
2. What effects would climate change have on a fluvial system? Choose either the effects of cooler temperatures and higher precipitation in a mountainous desert, or warmer temperatures and lower precipitation in a humid agricultural region.

Chapter 16
Landforms Made by Waves and Wind

The Arguin Bank lies in the mouth of the Arcachon Estuary, a large embayment of about 100 km^2 (about 40 mi^2) located on the Atlantic Coast of southern France. Formed from sand drifting along the coast and across the mouth of the estuary, the bank is an assemblage of islets and shoals that is constantly being worked and reworked by ocean waves and by tides that range up to 4 m (13 ft) in height. The bank is a nature reserve, founded in 1972, of about 1000 hectares (about 2500 acres) in size. It is a safe harbor for many migratory birds, providing a rest stop and nesting grounds for a number of important species.

This photo shows part of a long neck of sand at the northern end of the bank. The sand "waves" are created by both wind and current action. On the right, wind is actively working the sand surface, which is largely above sea level. The sand is moving toward the upper right, encroaching on the wide tidal channel being navigated by many types of watercraft. On the left, the sand is accumulating underwater in ripples formed by the ebb and flow of tidal currents.



Arguin Bank, Arcachon, France

Landforms Made by Waves and Wind

Wind creates landforms directly by moving sand and dust and indirectly by generating waves that shape shorelines and coasts. How do waves form, and how do they move sediment along shorelines? What distinctive landforms does wave action create? What types of coastlines do we find around the globe? What kinds of materials does wind erode, transport, and deposit? What types of sand dunes are there, and how do they form? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Global Change and Coastal Environments

Global climate change over the remainder of the twenty-first century will have major impacts on coastal environments. The changes include increases in sea-surface temperature and sea level, decreases in sea-ice cover, and changes in salinity, wave climate, and ocean circulation.

What changes have already occurred? According to recent reports of the Intergovernmental Panel on Climate Change, sea level has risen about 15 cm since 1870. Most of this rise is due to thermal expansion of sea water in response to global warming of about 0.75°C (1.35°F) since 1906, but some is also due to the melting of glaciers and ice caps. Arctic sea-ice cover is decreasing at a rate of about 3 percent per decade, with summer ice cover decreasing by about 7 percent per decade. Extreme weather events are increasing, including the number of heat waves, number of precipitation events leading to flooding, the extent of drought-affected regions, and the intensity and duration of tropical storms.

What changes are in store? Between 1990 and 2100, global average surface temperature will increase between 1.7 and 6.4°C (3.1 and 10.5°F), depending on the scenario for future economic growth and usage of fossil fuels. Sea level will rise from present levels by about 21 cm to 47 cm (8.3 to 18.5 in.), again depending on the scenario. Snow and ice cover will continue to decrease, and mountain glaciers and ice caps will continue their retreat of the twentieth century. Tropical cyclone peak wind and peak precipitation intensities will increase, and El Niño extremes of flood and drought will be exaggerated.

These changes are bad news for coastal environments. Let's begin with coastal erosion (Figure 16.1). Global warming will increase the frequency of high winds and heavy precipitation events, amplifying the effects of severe coastal storms. More frequent and longer El Niños will increase the severity and frequency of Pacific storms, leading to increased sea-cliff erosion along Southern California's south- and southwest-facing coastlines. During La Niña events, Atlantic hurricane frequency and intensity will increase with increased risk of damage to structures and coastal populations.

Rising sea level and increasing frequency and severity of storms will heighten future coastal erosion. Coastal wetlands will decrease in area and in quality. Warming will stress coral reefs and speed arctic shoreline recession.

How will sea-level rise impact coastlines? Over the past 100 years or so, about 70 percent of sandy shorelines have retreated and 10 percent have advanced. The long-term effect of sea level is to push beaches, salt marshes, and estuaries landward (Figure 16.2). Beaches disappear and are replaced by sea walls. Salt marshes are drained to reduce inland flooding. Estuaries become shallower and more saline. In this way, the most productive areas of the coast are squeezed between a rising ocean and a water's edge that is increasingly defended.

Sea-level rise will not be uniform. Modifying factors of waves, currents, tides, and offshore topography can act to magnify the rise, depending on the location. Some models predict doubled rates of sea-level rise for portions of the eastern United States, North American Pacific coast, and the western North American arctic shoreline.

Land subsidence is a contributing factor to the impact of sea-level rise. Many coastlines are fed by rivers that have now been dammed, often many times, which reduces the amount of fine sediment brought to the coast. Without new sediment, coastal wetlands slowly sink as the older sediment that supports them compacts. This subsidence increases the effects of sea-level rise.

16.1 Coastal erosion

This photo shows the effects of the waves and wind of Hurricane Dennis in 1999 on the barrier beach of North Carolina's Outer Banks. The high surf eroded the beach into a long, flat slope, undermining the supports for many beach structures. The winds then toppled them, leaving the surf to further demolish the remains. The result was widespread devastation in many barrier beach communities. This homeowner was lucky enough to have a house to come back to.

16.2 Beach breach

Storm waves from Hurricane Isabel breached the North Carolina barrier beach to create a new inlet, as shown in this aerial photo from September 2003. Notice also the widespread destruction of the shoreline in the foreground, with streaks of sand carried far inland by wind and wave action. As sea level rises, ocean waves will attack barrier beaches with increasing frequency and severity.

Delta coasts are especially sensitive to sediment starvation and subsidence. Here, rates of subsidence can reach 2 cm/yr (0.8 in./yr). The Mississippi has lost about half of its natural sediment load, and sediment transport by such rivers as the Nile and Indus has been reduced by 95 percent.

According to recent estimates, sea-level rise and subsidence could cause the loss of more than 22 percent of the world's coastal wetlands by the year 2100. Coupled with losses directly related to human activity, coastal wetlands could decrease by 30 percent or more, with major impacts on commercially important fish and shellfish populations.

Coral reefs, like coastal wetlands, perform important ecological functions. They are highly biodiverse. They also serve as protective barriers to coastlines against storm waves and surges. However, more than half of the total area of living coral reefs is thought to be threatened by human activities ranging from water pollution to coral mining. When stressed by a rise in temperature, many corals respond by "bleaching" (Figure 16.3). In this process, they expel the algae that live symbiotically inside their structures, leaving the coral without color. The bleaching may be temporary if the stress subsides, but if permanent, the corals die. Major episodes of coral bleaching have been associated with increased water temperatures during strong El Niños.

Many pristine stretches of arctic shoreline are threatened by global warming (Figure 16.4). As global temperatures rise, the shoreline is less protected by sea ice, frozen ground, and ground ice. Greater expanses of open sea allow larger waves to attack the coast. Moreover, global warming will be especially severe at high latitudes. Rapid coastal recession has already been reported along the Beaufort Sea.

It is apparent that global climate change will have major impacts on coastal environments, with very broad implications for ecosystems and natural resources. It will take careful management of our coastlines to reduce those impacts on both human and natural systems.

16.3 Bleached anemones

These anemones, observed in the shallow waters of the Maldives Islands, exhibit *bleaching*—a process in which coral animals expel symbiotic algae as a response to stress. The bleaching can be fatal.

16.4 Arctic shoreline

Pristine arctic shorelines, such as this beach on the coast of Spitsbergen Island, Svalbard archipelago, Norway, will be subjected to rapid change as the global climate warms. Thawing of ground ice will release beach sediments, and the early retreat of sheltering sea ice will expose the shoreline to enhanced summer wave attack.

The Work of Waves and Tides

Wind, like running water, glacial action, and mass wasting, is an agent that shapes distinctive landforms. Wind can move material directly, picking up fine particles and carrying them from one place to another. Or it can act indirectly, by the action of wind-driven waves. What makes wind and breaking waves different from the other agents is that they can move material against the force of gravity.

Waves are the most important agents that shape coastal landforms (Figure 16.5). When winds blow over broad expanses of water, they generate waves. Both friction between moving air and the water surface and direct wind pressure on the waves transfer energy from the atmosphere to the water. Most of this energy is used up in the constant churning of mineral particles and water as waves break at the shore. This churning erodes shoreline materials, moving the shoreline landward. Waves and currents can also move sediment along the shoreline for long distances. This activity can build beaches outward as well as form barrier islands just offshore.

Note that throughout this chapter we will use the term **shoreline** to mean the shifting line of contact between water and land. When we use the word **coastline**, or simply *coast*, we're referring to the zone in which coastal processes operate or have a strong influence. The coastline includes the shallow water zone in which waves perform their work, as well as beaches and cliffs shaped by waves, coastal dunes, and *bays*—bodies of water that are sheltered from strong wave action. Where a river empties into an ocean bay, the bay is called an *estuary*. In an estuary, fresh and ocean water mix, creating a unique habitat for many plants and animals that is neither fresh water nor ocean.

16.5 Storm waves

High surf can rapidly reshape a beach, flattening the beach slope and moving beach sediment just offshore. These large waves at Humbug Mountain State Park, Oregon, were most likely generated by an offshore storm (National Geographic Image Collection).

WAVES

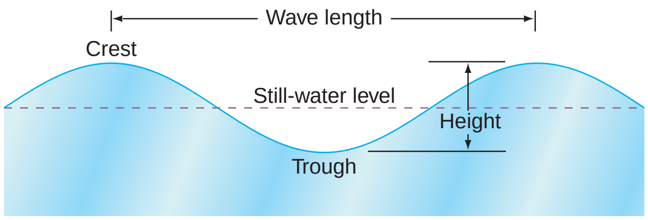
Water waves are a regular rising and falling of the water surface that moves a floating object up and down, forward and back. As shown in Figure 16.6, waves have *crests* and *troughs*. *Wave height* is the vertical distance between trough and crest. *Wave length* is the horizontal distance from trough to trough or from crest to crest. The wave typically travels in a forward direction as parallel fronts of crests and troughs. The *wave period* is the time in seconds between successive crests or successive troughs that pass a fixed point.

Wind-generated ocean waves are an example of *oscillatory waves*. In this type of wave, a tiny particle, such as a drop of water or a small floating object, completes one vertical circle, or *wave orbit*, with the passage of each wave length (Figure 16.7). The circle of motion grows rapidly smaller with depth.

For lake and ocean waves pushed by the wind, particles trace an orbit in which the forward speed of each particle at the crest is slightly greater than the backward speed at the trough. As a result, there is net forward motion of water associated with most lake and ocean wave trains. The amount of motion depends on the size and steepness of the waves, and strong waves are capable of pushing large amounts of water toward the beach. This causes local sea level to rise and generates local currents of water heading back out to sea.

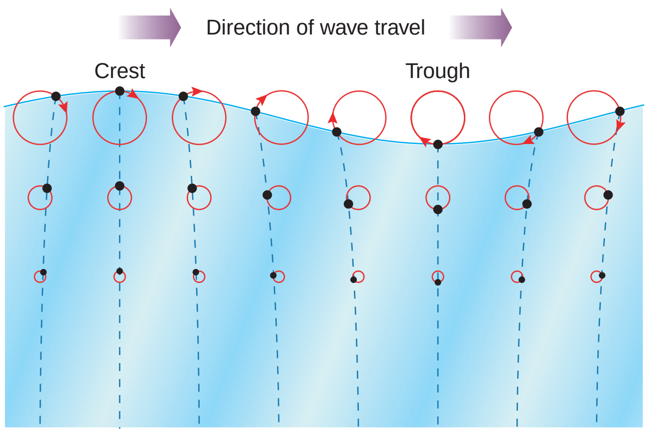
Waves are driven by wind. Wave height is related to wind speed, duration, and fetch. High winds over long distances and long durations can create very large waves.

The height of waves is determined by wind speed, wind duration, and *fetch*—the distance that the wind blows over the water. Table 16.1 shows how these factors are interrelated. Given a sustained wind, average and peak wave heights increase with fetch and duration, until waves are fully developed.



16.6 Terminology of water waves

We use the terms *crest, trough, wave height*, and *wave length* to describe water waves.



16.7 Motion in oscillatory waves

As each wave crest passes, particles move forward on the wave crest, downward as the crest passes, backward in the wave trough, and upward as the next crest approaches. At the sea surface, the orbit is of the same diameter as the wave height, but the size of the orbit decreases rapidly with depth.

Table 16.1 Wind speed and wave characteristics

For fully developed waves given a sustained wind speed. Wind speed is shown in knots—nautical miles per hour, where a nautical mile is one minute of longitude at the Equator. Fetch and duration are values required for full development.

Sustained wind speed, knots (m/s, mi/hr)	Average wave height, m (ft)	Height of largest waves, m (ft)	Fetch length, km (mi)	Duration, hrs
10 (5, 12)	0.3 (0.9)	0.5 (1.8)	18 (10)	2.4
15 (8, 17)	0.8 (2.5)	1.5 (5)	63 (34)	6
20 (10, 23)	1.5 (5)	3.0 (10)	140 (75)	10
25 (13, 29)	2.7 (9)	5.5 (18)	300 (160)	16
30 (15, 35)	4.3 (14)	8.5 (28)	520 (280)	23
40 (21, 46)	8.5 (28)	17 (57)	1300 (710)	42
50 (26, 58)	15 (48)	30 (99)	2600 (1420)	69

Wave height increases rapidly with increased wind speed. For example, the table shows that if sustained wind speed is doubled from 25 to 50 knots (13–26 m/s, 29–58 mi/hr), average wave height increases by more than fivefold, from 2.7 m (9 ft) to 15 m (48 ft), and peak waves reach 30 m (99 ft). When you coupled these values with the fact that the energy of a wave is proportional to the square of its height, you can appreciate how hurricane winds can generate waves with enormous destructive power.

Waves don't lose much energy as they travel across the deep ocean. But what happens when a wave reaches the shore? As it reaches shallow water, the drag of the bottom slows and steepens the wave. However, the wave top maintains its forward velocity and eventually falls down onto the face of the wave, creating a *breaker* (Figure 16.8). Tons of foamy turbulent water surge forward in a sheet, riding up the beach slope. This powerful *swash* moves sand and gravel on the beach landward. Once the force of the swash has been spent against the slope of the beach, the return flow, or *backwash*, pours down the beach. This "undercurrent" or "undertow" can sweep unwary bathers off their feet and carry them seaward beneath the next oncoming breaker. The backwash carries sand and gravel seaward, completing the wave cycle.

MARINE SCARPS AND CLIFFS

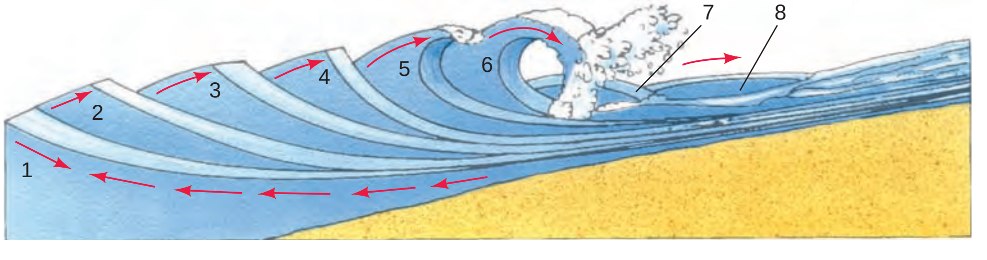
If you've ever visited a beach when waves are high, you've seen how the force of tons of water moving up and down the beach can do enormous amounts of work. If the coastline is made up of weak or soft materials—various kinds of regolith, such as alluvium—the force of the forward-moving water alone easily cuts into the coastline. Here, erosion is rapid, and the shoreline may recede rapidly. Under these conditions, a steep bank, or *marine scarp,* will form and steadily erode as it is attacked by storm waves (Figure 16.9).

If a **marine cliff** lies within reach of the moving water, it will be hit with tremendous force. The surging water carries rock fragments of all sizes that are thrust against the bedrock of the cliff. The impact breaks away new rock fragments and undercuts the cliff at the base. In this way, the cliff erodes shoreward, maintaining its form as it retreats. But since the marine cliff is made of hard bedrock, retreat is exceedingly slow. The wave erosion produces some unique landforms—*caves, stacks, arches,* and an *abrasion platform* (Figure 16.10).

Waves erode weak materials to make marine scarps and attack resistant rocks to make marine cliffs. Caves, arches, stacks, and abrasion platforms are landforms of marine cliffs.

BEACHES AND LITTORAL DRIFT

Where sand is available to wave action, it accumulates as a thick, wedge-shaped deposit, or **beach**. Beaches absorb the energy of breaking waves. During periods of storm activity (winter, for example), the beach is cut back, and sand is carried offshore a short distance by



16.8 Breaking wave

As the wave approaches the beach (1–3), it steepens (4–5), and finally falls forward (6–7), rushing up the beach slope (8).

16.9 Retreating shoreline

Mohegan Bluffs, Block Island, Rhode Island. This *marine scarp* of Ice Age sediments is being rapidly eroded, threatening historic Southeast Lighthouse. In 1993 the lighthouse was moved to a safer spot 73.5 m (245 ft) away.

EYE ON THE LANDSCAPE **What else would the geographer see?** The sediments exposed in the bluff were laid down by streams fed by melting stagnant continental ice sheets at the end of the Ice Age. Because the ice melted irregularly, the deposits are not very uniform, and the exposed bedding (A) gives that impression. The larger rocks in the deposits were let down from melting ice and were too large to be moved by the streams laying the sediments. A large lag deposit (B) of these stones remains at the water's edge, where it is being worked by waves.

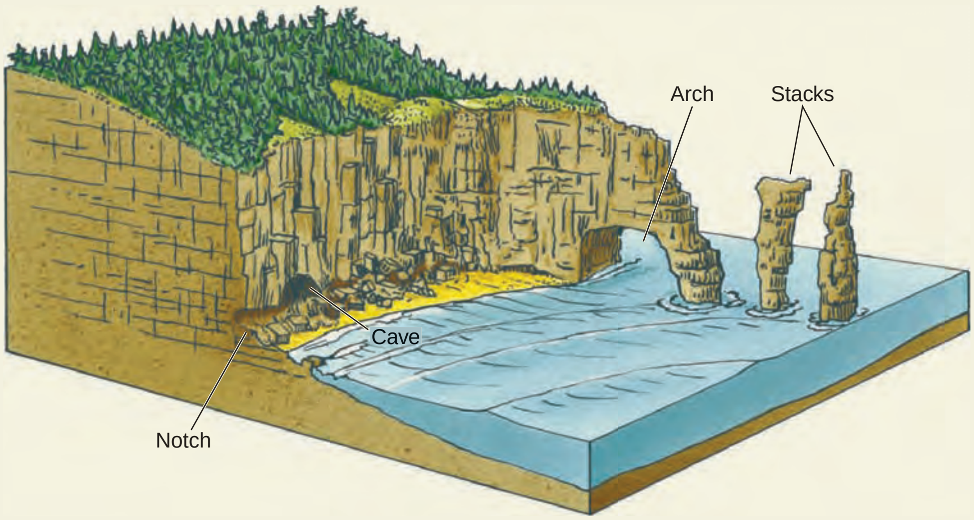
the heavy wave action. But the sand is slowly returned to the beach during long periods when waves are weak (summer). In this way, a beach may stay quite stable over the years—but alternate through narrow and wide configurations.

Although most beaches are made from particles of fine to coarse quartz sand, some beaches are built from rounded pebbles or cobbles (Figure 16.11). Still others are formed from fragments of volcanic rock or even shells.

16.10 Wave erosion of a marine cliff

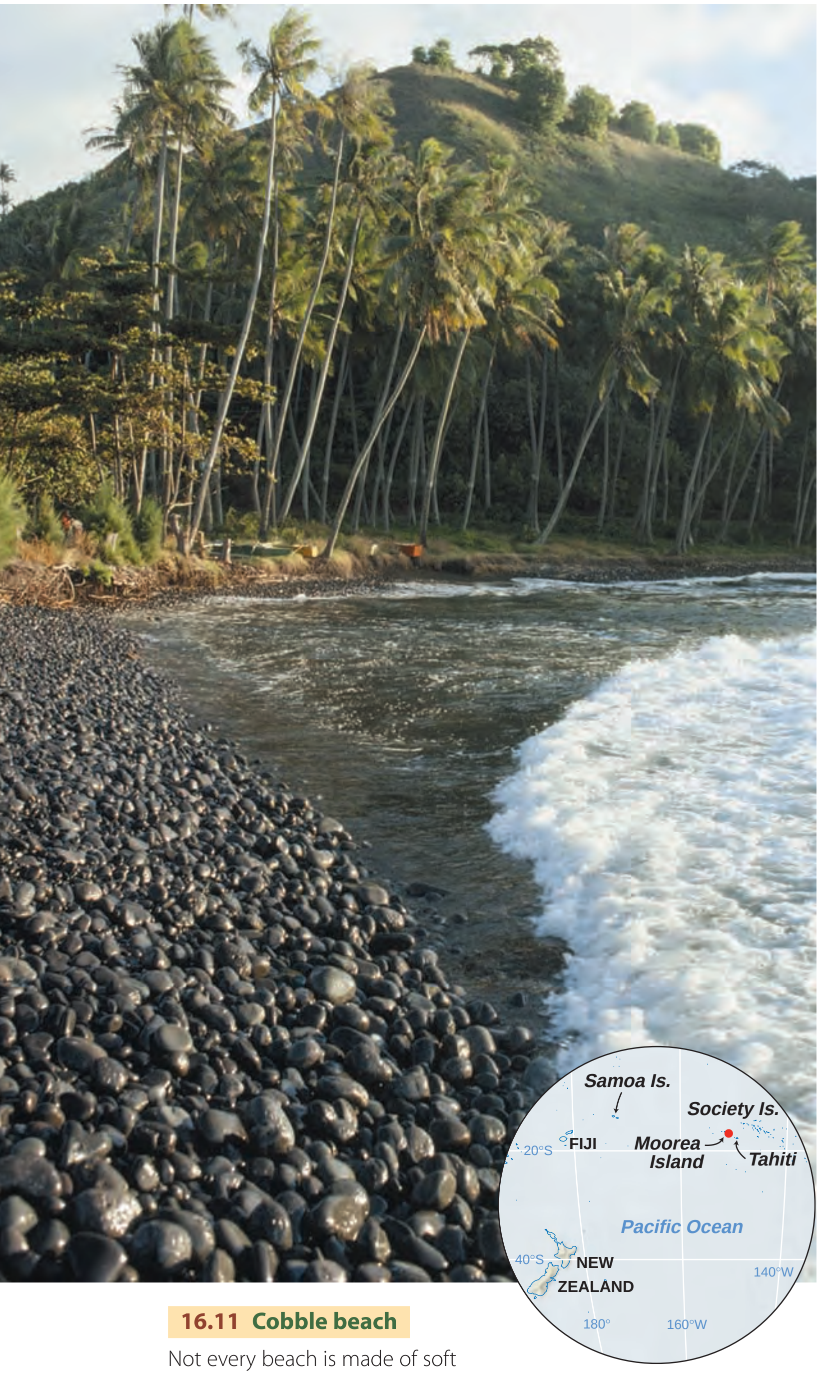
Wave action undercuts the marine cliff or headland, creating landforms such as sea stacks and arches.

▶ A deep basal indentation, the *wave-cut notch*, marks the line of most intense wave erosion. The waves find points of weakness in the bedrock and penetrate deeply to form crevices and *sea caves*. Where a more resistant rock mass projects seaward, it may be cut through from both sides to form a picturesque *sea arch*. After an arch collapses, a rock column, known as a *stack*, remains. Eventually, the stack is toppled by wave action and is leveled.



▼ **Abrasion platform** As the sea cliff retreats landward, continued wave abrasion forms an *abrasion platform*. This sloping rock floor is eroded and widened by abrasion beneath the breakers. If a beach is present, it is little more than a thin layer of gravel and cobblestones atop the abrasion platform. Montana d'Oro State Park, California.

▼ **Sea stacks** These stacks at Port Campbell National Park, Victoria, Australia, are dubbed the "Twelve Apostles." Remnants of a collapsed arch appear between the nearest stack and the headland.



16.11 Cobble beach

Not every beach is made of soft sand. Where sand is scarce but rocks are abundant, beaches can be composed of rounded cobbles, like these on Tahiti, Society Islands, Polynesia (National Geographic Image Collection).

Breaking waves also produce currents that move sediment along the shoreline (Figure 16.12). When waves attack at an angle, the swash and backwash move sand down the beach, away from the wind direction, as *beach drift*. Wave water piling up in the breaker zone sets up a *longshore current* just offshore from the breakers that moves sediment in the same direction. The two flows constitute **littoral drift**. Where the beach is straight, littoral drift forms *sand bars* and *sandspits* (Figure 16.13). Where the shoreline includes resistant headlands, littoral drift builds *pocket beaches* in bay heads from sediments eroded from the headlands (Figure 16.14).

Breakers attacking the shore at an angle produce littoral drift, which includes beach drift—a movement of sediment along the beach—as well as longshore drift—a sediment movement just offshore from the beach.

When sand arrives at a particular section of the beach more rapidly than it is carried away, the beach is widened and built oceanward. This change is called *progradation* (building out). When sand leaves a section of beach more rapidly than it is brought in, the beach is narrowed and the shoreline moves landward. This change is called *retrogradation* (cutting back).

Along stretches of shoreline affected by retrogradation, the beach may be seriously depleted or even entirely disappear, destroying valuable shore property. In some circumstances, we can take steps to encourage progradation and build a broad, protective beach. We can do this by installing groins at close intervals along the beach. A *groin* is simply a wall or an embankment usually built at right angles to the shoreline and made from large rock masses, concrete, or wooden pilings. Groins trap sediment moving along the shore as littoral drift (Figure 16.15).

In some cases, beach sand comes from sediment that is delivered to the coast by a river. That means that dams constructed far upstream on the river can cause retrogradation on a long stretch of shoreline by drastically reducing the sediment load of the river.

Groins are walls or embankments built at right angles to the shoreline. They trap littoral drift and help prevent beach retrogradation.

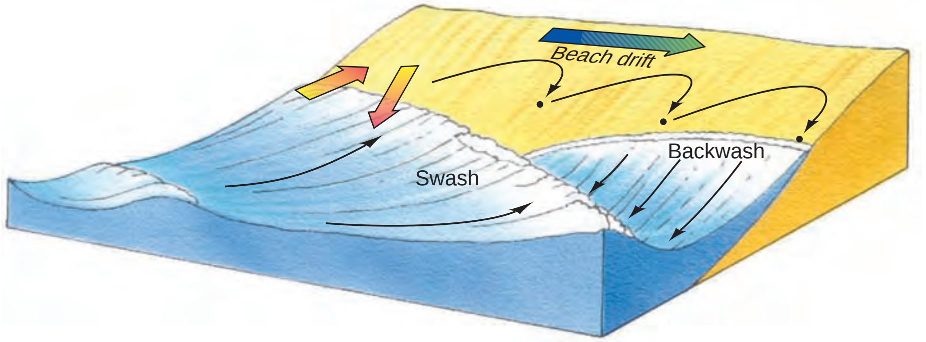
GEODISCOVERIES **The Work of Waves**

Watch this video to see examples of breaking waves and to review the processes by which waves transport sediment.

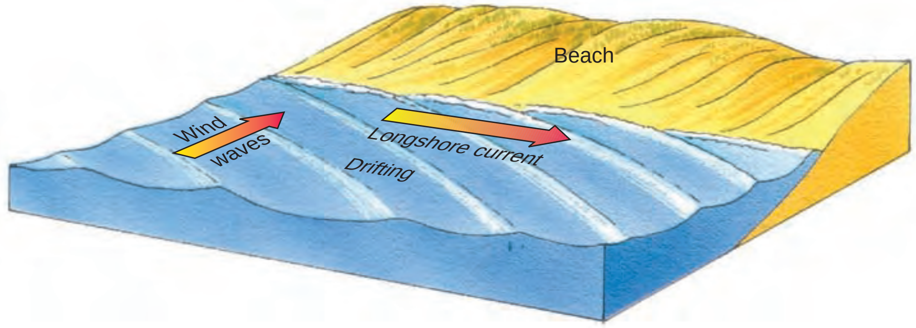
TIDAL CURRENTS

Most marine coastlines are influenced by the *ocean tide*—the rhythmic rise and fall of sea level under the influence of changing attractive forces of the Moon and Sun on the rotating Earth. If the tides are large, the changing water level and the tidal currents play an important role in shaping coastal landforms. Figure 16.16 shows the rise and fall of water level over a day at Boston Harbor in a *tide curve*.

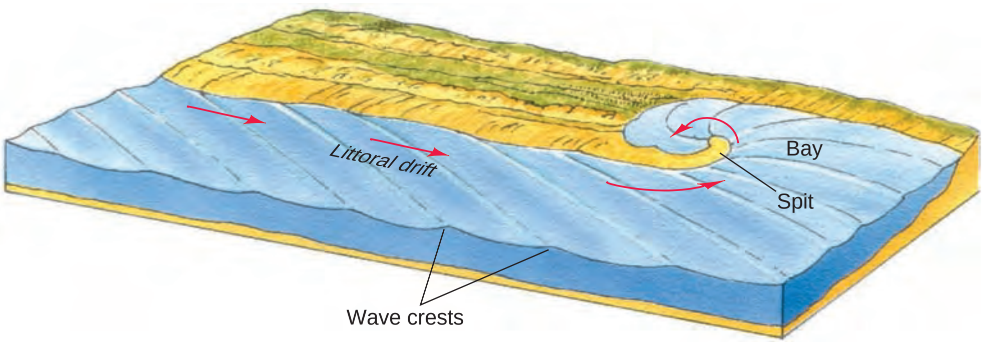
In bays and estuaries, the changing tide sets up *tidal currents*. When the tide begins to fall, an *ebb current* sets in. This flow ceases about the time when the tide is at



▲ **Beach drift** Swash tends to approach the shore at an oblique angle, carrying its burden of sand with it. But the backwash flows back along the most direct downhill direction. So, sand particles come to rest at a position to one side of the starting place. This movement is repeated many times, transporting particles long distances along the shore. This motion is called *beach drift.*



▲ **Longshore drift** When waves approach a shoreline at an angle to the beach, a current is set up parallel to the shore in a direction away from the wind. This is known as a *longshore current*. When wave and wind conditions are favorable, this current is capable of carrying sand along the sea bottom. This is *longshore drift*.



▲ **Littoral drift** Beach drift and longshore drift, acting together, move particles in the same direction for a given set of onshore winds. The total process is called *littoral drift*. ("Littoral" means "pertaining to a coast or shore.") Where the shoreline is straight or broadly curved for many kilometers at a stretch, littoral drift moves the sand along the beach in one direction for a given set of prevailing winds. If there is a bay, the sand is carried out into open water as a long finger, or *sandspit*. As the sandspit grows, it forms a barrier, called a *bar*, across the mouth of the bay.

16.12 Littoral drift

The cycle of swash and backwash produced by breaking waves transports sand and shapes beaches and coastlines.

its lowest point. As the tide begins to rise, a landward current, the *flood current*, begins to flow.

Ebb and flood currents perform several important functions along a shoreline.

Ocean tides produce tidal currents at the shoreline. These currents scour inlets and distribute fine sediment in bays and estuaries.

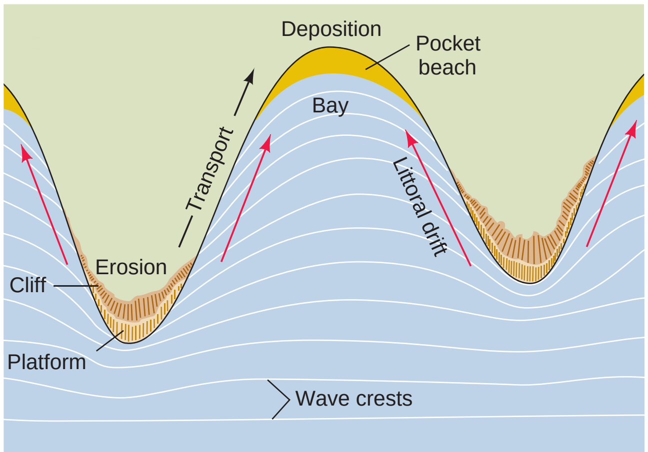
First, the currents that flow in and out of bays through narrow inlets are very swift—scouring the inlet. This keeps the inlet open, despite littoral drifting that tends to close the inlet with sand.

Second, tidal currents hold large amounts of fine silt and clay, suspended in the water. This fine sediment comes from streams that enter the bays or from mud

16.13 Sandspit

This white *sandspit* is growing in a direction toward the observer. Monomoy Point, Cape Cod, Massachusetts.

EYE ON THE LANDSCAPE **What else would the geographer see?** The freshness of the sand here (A) indicates that Monomoy Point is growing very rapidly. The sand is supplied by the erosion of marine cliffs at Nauset Beach to the north. Note the overwash channels (B) that are cut through the vegetated sand dunes by the high waters and high surf of severe storms. To the upper left is the town of Chatham (C), its low hills formed from rock debris shed by melting ice sheets during the Ice Age. The coastline has the "drowned" look of a coastline of submergence, with its many lakes and bays.

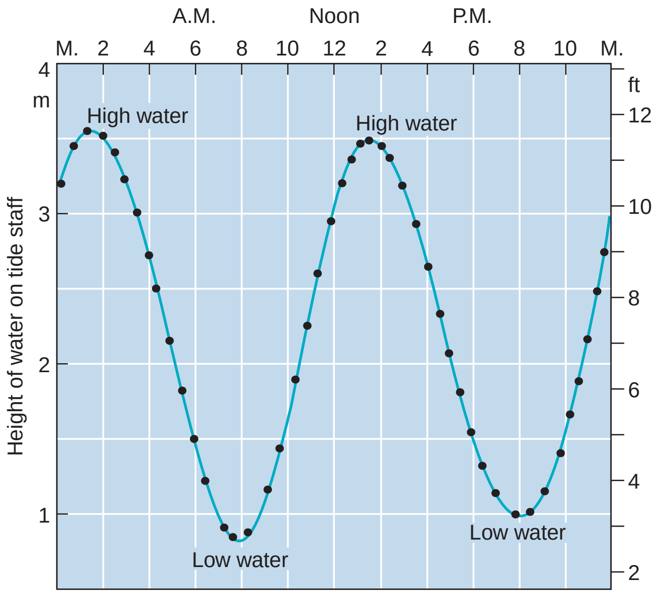


16.14 Pocket beach

When the coastline has prominent headlands that project seaward alternating with deep bays, approaching wave fronts slow when the water becomes shallow. This slowing effect causes the wave front to wrap around the headland, focusing wave energy on the resistant rock. Sediment is eroded from cliffs on the headland and is carried by littoral drift along the sides of the bay. The sand is deposited at the head of the bay, creating a crescent-shaped beach, often called a *pocket beach*.

16.15 Groins

Low walls of stone or sandbags, placed at right angles to the shoreline, trap sand as it is moved the coast by littoral drift. The groins on this beach in Maroochydore, Queensland, Australia, are trapping sand moving from left to right.



16.16 Tide curve

Height of water at Boston Harbor as measured every half hour. The water reached its maximum height, or high water, at 3.6 m (11.8 ft) and then fell to its minimum height, or low water, at 0.8 m (2.6 ft), about 6 1/4 hours later. There's a second high water about 12 1/2 hours after the previous high water, completing a single tidal cycle. In this example, the tidal range, or difference between heights of successive high and low waters, is about 2.8 m (9.2 ft).

that has been agitated up from the bottom by storm waves. The sediment settles to the floors of the bays and estuaries, and builds up in layers, gradually filling the bays. It contains a lot of organic matter.

In time, tidal sediments fill the bays and produce mud flats, which are barren expanses of silt and clay. They are exposed at low tide but covered at high tide. Next, salt-tolerant plants start to grow on the mud flat. The plant stems trap more sediment, and the flat builds up, becoming a *salt marsh* (Figure 16.17). A thick layer of peat eventually forms at the salt marsh surface.

GEODISCOVERIES **Tides**

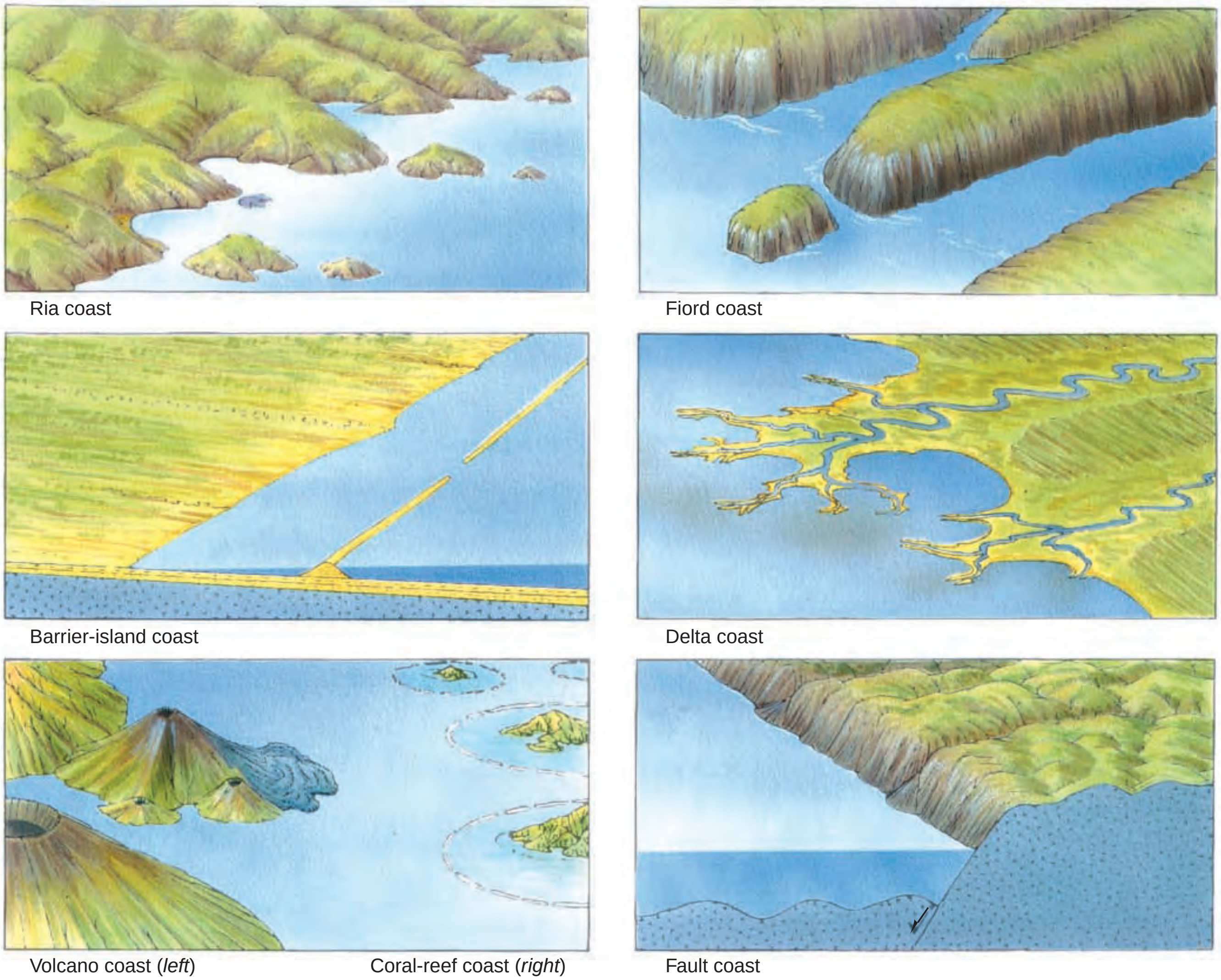
Watch this animation to see how the tides result from the Moon's gravity and the rotation of the Earth and Moon around their common center of mass.

Types of Coastlines

Although every coastline is a unique creation of ocean waves acting on distinctive land masses, we can identify seven important types of coasts, shown in Figure 16.18. Coastlines of **submergence** are formed when the rising sea level partially drowns a coast or when part of the crust

16.17 Salt marsh

Salt marshes are abundant on the southeastern coastal plain. This marsh, photographed at high water, is near Brunswick, Georgia. At low tide, receding water will reveal the muddy bottom of the broad channel (National Geographic Image Collection).



16.18 Seven types of coastlines

These sketches illustrate the important features of seven types of coastlines.

sinks. This group includes ria coasts and fiord coasts. Another group of coastlines are formed by the process of **emergence**, when submarine landforms are exposed by a falling of sea level or a rising of the crust. This group includes barrier-island coasts, volcano coasts, delta coasts, fault coasts, and coral-reef coasts.

RIA COASTS AND FIORD COASTS

Coastlines of submergence include ria coasts and fiord coasts. A *ria coast* is formed when a rise of sea level or a crustal sinking (or both) brings the shoreline to rest against the sides of river valleys previously carved by streams. Because the new embayments are fed fresh water from the streams the valleys formerly contained, they become estuaries. Figure 16.19 describes the formation of a ria coast in more detail.

Ria coasts and fiord coasts result from submergence of a land mass. Islands, bars, estuaries, and bays are characteristic of these "drowned" coastlines.

The *fiord coast* is similar to the ria coast (Figure 16.20). Steep-walled fiords are created from submerged glacial troughs rather than from submerged stream valleys, as in the case of ria coasts.

BARRIER-ISLAND COASTS

The *barrier-island coast* is associated with a recently emerged coastal plain (Figure 16.21). A *barrier island* is a low ridge of sand, lying a short distance from the coast, that is created by wave action and increases in height as coastal winds fortify the island with dunes. Much of the Atlantic and Gulf coast from New York to Texas is flanked by barrier islands.

Behind the barrier island is a *lagoon*—a broad expanse of shallow water in places largely filled with tidal deposits.

16.19 Evolution of a ria coastline

A *ria coast* is deeply embayed, resulting from submergence of a land mass. ("Ría" means estuary or narrow sea inlet in Spanish.)

◀ **Before submergence** This is the terrain before sea level rises (or the crust subsides, or both). Active streams have carved the valleys and continue to do so.

◀ **Submergence** Rising sea levels and/or crustal sinking submerge the existing coastline. The shoreline rises up the sides of the stream-carved valleys, creating bays. Streams that occupied the valleys add fresh water to the bays, making them estuaries of mixed fresh and salt waters. Streams also provide sediment to the shoreline.

◀ **Sandspit formation** Wave attack forms cliffs on the exposed seaward sides of islands and headlands. Sediment from wave erosion and inflowing rivers collects to form beaches along cliffed headlands and the heads of bays. This sediment is carried by littoral drift and often builds sandspits across bay mouths, creating connecting links between islands and mainland.

◀ **Estuaries** Eventually, the sandspits seal off the bays, reducing water circulation and enhancing the estuarine environment.

▶ **Cliffed coast** If sea level remains at the same height for a long time and headland rocks are not resistant to erosion, the coast may evolve into a cliffed shoreline of narrow beaches.

◀ **Ría Ortigueira, Coruña, Spain** This photo shows many of the features of the ria coastline, including submerged valleys, islands, and sand bars.

16.20 Fiord coast

Like the ria coast, the *fiord coast* is "drowned" by recent submergence. But here the valleys were recently occupied by glaciers that eroded their walls and scraped away loose sediment and rock to form broad, steep-sided valleys that are now flooded. Fiordland National Park, South Island, New Zealand (National Geographic Image Collection).

Characteristic gaps, known as *tidal inlets*, along the barrier island connect the lagoon with the ocean. Strong currents flow back and forth through these gaps as the tide rises and falls. New inlets are formed in severe storms and are then kept open by the tidal currents. In many cases, these inlets are later closed by littoral drift.

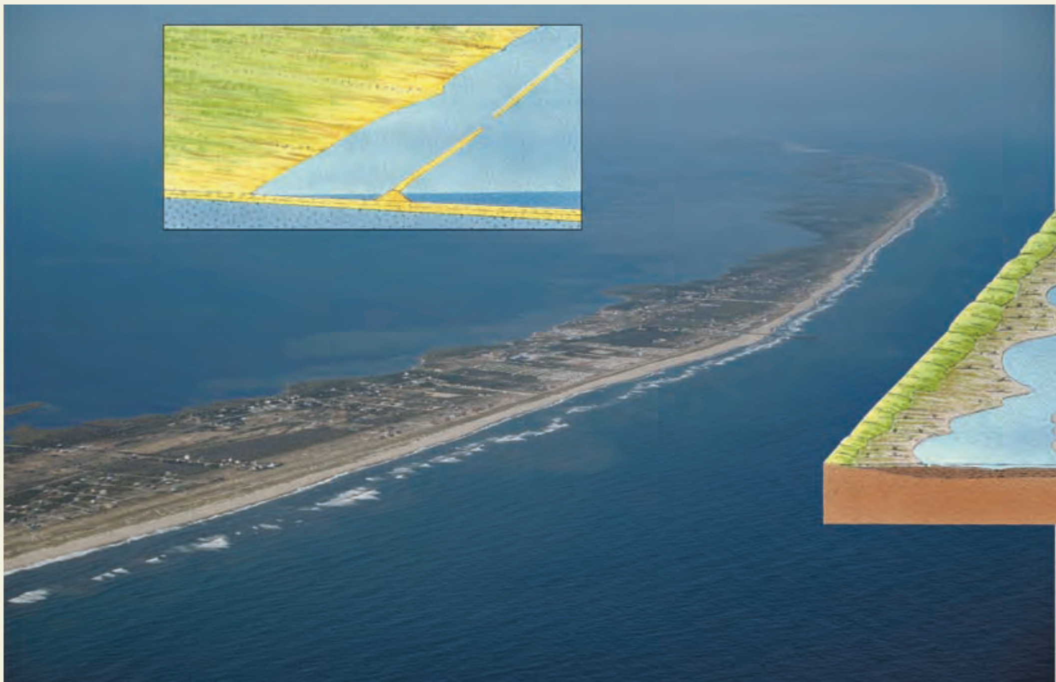
Barrier island coasts occur where a gently sloping coastal plain emerges from the sea. Barrier island beaches protect a shallow lagoon that is serviced by tidal inlets crossing the barrier beach.

DELTA COASTS

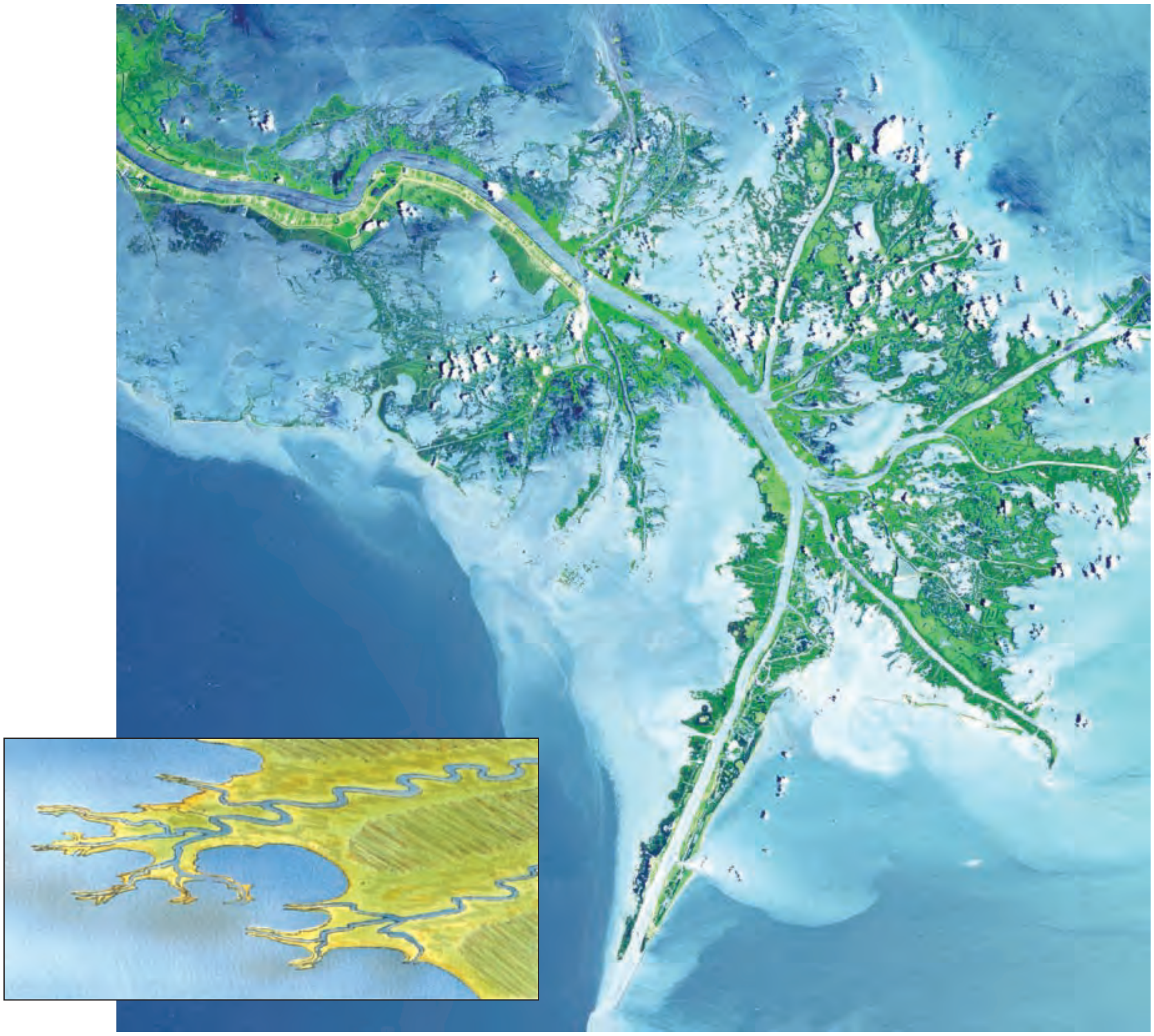
The deposit of clay, silt, and sand made by a stream or river where it flows into a body of standing water is known as a **delta** (Figure 16.22). The sediment is deposited because the current is rapidly slowed as it pushes out into the standing water. The river channel divides and subdivides into lesser channels called *distributaries*. The coarser sand and silt particles settle out first, while the fine clays continue out farthest and eventually come to rest in fairly deep water. When the fine clay particles in fresh water come into contact with salt water, they clot together into larger particles that settle to the seafloor.

16.21 Barrier-island coast

▼ Where a gently sloping coastal plain meets the ocean, wave action builds a *barrier-island coast* of barrier islands and beaches (National Geographic Image Collection).



▼ A barrier island is separated from the mainland by a wide *lagoon*. Sediments fill the lagoon, while dune ridges advance over the tidal flats. An *inlet* allows tidal flows to pass in and out of the lagoon.



16.22 The delta coast

Delta coasts show a wide variety of outlines. The Mississippi Delta has long, branching fingers that grow far out into the Gulf of Mexico at the ends of the distributaries, giving the impression of a bird's foot. This image, acquired by the ASTER instrument on NASA's Terra satellite platform, also shows the great quantity of suspended clay and fine silt being discharged by the river into the Gulf—about 250,000 to 500,000 metric tons (about 275,000 to 550,000 English tons) per day.

Deltas can grow rapidly, at rates ranging from 3 m (about 10 ft) per year for the Nile Delta to 60 m (about 200 ft) per year for the Mississippi Delta. Some cities and towns that were at river mouths several hundred years ago are today several kilometers inland.

A delta results when a river empties into the ocean. The Mississippi Delta has a bird's foot plan, with branching distributaries carrying river water and sediment to the ocean.

GEODISCOVERIES **Satellite Imagery and the Earth's Rivers Interactivity**

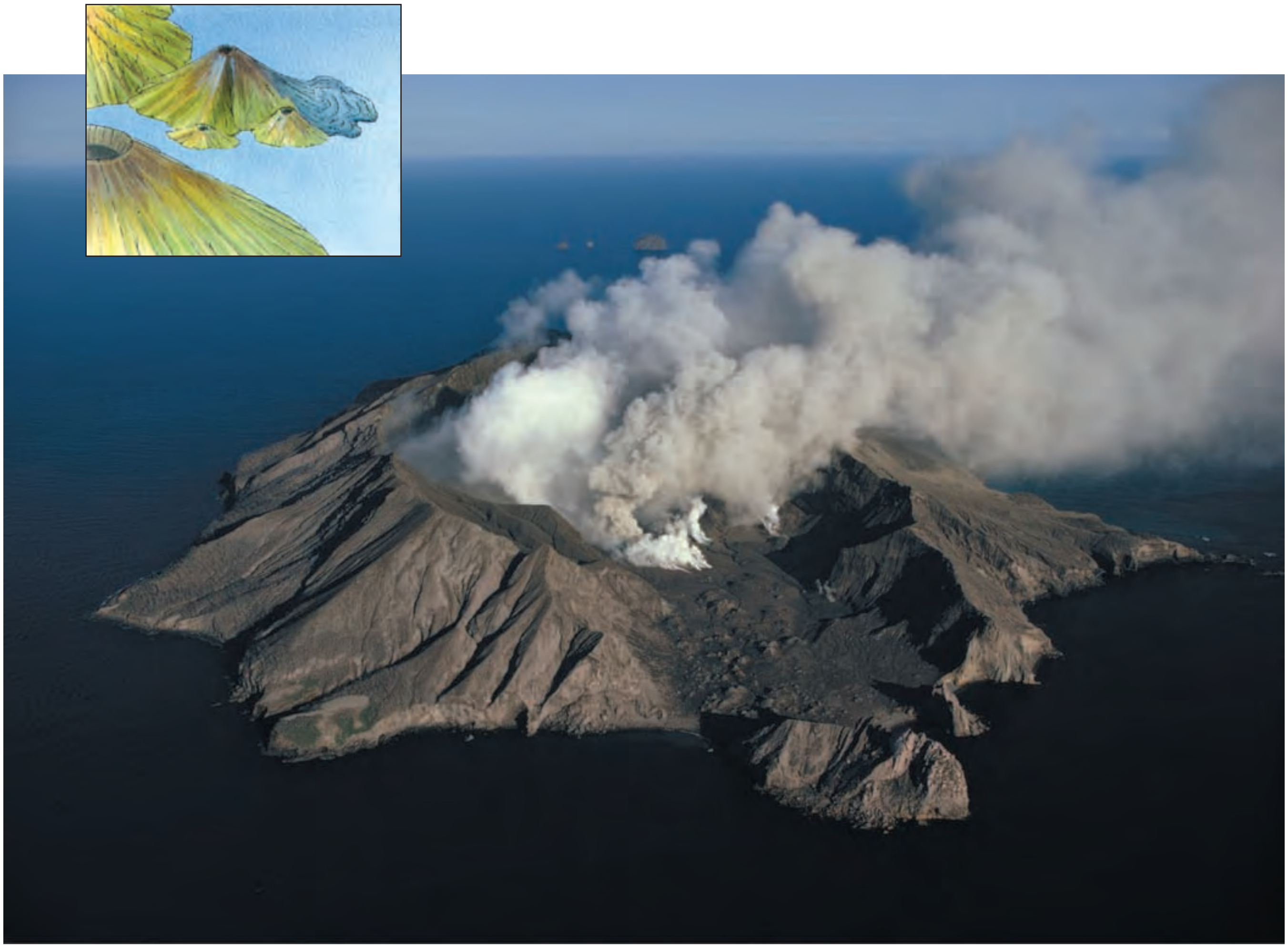
View the deltas of the Earth's major rivers as seen from space. Includes Colorado, Nile, Yangtze, Ganges, Mississippi, Amazon, and Okavango rivers.

VOLCANO AND CORAL-REEF COASTS

Volcano coasts arise where volcanic deposits—lava and ash—flow from active volcanoes into the ocean (Figure 16.23). Wave action erodes the fresh deposits, creating low cliffs. Beaches are typically narrow, steep, and composed of fine particles of the extrusive rock.

Coral-reef coasts are unique because the new land is made by organisms—corals and algae. Growing together, these organisms secrete rock-like deposits of carbonate minerals, called **coral reefs**. As coral colonies die, new ones are built on them, accumulating as limestone. Coral fragments are torn free by wave attack, and the pulverized fragments accumulate as sand beaches.

We find *coral-reef coasts* in warm tropical and equatorial waters between lat. 30° N and 25° S (Figure 16.24).



16.23 Volcano coast

White Island, New Zealand, is an active stratovolcano with a *volcano coast*. Waves have notched its flanks into steep cliffs as abundant rainfall has carved valleys into its slopes. The large central crater, opening out toward the viewer, was formed by the collapse of three overlapping circular craters (National Geographic Image Collection).

Volcano coasts are found where fresh volcanic deposits of lava and ash reach the ocean. Coral reef coasts occur in warm oceans where corals build reefs at the land–sea margin.

This is because water temperatures above 20°C (68°F) are needed for dense coral reefs to grow. Reef corals live near the water surface. The sea water must be free of suspended sediment, and it must be well aerated for vigorous coral growth to take place. For this reason, corals thrive in positions exposed to wave attack from the open sea. Because muddy water prevents coral growth, coral reefs are absent at the mouths of muddy streams. Coral reefs are remarkably flat on top. They are exposed at low tide and covered at high tide. As noted earlier, some coral reefs have been damaged by increased ocean temperatures and water pollution.

There are three distinctive types of coral reefs—fringing reefs, barrier reefs, and atolls. *Fringing reefs* are built as platforms attached to shore. They are widest in front of headlands where the wave attack is strongest. *Barrier reefs* lie out from shore and are separated from the mainland by a lagoon. There are narrow gaps at intervals along barrier reefs, through which excess water from breaking waves is returned from the lagoon to the open sea.

Atolls are more or less circular coral reefs enclosing a lagoon but have no land inside. Most atolls are rings of coral growing on top of old, sunken volcanoes. They begin as fringe reefs surrounding a volcanic island, then, as the volcano sinks, the reef continues to grow, and eventually only the reef remains.

FAULT COASTS

The final type of coastline is a *fault coast* (Figure 16.25). Faulting of the coastal margin of a continent can leave the shoreline resting against a fault scarp. A classic

16.24 Coral reef coast

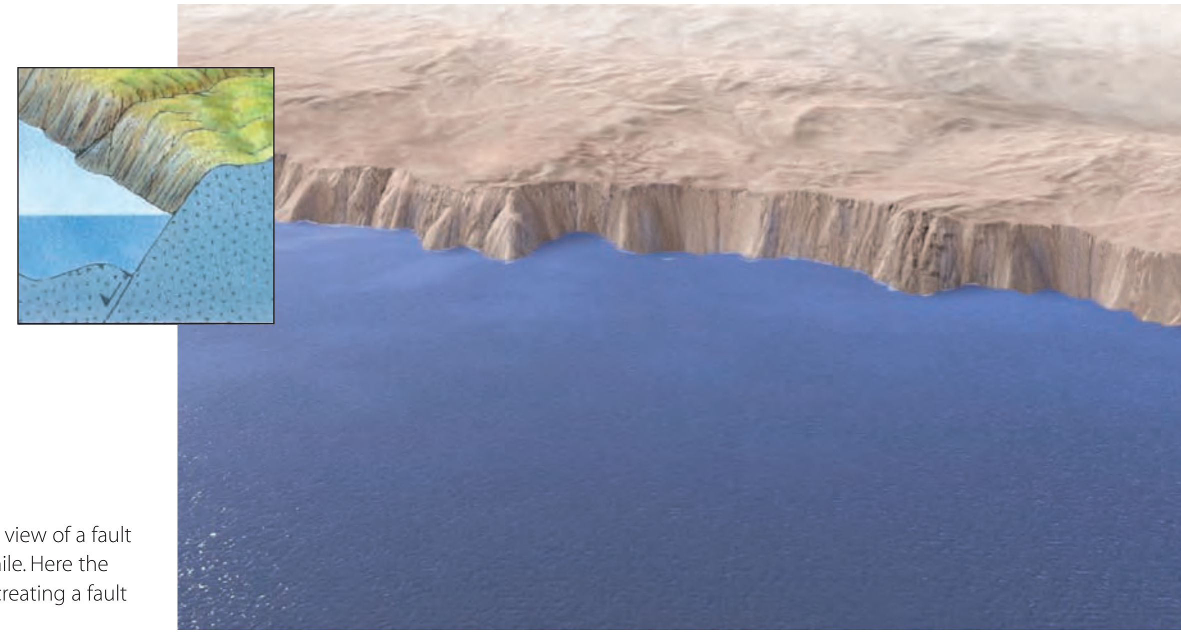
A coral *barrier reef* with a lagoon rings the Island of Moorea, Society Islands, South Pacific Ocean. The island is a deeply dissected volcano with a history of submergence.

example occurs on the northern coast of Chile, where the Andes Mountains rise from the Peru–Chile trench. In central California, near the coastal town of Lucia, the continental shelf is very narrow, suggesting that the marine cliffs there are the result of faulting.

RAISED SHORELINES AND MARINE TERRACES

The active life of a shoreline is sometimes cut short by a drop in sea level. When this happens, a *raised shoreline results*. Wave erosion stops and an abrasion platform, now above sea level, will become a **marine terrace**. As we will see in Chapter 17, sea level remains relatively stable during interglacial periods and then falls hundreds of meters as the Earth's water is locked up in continental glaciers.

If we superimpose episodes of rising and falling sea level on a coastline that is slowly being raised by tectonic activity, a series of raised shorelines is created, including sequences of marine terraces (Figure 16.26). Raised shorelines are common along the continental



16.25 Fault coast

This artist's image reconstructs a 3-D view of a fault coast along the coast of northern Chile. Here the Peru-Chile Trench falls just offshore, creating a fault along the continent's western edge.

and island coasts of the Pacific Ocean. Here tectonic processes are active along mountain and island arcs.

GEODISCOVERIES **Coastal Landforms Interactivity**
Review key concepts and terms of coastal landforms. Examine photos of shorelines from ground to satellite. Build spits and barrier islands, varying sand supply and wind direction.

Wind Action

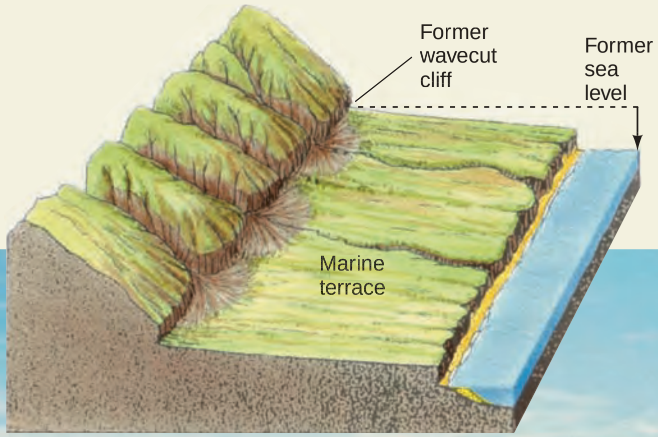
Wind plays a direct role in shaping coastal landforms, carrying sand and other sediments, and depositing them at new locations. We use the term *eolian*, which comes from "Aeolus," the name of the Greek god of the winds, to describe wind-generated landforms and processes. Dunes are thus *eolian landforms*. Figure 16.27 is a global map showing regions where eolian processes and landforms are found.

Ordinarily, wind isn't strong enough to dislodge mineral matter from the surfaces of unweathered rock, from moist, clay-rich soils, or from soils bound by a dense plant cover. Normal winds only erode and transport sediment on land surfaces where small mineral and organic particles are in a loose, dry state—typically, deserts and semiarid lands (steppes). In coastal environments, beaches can also provide a supply of loose sand to be shaped. Here the wind builds coastal dunes, even

Wind action normally moves mineral particles only when they are dry and unprotected by a vegetation cover. These conditions are found in deserts and semiarid regions of the world, as well as on sandy shorelines.

16.26 Marine terraces

▼ A *raised shoreline* becomes a cliff parallel with the newer, lower shoreline. The former abrasion platform is now a marine terrace.



▼ This series of *marine terraces* appears on the western slope of San Clemente Island, off the Southern California coast. More than 20 different terrace levels have been identified. The highest has an elevation of about 400 m (about 1300 ft).

16.27 Eolian landforms

Wind works best as a geomorphic agent when wind velocity is high and moisture and vegetation cover are low. Desert and coastal dunes are the most common eolian landforms. During the Ice Age, strong winds carried vast clouds of silt, picked up from flooding rivers draining ice sheets, that formed deep layers in continental interiors. These wind-borne deposits are known as *loess* (National Geographic Map Collection).

where the climate is humid and the land surface inland from the coast is well protected by a plant cover.

EROSION BY WIND

Wind performs two kinds of erosional work: abrasion and deflation. Loose particles lying on the ground surface may be lifted into the air or rolled along the ground by wind action. In the process of *wind abrasion*, wind drives mineral particles against an exposed rock or soil surface, wearing down the surface.

The sandblasting action of wind abrasion is usually limited to the bottom meter or two of exposed rock above a flat plain. That's because sand grains don't rise much higher into the air. Wind abrasion produces pits, grooves, and hollows in the rock. You'll often see that wooden utility poles on windswept plains have a protective metal sheathing or a heap of large stones placed around the base. Without this protection, they would quickly be cut through at the base.

Deflation is the removal of loose particles from the ground by wind. Deflation acts on loose soil or sediment, and so dry river courses, beaches, and areas of recently formed glacial deposits are susceptible. In dry climates, much of the ground surface can be deflated because the soil or rock is largely bare of vegetation.

The finest particles, those of clay and silt sizes, are lifted and raised into the air—sometimes to a height of a thousand meters (about 3300 ft) or more. Sand grains are moved by moderately strong winds and usually travel within a meter or two (about 3 to 6 ft) of the ground. Gravel fragments and rounded pebbles can be rolled or pushed over flat ground by strong winds, but they don't travel far. They become easily lodged in hollows or between other large particles. If there's a mixture of particles of different sizes on the ground, deflation removes the finer sized particles and leaves the coarser particles behind.

16.28 Blowout

A *blowout* forms when fine-grained soil is disturbed, breaking up the vegetation cover. Wind then picks up silt and fine particles, leaving sand and coarser particles behind.

A **blowout** is a shallow depression produced by deflation (Figure 16.28). The size of the depression may range from a few meters (10 to 20 ft) to a kilometer (0.6 mi) or more in diameter, although it is usually only a few meters deep. Blowouts form in plains regions of dry climate. Any small depression in the surface of the plain, especially where the grass cover has been broken or disturbed, can form a blowout. Rains fill the depression and create a shallow pond or lake. As the water evaporates, the mud bottom dries out and cracks, leaving small scales or pellets of dried mud. These particles are lifted out by the wind.

Deflation is also active in semidesert and desert regions. In Chapter 15, we saw that the centers of desert basins often hold saline playa deposits. In the southwestern United States, playas often occupy large areas. Deflation has reduced many of these playas by several meters.

Rain beating down on the ground, overland flow, and deflation may be active for a long period on the gently sloping surface of a desert alluvial fan or alluvial terrace. These processes remove fine particles, leaving coarser, heavier materials behind. As a result, rock fragments ranging in size from pebbles to small boulders become concentrated into a surface layer known as a **desert pavement** (Figure 16.29). The large fragments become closely fitted together, concealing the smaller particles—grains of sand, silt, and clay—that remain beneath. The pavement acts as an armor that protects the finer particles from rapid removal by deflation. However, the pavement is easily disturbed by wheeled or tracked vehicles, exposing the finer particles and allowing severe deflation and water erosion to follow.

Wind deflation can produce blowouts and help form desert pavement—a surface armor of coarse particles that reduces further deflation.

DUST STORMS

Strong, turbulent winds blowing over barren surfaces can lift great quantities of fine dust into the air, forming a dense, high cloud called a **dust storm**. In semiarid grasslands, dust storms are generated where ground surfaces have been stripped of protective vegetation cover by cultivation or grazing. Strong winds cause soil particles and coarse sand grains to hop along the ground. This motion breaks down the soil particles and disturbs more soil. With each impact, fine dust is released that can be carried upward by turbulent winds.

A dust storm approaches as a dark cloud extending from the ground surface to heights of several thousand

16.29 Desert pavement

A *desert pavement* is formed from closely fitted rock fragments. Lying on the surface are fine examples of wind-faceted rocks, which attain their unusual shapes by long-continued sandblasting.

16.30 Dust storm

In a front reaching up to 1000 m (3300 ft) in altitude, a dust storm approaches an American facility in Iraq. It passed over in about 45 minutes, leaving a thick layer of dust in its wake.

meters (Figure 16.30). Typically, the advancing cloud wall represents a rapidly moving cold front. Standing within the dust cloud, you are shrouded in deep gloom or even total darkness. Visibility is cut to a few meters, and a fine choking dust penetrates everywhere.

Sand Dunes and Loess

A **sand dune** is any hill of loose sand shaped by the wind. Sand dunes form where there is a source of sand—for example, a sandstone formation that weathers easily to release individual grains, or perhaps a beach supplied with abundant sand from a nearby river mouth. Active dunes constantly change shape under wind currents, but they must be free of a vegetation cover in order to form and move. They become inactive when stabilized by a vegetation cover, or when patterns of wind or sand sources change.

Dune sand is usually composed of quartz, which is extremely hard and doesn't easily decay. Dune sand grains are beautifully rounded by abrasion. In strong winds, sand grains move downwind in long, low leaps, bouncing after impact with other grains. This type of hopping, bouncing movement is called *saltation.*

TYPES OF SAND DUNES

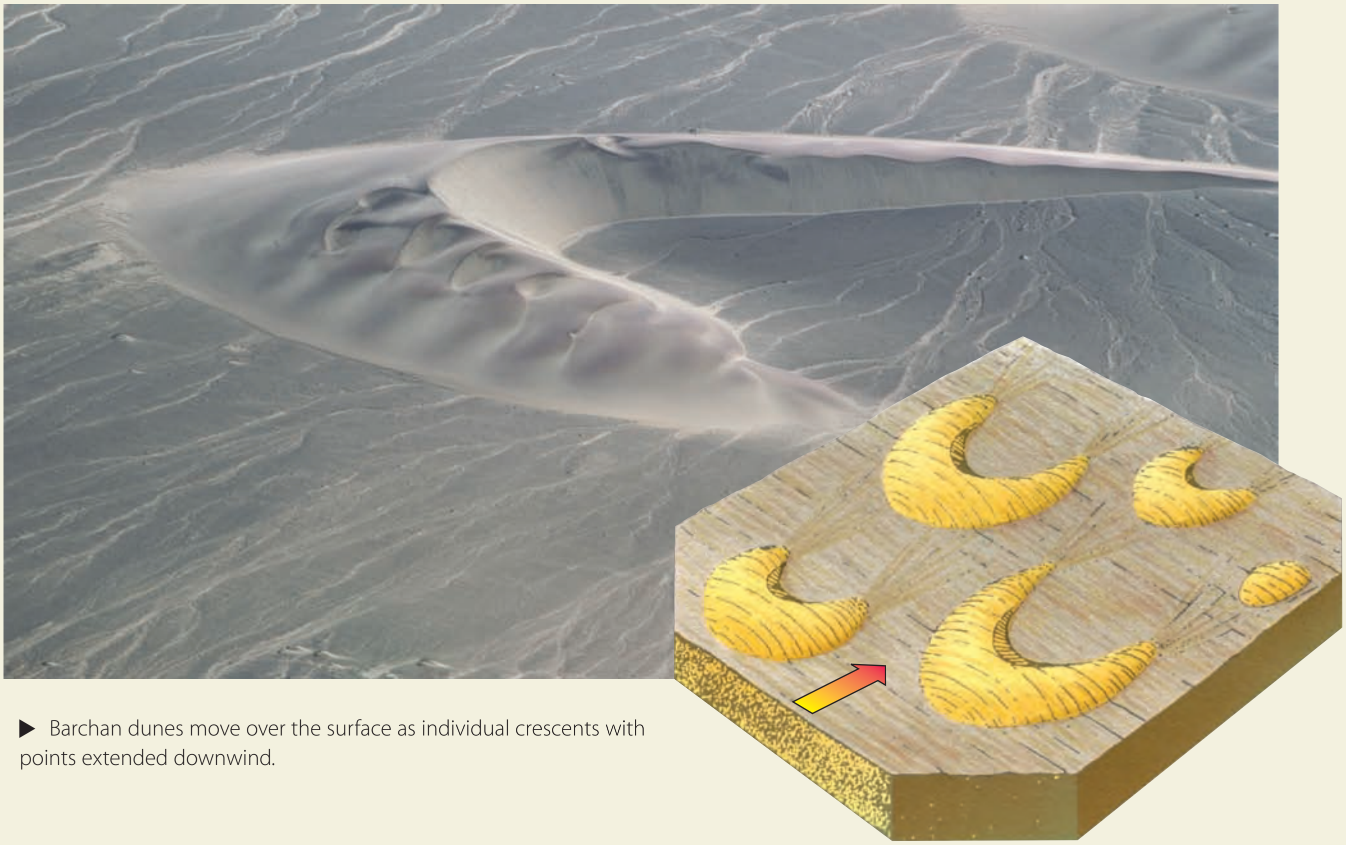
One common type of sand dune is an isolated dune of free sand called a *barchan*, or *crescent dune.* This type of dune has the outline of a crescent, and the points of the crescent are directed downwind (Figure 16.31). Barchan dunes usually rest on a flat, pebble-covered ground surface. They begin as a sand drift in the lee of some obstacle, such as a small hill, rock, or clump of brush. Once a sufficient mass of sand has gathered, it begins to move downwind, becoming a crescent. We usually find barchan dunes arranged in chains extending downwind from the sand source.

The barchan dune is a crescent-shaped heap of sand that moves across a flat, pebble-covered plain. The points of the crescent are directed downwind.

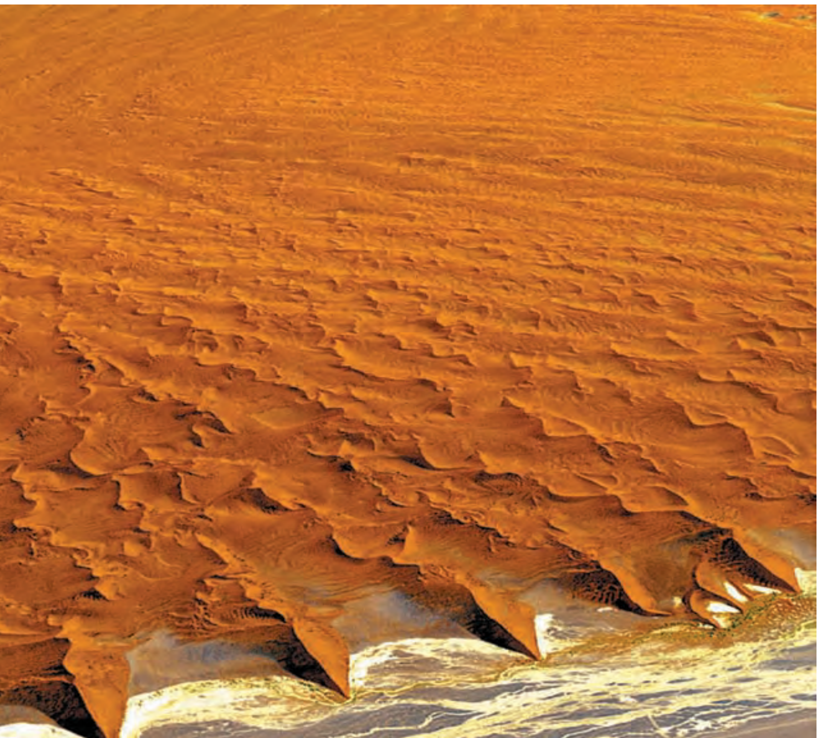
Transverse dunes are formed when there is so much sand that it completely covers the solid ground. These dunes are wave-like ridges separated by trough-like furrows. They are called transverse dunes because their crests are at right angles to the wind direction, much like waves on an ocean (Figure 16.32). The entire area is

16.31 Barchan dune

▼ These barchan dunes in Skeleton Coast National Park, Namibia, are traveling from left to right. Pushed by the prevailing wind, sand blows up the windward dune slope, passes over the dune crest, and slides down the steep *slip face*, moving the dune forward. The slip face maintains a more or less constant angle from the horizontal, which is known as the *angle of repose*. For loose sand, this angle is about 35° (National Geographic Image Collection).



▶ Barchan dunes move over the surface as individual crescents with points extended downwind.



16.32 A sea of transverse dunes

The sand ridges of *transverse dunes* have sharp crests and are asymmetrical, with the gentle slope on the windward side and the steep slip face on the lee side. There are deep depressions between the dune ridges. Sand seas require enormous quantities of sand, supplied by material weathered from sandstone formations or from sands in nearby alluvial plains. Transverse dune belts also form next to beaches that supply abundant sand and have strong onshore winds. These transverse dunes are in the Namib Desert of Namibia. The intense red color is produced by iron oxide, which stains the quartz dune grains.

known as a *sand sea* because it resembles a storm-tossed sea that is suddenly frozen in motion.

In the Sahara Desert, enormous quantities of reddish dune sand have been weathered from sandstone. This sand makes up a great sand sea, called an *erg*. Elsewhere, you find a desert pavement of pebbles on top of vast flat-surfaced sheets of sand. This type of surface is called a *reg*.

Saharan dunes can be elaborately shaped. For example, Arabian *star dunes* have served for centuries as reliable landmarks for desert travelers because they remain fixed in place (Figure 16.33). You can also see star dunes in the deserts of the border region between the United States and Mexico.

Parabolic dunes have the opposite curvature, with respect to wind direction, as the barchan dune (Figure 16.34). A common type of parabolic dune is the *coastal blowout dune* (Figure 16.35). These dunes form along shorelines where sand is abundant.

On semiarid plains, where vegetation is sparse and winds are strong, groups of parabolic blowout dunes develop to the lee of shallow deflation hollows. Sand is caught by low bushes and accumulates on a broad, low ridge. These dunes have no steep slip faces and may remain relatively immobile. In some cases, the dune ridge migrates downwind, forming *hairpin dunes* with long parallel sides.

Parabolic dunes develop on semiarid plains. They are sometimes drawn out into hairpin dunes. Longitudinal dunes are long, low sand ridges parallel to the prevailing wind direction.

Another class of dunes consists of long, narrow ridges oriented parallel with the direction of the prevailing wind. These *longitudinal dunes* may be many kilometers long and cover vast areas of tropical and subtropical deserts in Africa and Australia (Figure 16.36). In the United States, longitudinal and parabolic dunes occur on the Colorado Plateau, near the adjacent northern corners of Arizona and New Mexico.

GEODISCOVERIES **Types of Dunes**

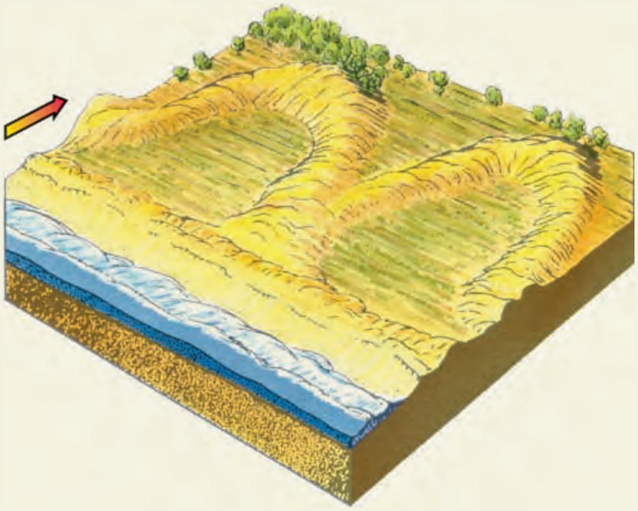
Interact with a chart of sand dune types organized by wind, sand supply, and amount of vegetation to see photos of common types of dunes. An animation.

16.33 Star dune

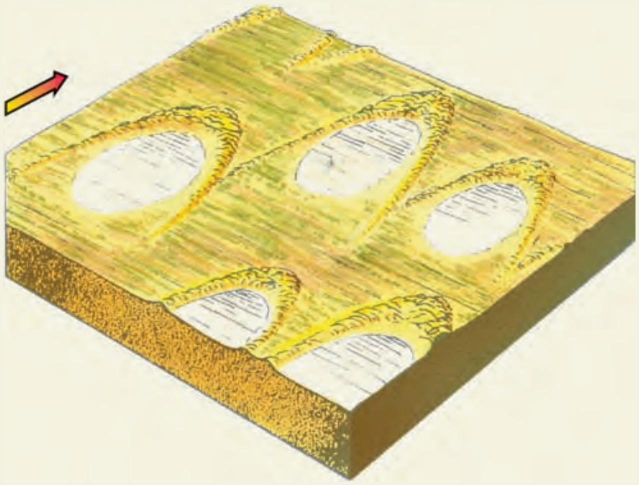
These large sand hills with dune crests radiating away from the center are known as *star dunes*. They are common in the Sahara and Arabian deserts and are stable, almost-permanent features of the desert landscape (National Geographic Image Collection).

16.34 Parabolic dunes

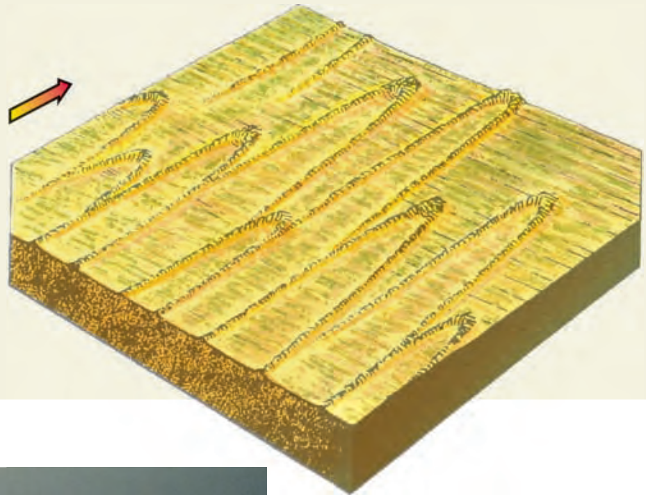
▼ **Coastal blowout dunes** The *coastal blowout dune* is a type of *parabolic dune* that forms next to beaches with plenty of sand. The sand is blown landward by prevailing winds. Deflation creates a saucer-shaped depression, or *blowout*. The removed sand is heaped on the outside, in a curving ridge that resembles a horseshoe. On the landward side is a steep slip face that moves away from the beach and can advance into nearby forests or built-up areas.



▼ **Parabolic dunes on a semiarid plain** Parabolic dunes also form on sparsely vegetated surfaces covered with loose material. The dunes gather downwind from blowouts and can remain stable for long periods.



▶ **Hairpin dunes** Sometimes parabolic dune ridges migrate downwind, forming dunes with elongated, hairpin shapes.

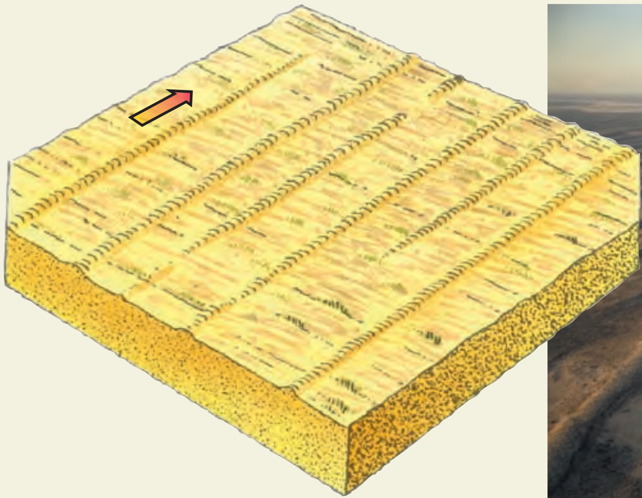


16.35 Coastal blowout dunes

These dunes are located on the shore of Lake Michigan. Although many of the dunes are now stabilized with vegetation, the strong winds across the lake still create blowouts, shown here, and push sand inland (National Geographic Image Collection).

16.36 Longitudinal dunes

▼ Large areas of the Australian central desert are covered with longitudinal dunes. This example is near Lake Eyre in South Australia (National Geographic Image Collection).



▲ *Longitudinal dunes* are parallel to the prevailing wind direction. They are often only a few meters high but may be several kilometers in length.

COASTAL FOREDUNES

Landward of beaches, there is often a narrow belt of dunes guarding the coastline. These *coastal foredunes* are irregularly shaped hills and depressions. They are normally covered by beach grass with a few other species of plants that can survive the severe environment (Figure 16.37). This plant cover traps sand moving landward from the adjacent beach. As a result, the foredune ridge builds upward, becoming a barrier several meters above high-tide level.

Foredunes form a protective barrier for tidal lands on the landward side of a beach ridge or barrier island. In a severe storm, the swash of storm waves cuts away the upper part of the beach. Although the foredune barrier may then be attacked by wave action and partly cut away, it will not usually yield. Between storms, the beach is rebuilt, and, in due time, wind action restores the dune ridge, if plants are maintained.

But if the plant cover of the dune ridge is trampled and reduced by traffic—from vehicles or by foot—deflation will rapidly create a blowout. The new cavity becomes a trench across the dune ridge. When storms bring high water levels and intense wave action, swash is funneled through the gap and spreads out on the tidal marsh or tidal lagoon behind the ridge. Sand swept through the gap is spread over the tidal deposits. If eroded, the gap can become a new tidal inlet for ocean water to reach the bay beyond the beach. For many coastal communities of the eastern U.S. seaboard, dune ridges protect tidal marshes and estuaries from overwash.

Coastal foredunes form a protective barrier against storm wave action that keeps waves from overwashing a beach ridge or barrier island.

LOESS

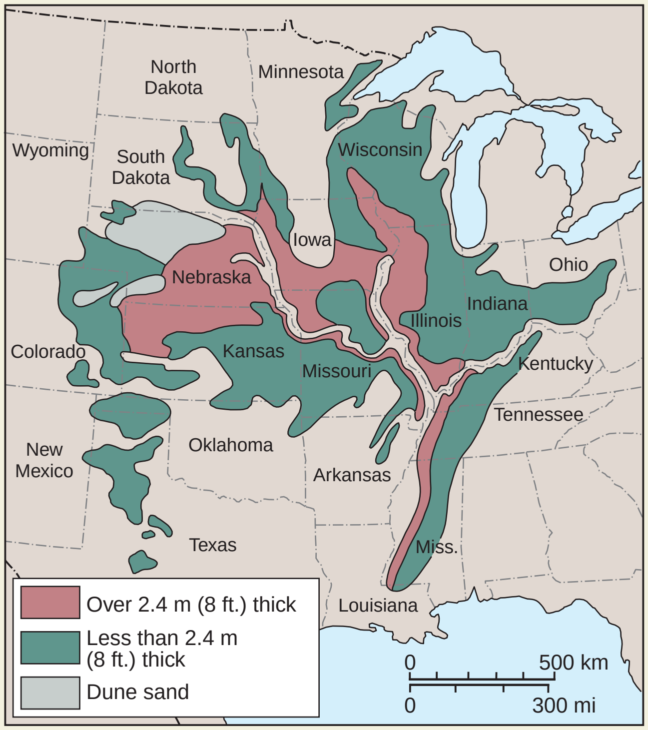
In several large midlatitude areas of the world, the surface is covered by deposits of wind-transported silt that have settled out from dust storms over thousands of years. This material is known as **loess**. (The pronunciation of this German word is somewhere between “lerse” and “luss.”) Loess is usually a uniform yellowish to buff color and lacks any visible layering. It tends to break away along vertical cliffs wherever it is exposed by the cutting of a stream or grading of a roadway (Figure 16.38). It is also very easily eroded by running water, and when the vegetation cover that protects it is broken, it is rapidly carved into gullies. Loess has been widely used for cave

16.37 Coastal foredunes

Beach grass thriving on *coastal foredunes* has trapped drifting sand to produce a dune ridge. Queen's County, Prince Edward Island, Canada.

16.38 Loess

◀ This thick layer of wind-transported silt, or *loess*, in New Zealand was deposited during the Ice Age. Loess has excellent cohesion and often forms vertical faces as it wastes away.



▶ A map of loess distribution in the central United States shows large areas of the prairie plains region of Indiana, Illinois, Iowa, Missouri, Nebraska, and Kansas are underlain by loess ranging in thickness from 1 to 30 m (about 3 to 100 ft). Extensive deposits also occur in Tennessee and Mississippi in areas bordering the lower Mississippi River floodplain. Still other loess deposits are in the Palouse region of northeast Washington and western Idaho.

dwellings both in China and in Central Europe because it's easily excavated.

Figure 16.27 shows the world's major areas of loess. The thickest deposits of loess are in northern China, where layers over 30 m (about 100 ft) thick are common and a maximum thickness of 100 m (about 300 ft) has been measured. This layer covers many hundreds of square kilometers and appears to have been brought as dust from the interior of Asia. In the United States, there are thick loess deposits in the Missouri-Mississippi Valley (Figure 16.38).

The American and European loess deposits are directly related to the continental glaciers of the Ice Age. At the time when the ice covered much of North America and Europe, the winter climate was generally dry in the land bordering the ice sheets. Strong winds blew southward and eastward over the bare ground, picking up silt from the floodplains of braided streams that discharged the meltwater from the ice. This dust settled on the ground between streams, gradually building up a smooth, level ground surface. The loess is particularly thick along the eastern sides of the valleys because of prevailing westerly winds. It is well exposed along the bluffs of most streams flowing through these regions today.

Loess is a deposit of wind-blown silt that may be as thick as 30 m (about 100 ft) in some regions of North America. It forms highly productive soils.

Loess is an important agricultural resource. It forms rich black soils that are especially suited to cultivation of grains. The highly productive plains of southern Russia, the Argentine pampa, and the rich grain region of north China are underlain by loess. In the United States, corn is extensively cultivated on the loess plains in Kansas, Iowa, and Illinois. Wheat is grown farther west on the loess plains of Kansas and Nebraska and in the Palouse region of eastern Washington.

INDUCED DEFLATION

Induced deflation is a frequent occurrence when short-grass prairie in a semiarid region is cultivated without irrigation. Plowing disturbs the natural soil surface and grass cover, and in drought years, when vegetation dies out, the unprotected soil is easily eroded by wind action. That's why much of the Great Plains region of the United States has suffered from dust storms generated by turbulent winds. Strong cold fronts frequently sweep over this area and lift dust high into the atmosphere at times when soil moisture is low. The "Dust Bowl" of the 1930s resulted from induced deflation (Figure 16.39).

16.39 Dust bowl

A dust storm approaches Goodwell, Oklahoma, in 1937. Prolonged drought coupled with overgrazing and extension of farming into marginal lands led to widespread induced deflation (National Geographic Image Collection).

Human activities in very dry, hot deserts have also significantly helped raise high dust clouds. As grazing animals and humans trample the fine-textured soils of the desert of northwest India and Pakistan (the Thar Desert bordering the Indus River), they produce a dust cloud. Such clouds hang over the region for long periods and can extend to heights of 9 km (about 30,000 ft).

GEODISCOVERIES Web Quiz
Take a quick quiz on the key concepts of this chapter.

A Look Ahead

This chapter has described the processes and landforms associated with wind action, either directly or as wind-driven waves. In our final chapter, we turn to the last of the fluid agents that create landforms—glaciers. Compared to wind and water, glacial ice moves much more slowly but is far steadier in its motion. Like a vast conveyor belt, glacial ice moves sediment forward relentlessly, depositing the sediment at the ice margin, where the ice melts. By plowing its way over the landscape, glacial ice also shapes the local terrain—bulldozing loose rock from hillsides and plastering sediments underneath its vast bulk. This slow but steady action is very different from that of water, wind, and waves, and produces a set of landforms that is the subject of our last chapter.

GEODISCOVERIES Web Links
This chapter's web links let you visit sites of coastal erosion from San Diego to the Carolinas. Explore dunes and deserts to see wind in action.

IN REVIEW LANDFORMS MADE BY WAVES AND WIND

- Global climate change will have major impacts on coastal environments. Sea level will rise, storms will increase in size and severity, and extremes of flood and drought will be exaggerated.
- Coastal erosion will increase. Sea-level rise and land subsidence will cause the loss of many coastal wetlands. Sensitive coral reefs will die from high water temperatures. Arctic shorelines will erode as sea ice thins and ground ice and permafrost thaw.
- Wind and waves are important landform-making agents. Wind moves material directly by moving fine particles. Waves transfer wind energy to water motion that erodes and transports coastline materials.
- Waves act at the **shoreline**—the boundary between water and land. The **coastline** is the zone where coastal processes operate.
- Waves have *crests* and *troughs*, and are characterized by *wave height*, *wave length*, and *wave period*. Waves cause particles at or near the water surface to travel in a circular path.
- Wave height increases rapidly with increasing wind speed, duration, and *fetch*.
- Waves expend their energy as *breakers* that push a *swash,* laden with sand and gravel, onto the beach. The *backwash* returns water and sediment seaward.
- Waves erode soft sediments into *marine scarps*. Wave-thrown rocks cut into bedrock to form **marine cliffs**, creating *caves, arches, stacks*, and *abrasion platforms*.
- Waves build *beaches* of sand, pebbles, cobbles, or even shell fragments.
- Wave action produces *beach drift* and *longshore drift*, which act together as **littoral drift** to move sediment along the shoreline. *Sand bars*, *sandspits*, and *pocket beaches* are formed.
- Depending on sediment supply, beaches experience *progradation* (building out) or *retrogradation* (cutting back). *Groins* help trap sand and sustain beaches.
- Sea level experiences a rhythmic rise and fall called the *ocean tide*. The change of level produces *tidal currents* in bays and estuaries that move sediment and form *salt marshes*.
- Coastlines of **submergence** result when coastal lands sink below sea level or sea level rises rapidly. Coastlines of **emergence** form when sea level falls or submarine landforms are elevated and exposed.
- *Ria coasts* form when fluvial landforms are submerged. *Fiord coasts* form when glacial valleys and troughs are submerged.
- **Barrier-island coasts** have a flanking low ridge of sand at the edge of a tidal *lagoon*.
- *Delta coasts* bring new river sediment deposits to the shoreline.
- *Volcano coasts* arise where volcanic deposits reach the shoreline.
- *Coral-reef coasts* occur in warm ocean waters where coral reefs build up in shallow water. Reefs may be *fringing* platforms, *barrier reefs* with lagoons, or *atolls*.
- *Fault coasts* occur where tectonic activity brings a fault scarp to the shoreline.
- **Marine terraces** form when shorelines are raised by tectonic activity.
- *Eolian* landforms and processes result when sediments are transported by wind.
- Wind erodes by *abrasion* and **deflation**. Deflation creates *blowouts* in semidesert regions and lowers playa surfaces in deserts. In arid regions, deflation produces *desert pavement* and *dust storms*.

- **Sand dunes** form when a source, such as a sandstone outcrop or a beach, provides abundant sand that can be moved by wind action.
- *Barchan dunes* are arranged individually or in chains leading away from the sand source. They are shaped like crescents with points elongated downwind.
- *Transverse dunes* form a sand sea of frozen "wave" forms arranged perpendicular to the wind direction.
- *Star dunes* are large pyramids of sand that remain fixed in place.
- *Parabolic dunes* are arc-shaped with points elongated upwind.
- *Coastal blowout dunes* are parabolic dunes that form on shorelines with abundant sand.
- *Longitudinal dunes* parallel the wind direction and cover vast desert areas.
- *Coastal foredunes* are stabilized by dune grass and help protect the shoreline from storm wave action.
- **Loess** is a surface deposit of fine, wind-transported silt. It can be quite thick, and it typically forms vertical banks. Loess is very easily eroded by water and wind.
- In eastern Asia, the silt forming the loess was transported by winds from extensive interior deserts located to the north and west. In Europe and North America, the silt was derived from fresh glacial deposits during the Pleistocene Epoch.
- Human activities can create *induced deflation* by breaking protective surface covers of vegetation and desert pavement, yielding dust storms and dust bowls.

KEY TERMS

shoreline, p. 526
coastline, p. 526
marine cliff, p. 528
beach, p. 528
littoral drift, p. 531
submergence, p. 534
emergence, p. 535
delta, p. 537
coral reef, p. 538
marine terrace p. 540
deflation, p. 542
blowout, p. 542
desert pavement, p. 543
dust storm, p. 543
sand dune, p. 544
loess, p. 548
induced deflation, p. 550

REVIEW QUESTIONS

1. How has the coastal environment changed in response to climate change, and what changes are predicted for the future? What will be the impact of these changes on coastlines and shorelines?
2. How do ocean waves arise? Where do they obtain their energy, and how do they use that energy?
3. Contrast the terms *shoreline* and *coastline*.
4. Explain how wave height is related to *wind speed, duration*, and *fetch* of the wind.
5. Compare a *marine scarp* with a *marine cliff*. What landforms are associated with marine cliffs?
6. What is *littoral drift*, and how is it produced by wave action? Use the terms *beach drift* and *longshore drift* in your answer. Identify some landforms produced by littoral drift.
7. Identify *progradation* and *retrogradation*. How can human activity influence retrogradation?
8. Describe *ocean tides* and their effects on *bays* and *estuaries*. How are *salt marshes* formed? How can they be reclaimed for agricultural use?
9. What key features identify a coastline of *submergence*? Identify and compare the two types of coastlines of submergence.
10. What are the typical features of a *barrier-island coast*? Sketch an example of a barrier-island coast.
11. Describe the features of a *delta coast* and give an example.
12. Describe the shoreline of a *volcano coast*.
13. What conditions are necessary for the development of *coral reef coastlines*? Identify three types of coral reefs, depending on their setting.
14. Describe the features of a *fault coast*. Where would you expect to find one?
15. How are *marine terraces* formed?
16. Identify and describe two types of erosional work done by wind.
17. What process produces *blowouts?* What is *desert pavement* and how does it form?
18. Describe what it might be like to experience a *dust storm*. What are some sources of the dust?
19. What is a *sand dune*? What are the properties of the particles that form a sand dune?
20. How do sand dunes form? Describe and compare barchan dunes, transverse dunes, star dunes, parabolic dunes, coastal blowout dunes, and longitudinal dunes.
21. How do coastal foredunes arise, and how are they maintained? How does human activity affect coastal foredunes, and what is the result?
22. Define the term *loess*. What is the source of loess, and how are loess deposits formed? Identify several global locations of extensive loess deposits.

VISUALIZING EXERCISES

1. Sketch a profile of the surface of an ocean wave, and use it to define the following terms: *wave height, wave length,* and *wave period.* Add circles with directional arrows to show the motion of water particles at key points on the wave.
2. Take a piece of paper and let it represent a map with winds coming from the north, at the top of the page. Then sketch the shapes of the following types of dunes: barchan, transverse, parabolic, hairpin, and longitudinal.

ESSAY QUESTIONS

1. Consult an atlas or GoogleEarth to identify a good example of each of the following types of coastlines: ria coast, fiord coast, barrier-island coast, delta coast, coral-reef coast, and fault coast. For each example, provide a brief description of the key features and other knowledge you used to identify the coastline type.
2. Wind action moves sand close to the ground in a bouncing motion, whereas silt and clay are lifted and carried longer distances. Compare landforms and deposits that result from wind transportation of sand with those that result from wind transportation of silt and finer particles.

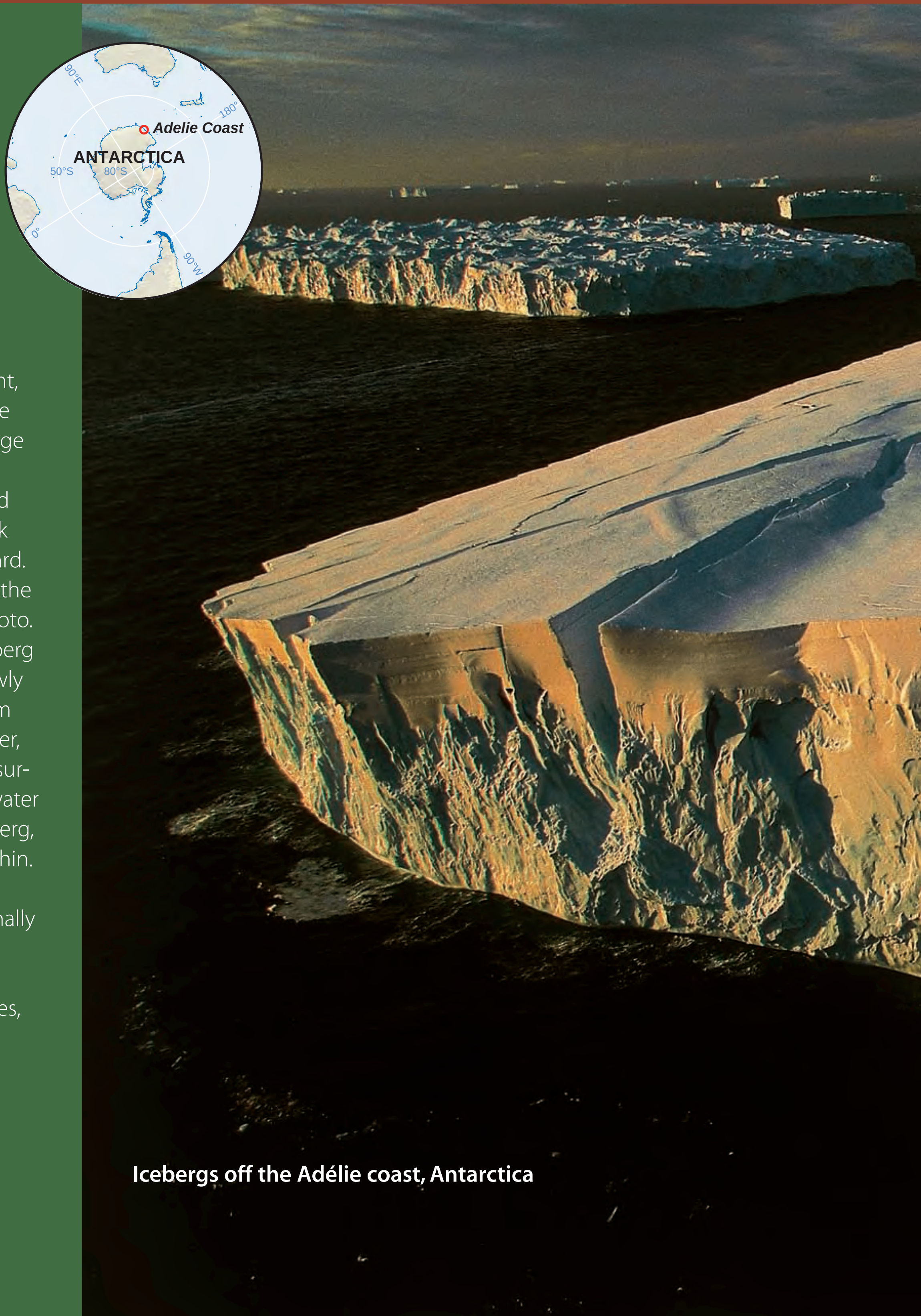
Chapter 17
Glacial Landforms and the Ice Age

The continent of Antarctica is the home of a vast dome of flowing glacial ice that goes from sea level to about 4000 m (about 13,000 ft) elevation. The ice averages about 2000 m (about 6500 ft) in thickness, with a greatest measured thickness of more than 4770 m (15,650 ft).

At the edges of the continent, this vast ice sheet flows into the Antarctic Ocean, building a fringe of floating ice shelves. As the floating ice begins to warm and decay, great chunks of ice break free and begin to drift northward. These are tabular icebergs, like the one shown in this dramatic photo.

Most of the mass of the iceberg is below the surface, and it slowly melts away as it gains heat from the ocean waters. In the summer, meltwater ponds form on the surface of the ice, feeding warm water deep into crevasses in the iceberg, helping it to break up from within. The iceberg may drift for thousands of kilometers before it finally melts away.

As hazards to navigation, icebergs are tracked by airplanes, radars, and satellites and their positions in shipping lanes are reported to ships at sea.



Icebergs off the Adélie coast, Antarctica

Glacial Landforms and the Ice Age

The Earth has recently emerged from a glaciation that covered much of the northern hemisphere with sheets of ice. How do glaciers form? How do they make landforms? How are alpine glaciers different from ice sheets? Are ice caps now receding? Is arctic sea-ice cover changing? Why has the Earth entered an Ice Age? What causes glaciers to come and go during an Ice Age? These are some of the questions we will answer in this chapter.

EYE ON GLOBAL CHANGE

Ice Sheets, Sea Ice, and Global Warming

What effects will global warming have on the Earth's ice sheets and sea ice? In general, global climate models predict two types of changes in the Earth's ice sheets. First, warming on land and ocean will cause the melting and thinning of the edges and ice shelves of the Greenland and Antarctic ice caps. This will increase sea level. Second, warming will increase the water vapor content of the atmosphere, leading to more snow over the center portions of the ice caps. This will decease sea level by storing water in new ice. Both of these predictions seem to be coming true.

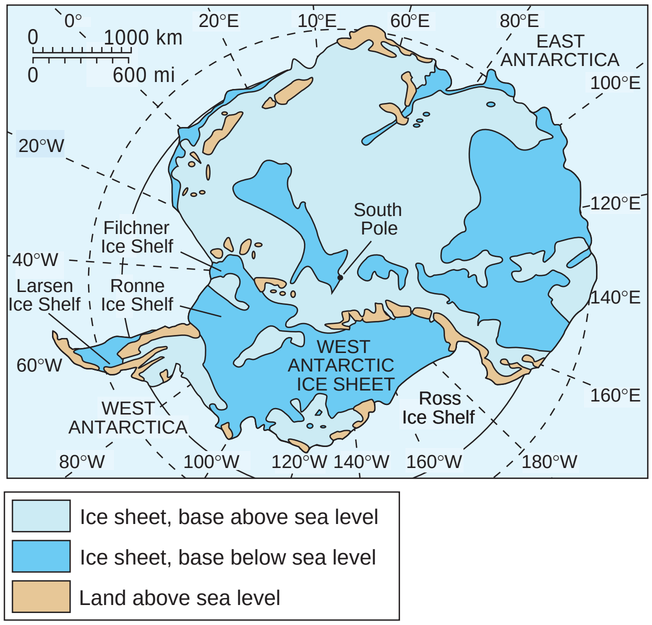
Let's look first at the Antarctic Ice Sheet. This huge mass holds 91 percent of the Earth's ice and is the Earth's largest accumulation of fresh water. There are two different parts of the Antarctic Ice Sheet, as shown in Figure 17.1—east and west. The East Antarctic Ice Sheet is presently growing, rather than shrinking, as a result of increased snowfall. A recent study funded by NASA and NSF used satellite radar altimeters to measure elevation change from 1992 to 2006, and researchers found that the growth corresponded well with changes in precipitation predicted by global climate models. The amount of growth, however, was quite small, and only slowed sea-level rise by about a tenth of a millimeter per year.

For the West Antarctic Ice Sheet, the story is different. This part of the ice cap contains about 10 percent of the total mass of the ice cap, and it is thinning significantly. In fact, the rate of loss of ice mass for the West Antarctic Ice Sheet increased by about 60 percent in 10 years leading up to 2006, according to a study published in 2008 using satellite radar data.

Considering all parts of the antarctic ice cap, ice thickness obtained from precise satellite measurements of gravity recently showed that the ice sheet's mass decreased by about 150 km^3/yr (36 mi^3/yr)from 2002 to 2005, accounting for about 13 percent of the rise in sea level experienced during that period.

The Greenland and Antarctic Ice Sheets are now shrinking from global warming by melting at the margins, in spite of enhanced snowfall in central regions.

The Greenland Ice Cap, too, has been thinning at the edges while growing at the center. Large losses from melting ice along the southeastern coast were slightly exceeded by an increase in ice thickness during the 10-year period ending in 2002. However, that situation may be changing. Since 2002, glaciers flowing into the sea from Greenland have been speeding up. In fact, the rate of glacier flow increased from 63 km^3 (15.1 mi^3)



17.1 West Antarctic Ice Sheet

A map of Antarctica showing the Western Antarctic Ice Sheet.

in 1996 to 162 km^3 (38.9 mi^3) in 2005, according to recently analyzed satellite radar data.

At the other pole, recent attention has focused on the Western Antarctic Ice Sheet. Much of this vast expanse of antarctic ice is "grounded" on a bedrock base that is well below sea level. That is, a large portion of the ice sheet rests directly on deep bedrock without sea water underneath. At present, the grounded ice shelves act to hold back the flow of the main part of the ice sheet.

Geophysicists regard this as an unstable situation. A rapid melting or deterioriation of the ice shelves, perhaps in response to global warming, would release the back pressure on the main part of the ice sheet, which would then move forward and thin rapidly. With a reduced thickness, reduced pressure at the bottom of the ice would allow sea water to enter, and soon most of the sheet would be floating in ocean water. The added bulk would then raise sea level by as much as 6 m (about 20 ft). Could this actually happen?

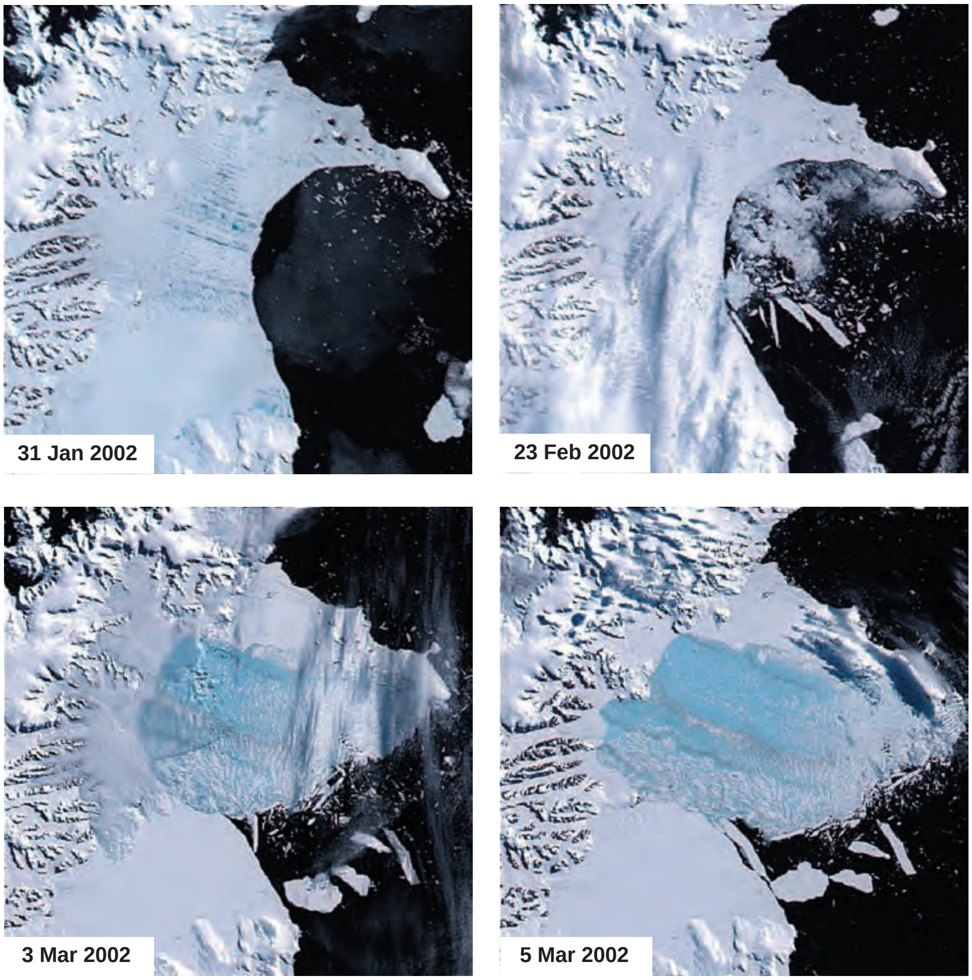
New evidence from fossil shoreline deposits suggests that a portion of the antarctic ice sheet collapsed into the ocean as recently as 14,200 years ago. In response, sea level rose about 20 m (65 ft) in a period of about 500 years. This rate is about 20 times larger than the slow rise of sea level measured today and about 4 times larger than the average rate at which sea level rose following the end of the last glacial period. Whether this might occur again is still uncertain.

Meanwhile, the climatic warming of the past few decades has caused some ice shelves to thin and fracture more easily. An example is the Larsen B ice sheet which collapsed in 2002 (Figure 17.2). The four MODIS images in Figure 17.2 show the disintegration of the Larsen B ice shelf during the austral summer in 2002.

Global warming is also affecting arctic sea ice. The ice pack is shrinking in size and becoming significantly thinner, according to a 2009 NASA study using satellite-borne lasers. Between 2004 and 2008, overall sea ice thickness decreased by 0.17 m/yr (7 in./yr), and the proportion of area covered by thicker, older multiyear ice decreased from 62 percent to 23 percent. Summer ice extent in 2007 was the lowest on record, with 2008 and 2005 showing the second- and third-lowest extent since recording began in 1979.

As the ice cover decreases, more solar energy is absorbed by the ocean water that becomes exposed to the Sun, warming the Arctic Ocean further. This effect, coupled with enhanced global warming at high latitudes, has led some scientists to predict that the Arctic Ocean will be ice-free in the summer by 2050.

According to recent satellite studies, arctic sea ice is thinning and summer ice cover is shrinking.



17.2 Breakup of the Larsen B ice shelf as seen by MODIS

These four MODIS images document the disintegration of the Larsen B ice shelf during the austral summer of 2002. Over a period of 35 days, 3250 km^2 (1254 mi^2) of floating ice, an area about 20 percent larger than Rhode Island, fractured and collapsed into thousands of individual icebergs. The sheet was about 220 m (720 ft) thick and freed a volume of about 720 billion metric tons (792 billion tons) of ice. The collapse was the largest single event in a 30-year history of decline of the Larsen ice shelf, which has lost an area of about 13,500 km^2 (about 5200 mi^2) since 1974.

Glaciers

Not long ago, during the Ice Age, much of northern North America and Eurasia was covered by massive sheets of glacial ice. As a result, glacial ice has shaped large landforms in midlatitude and subarctic zones. Today, we find glacial ice in the Greenland and Antarctic Ice Sheets and in many smaller masses in high mountains.

Glacial ice sheets have a significant impact on our global climate. Because of their intense whiteness, the glacial ice sheets of Greenland and Antarctica reflect much of the solar radiation they receive, influencing the Earth's radiation and heat balance. The vast temperature difference between these intensely cold ice sheets and regions near the Equator helps drive the system of heat transport around the world.

These collections of ice also hold an enormous amount of water in solid state. When the volume of glacial ice increases, as it does during an ice age, sea levels must fall to maintain the global water balance. When ice sheets melt away, sea level rises. In fact, today's coastal environments evolved during a rising sea level accompanying the melting of the last ice sheets of the Ice Age.

GLACIER FORMATION

When we think of ice, we normally picture a brittle, crystalline solid. But large bodies of ice, with a great thickness, are much more plastic. That's because the pressure on the ice at the bottom of an ice mass forces it to lose its rigidity. A thick mass of ice can flow in response to gravity, slowly spreading out over a larger area or moving downhill. Ice also slides on steep mountain slopes. This ability to move is the key characteristic of a **glacier**, which is defined as any large natural accumulation of land ice affected by present or past motion.

Glacial ice builds up when the average snowfall of the winter exceeds the amount of snow that is lost in summer by evaporation and melting. Each year, a new layer of snow adds to the snow that has already collected. Snow on the surface melts and refreezes, compacting the snow and turning it into granular ice. This ice is then compressed into hard crystalline ice by the weight of the layers above it. When the ice mass becomes so thick that the lower layers become plastic, it will start to flow outward or downhill. The ice mass is now an active glacier (Figure 17.3).

When snow accumulates to a great thickness, it can turn into flowing glacial ice. Alpine glaciers form in high mountains, while ice sheets form on continental interiors at high latitudes.

Glacial ice forms in regions where there are low temperatures and high amounts of snowfall. This can occur at both high elevations and high latitudes. In mountains, glacial ice can form even in tropical and equatorial zones if the elevation is high enough to keep

17.3 An alpine glacier

Aerial view of the Grand Plateau Glacier, Saint Elias Mountains, Glacier Bay National Park, Alaska. The dark stripes are *medial moraines*—deposits of rock and debris accumulated at the edges of glaciers that later merge.

EYE ON THE LANDSCAPE **What else would the geographer see?** This alpine glacial landscape shows many of the glacial landforms and features described in this chapter. In the near distance are sharp peaks, or *horns* (A), and knife-edge ridges, or *arêtes* (B). In the middle foreground is a bowl-shaped *cirque* (C) that no longer bears glacial ice, although the glacier from the adjacent cirque spills into the empty cirque across a low pass (*col*). Glacial flow features include a *medial moraine* (D), *lateral moraines* (E), and *crevasses* (F) that open as the ice falls across a rock step.

average annual temperatures below freezing. In high mountains, glaciers flow from small high-elevation collecting grounds down to lower elevations, where temperatures are warmer. Here the ice disappears as it melts and evaporates. Typically, mountain glaciers are long and narrow because they occupy former stream valleys. These **alpine glaciers** are a distinctive type of glacier that we will look at in the next section.

In arctic and polar regions, temperatures are low enough for snow to collect over broad areas, eventually forming a vast layer of glacial ice. Snow begins to accumulate on uplands, which are eventually buried under enormous volumes of ice. The layers of ice can reach a thickness of several thousand meters. The ice then spreads outward, over surrounding lowlands, and covers all landforms it encounters. We call this extensive type of ice mass an **ice sheet**.

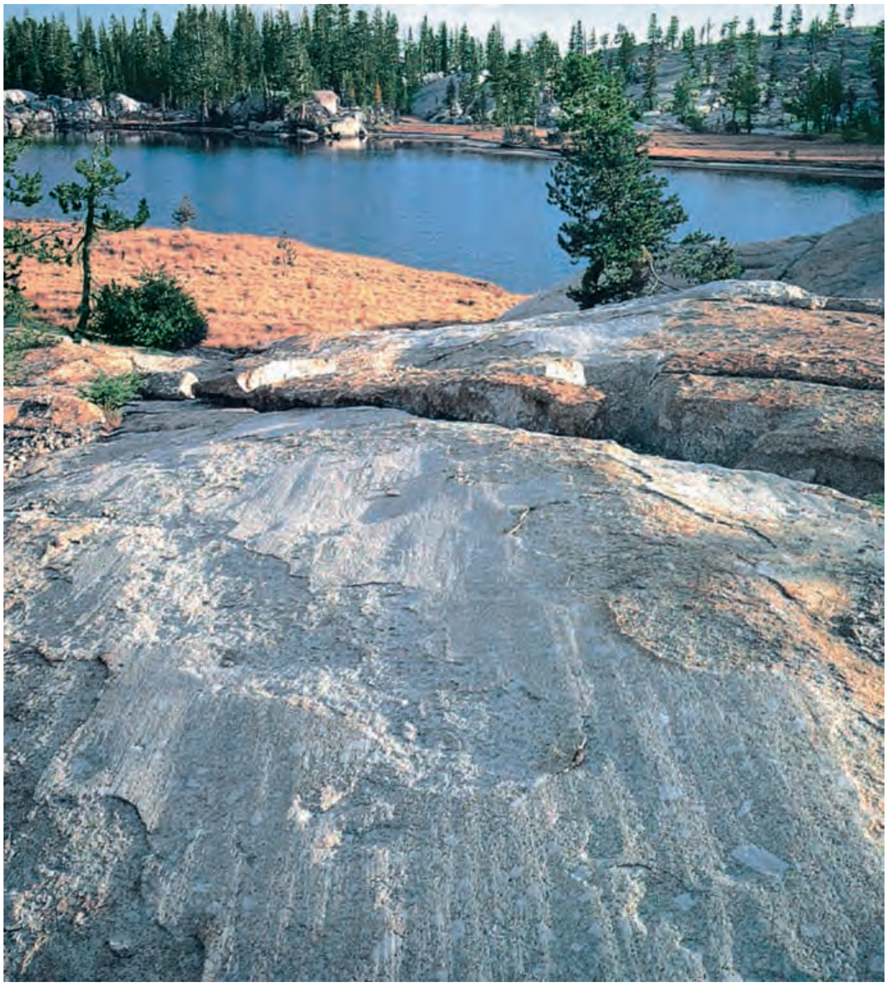
GLACIAL EROSION AND DEPOSITION

Glacial ice normally contains rock that it has picked up along the way. These rock fragments range from huge angular boulders to pulverized rock flour. Most of this material is loose rock debris and sediments found on the landscape as the ice overrides it, but some is eroded from the rock floor on which the ice moves. Alpine glaciers also carry rock debris that slides or falls from valley walls onto the surface of the ice.

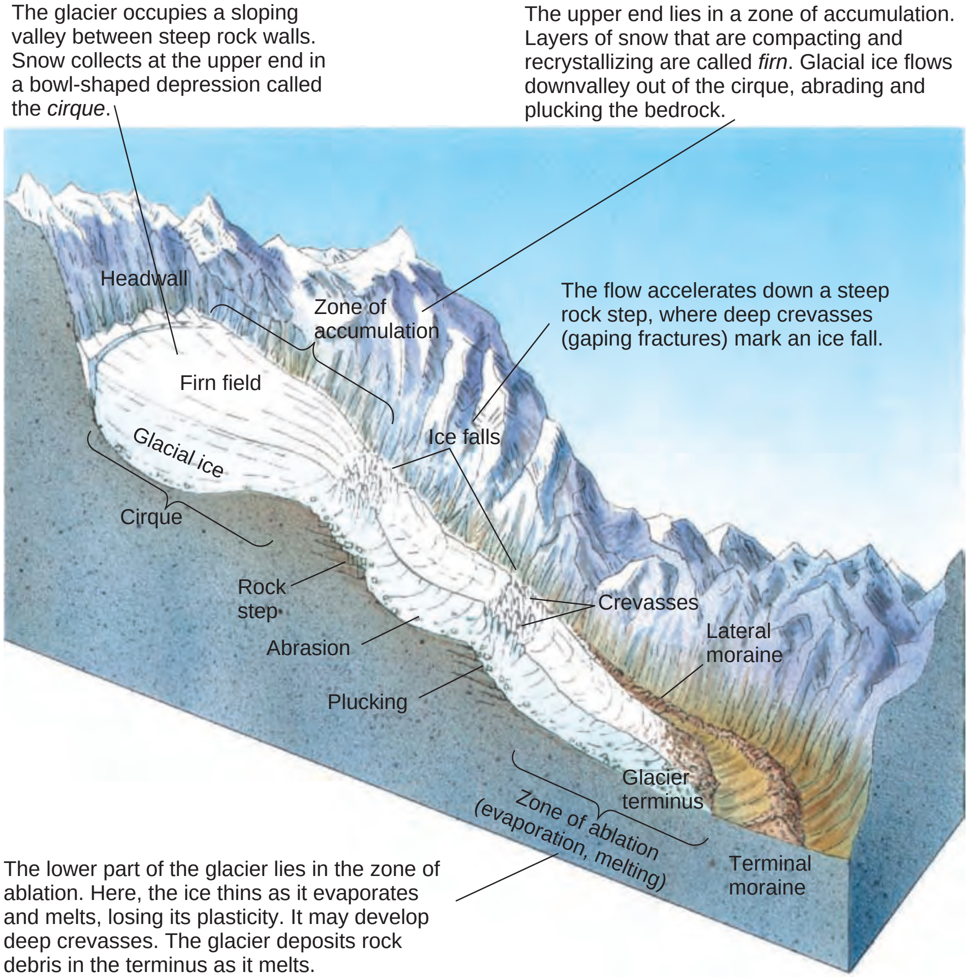
Glaciers and ice sheets erode and deposit great quantities of sediment. The rock fragments held within the ice scrape and grind against bedrock (Figure 17.4). We call this erosion process *glacial abrasion*. Moving ice also erodes surfaces by *plucking*, as blocks that have been loosened by weathering are lifted out of bedrock. Abrasion and plucking smooth the glacier bed as the glacial flow continues through time. The glacier finally deposits the rock debris at its lower end, where the ice melts. Both erosion and deposition create distinctive glacial landforms.

Glaciers sweep up and move loose soil, regolith, and sediments in their paths. They erode bedrock by abrasion and plucking.

GEODISCOVERIES Glacier Mass Balance
View this animation to visualize how an alpine glacier gains mass in its upper regions and loses mass in its lower regions.



17.4 Glacial abrasion
This grooved and polished surface, now partly eroded, marks the former path of glacial ice. Cathedral Lakes, Yosemite National Park, California.



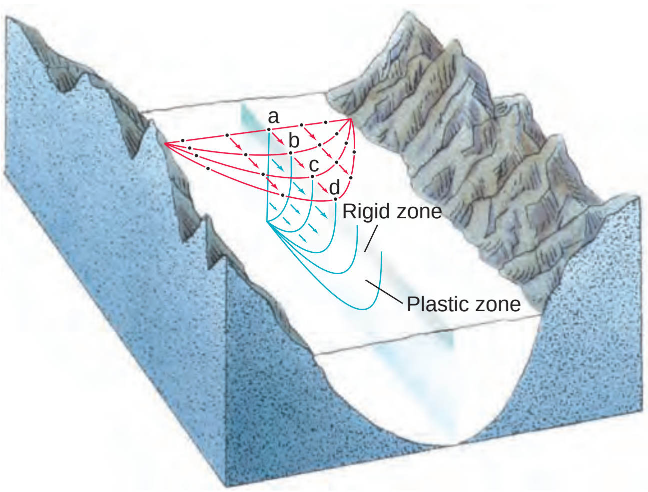
17.5 Cross section of an alpine glacier

Alpine Glaciers

Figure 17.5 shows a cross section of an alpine glacier, illustrating a number of features. The glacier forms in a *cirque*—a high rock basin in which snow accumulates for year after year until it forms a glacier. Although the uppermost layer of a glacier is brittle, the ice beneath behaves as a plastic substance that flows slowly (Figure 17.6). An alpine glacier can also slide downhill, lubricated by meltwater and mud at its base.

A glacier has a dynamic balance in which the rate of snow accumulation at the upper end balances the rate of evaporation and melting at the lower end. But this balance is easily upset by changes in the average annual rates of snowfall or evaporation and melting, causing the glacier's terminus to advance or retreat.

Glacial flow is usually very slow. It amounts to a few centimeters per day for large ice sheets and the more sluggish alpine glaciers, but can be as fast as several meters per day for an active alpine glacier. However, some alpine glaciers experience episodes of very rapid



17.6 Motion of glacial ice

Ice moves most rapidly on the glacier's surface at its midline. Movement is slowest near the bed, where the ice contacts bedrock or sediment.

movement, known as *surges*. A surging glacier may travel downvalley at speeds of more than 60 m (about 200 ft) per day for several months.

We don't fully understand the reasons for surging, but it probably involves mechanisms that increase the amount of meltwater beneath the ice, enhancing sliding. Most glaciers do not surge.

Cirques are rounded rock basins that contain the heads of alpine glaciers. They form high on glaciated peaks.

GEODISCOVERIES The Cascade Range Interactivity
Tour the mountains and glaciers of the Cascade Range and view the impact of volcanic activity on glacial activity.

LANDFORMS MADE BY ALPINE GLACIERS

Figure 17.7 shows how alpine glaciers erode mountain masses to create landforms such as *arêtes*, *horns*, *cols*, **moraines**, *tarns*, *hanging valleys*, and *glacial troughs*. Flowing down mountain slopes and valleys from areas of snow accumulation at high elevations, the ice scrapes loose soil and regolith from the slopes and scoops alluvium out of the valleys. Glacial abrasion smoothes the bed of the glacier and erodes projecting rock masses.

When the ice melts, a system of steep-walled **glacial troughs** is revealed. The floors of these valleys are normally covered with alluvium, carried by meltwater streams from the receding ice fronts. Tributary glaciers also produce troughs, but they are smaller in cross section and less deeply eroded by their smaller glaciers. Sometimes the floors of these troughs lie well above the level of the main trough, producing *hanging valleys*. When streams later occupy these abandoned valleys, they create scenic waterfalls and rapids that cascade down steep slopes to the main trough below. Major troughs sometimes hold large, elongated trough lakes.

When the floor of a trough open to the sea lies below sea level, the sea water enters as the ice front recedes, creating a **fiord.** Fiords are opening up today along the Alaskan coast, where some glaciers are melting back rapidly and ocean waters are filling their troughs. Fiords are found largely along mountainous coasts between lat. 50° and 70° N and S.

Alpine glaciers strip high valleys of their soil, regolith, and sediment to form glacial troughs.

GEODISCOVERIES Hanging Valleys
Watch alpine glaciers grow and coalesce to carve U-shaped valleys, then retreat to expose hanging valleys. An animation.

Ice Sheets and Sea Ice

The ice sheets of Antarctica and Greenland are huge plates of ice, thousands of meters thick in the central areas, resting on large land masses. The Greenland Ice Sheet has an area of 1.7 million km^2 (about 670,000 mi^2) and occupies about seven-eighths of the entire island of Greenland (Figure 17.11). The only land exposed is a narrow, mountainous coastal strip. The Antarctic Ice Sheet covers 13 million km^2 (about 5 million mi^2) (Figure 17.12). Both ice sheets are developed on large, elevated land masses in high latitudes. No ice sheet exists near the North Pole, which is positioned in the vast Arctic Ocean. Ice there occurs only as floating sea ice.

The Greenland Ice Sheet surface is a very broad, smooth dome. Underneath the ice sheet's central region, the rock floor lies near or slightly below sea level, but it is higher near the edges. At its margins, the Greenland Ice Sheet has a number of outlet glaciers that reach the sea.

The Antarctic Ice Sheet is thicker than the Greenland Ice Sheet—as much as 4700 m (about 15,500 ft) at maximum. Antarctica also has great plates of floating glacial ice, called **ice shelves**. Ice shelves are fed by the ice sheet, but they also accumulate new ice through the compaction of snow. At some locations, the ice sheet produces rapid-flowing *ice streams* that feed into the ice shelves.

Earth has two great ice sheets in Greenland and Antarctica. The Antarctic Ice Sheet has large ice shelves of floating glacial ice at its ocean margin.

GEODISCOVERIES Greenland's Glaciers
This video features dramatic aerial views of the glaciers and fiords of Greenland.

SEA ICE AND ICEBERGS

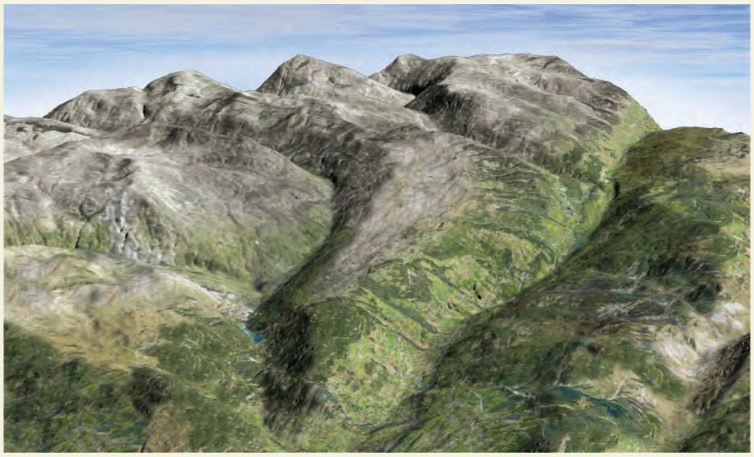
Free-floating ice on the sea surface takes two forms—sea ice and icebergs. **Sea ice** (Figure 17.13) is formed by direct freezing of ocean water and accumulation of snow atop the ice. The surface zone of sea ice is composed of fresh water, while the deeper ice is salty.

Pack ice is sea ice that completely covers the sea surface. Under the forces of wind and currents, pack ice breaks up into individual patches called *ice floes*. The narrow strips of open water between floes are known as *leads*. Winds can force ice floes together, making the ice margins buckle and turn upward into pressure ridges that resemble walls of ice. These obstacles can make traveling across polar sea ice on foot very difficult.

Icebergs are masses of ice that have broken free from alpine glaciers terminating in the ocean or from

17.7 Landforms produced by alpine glaciers

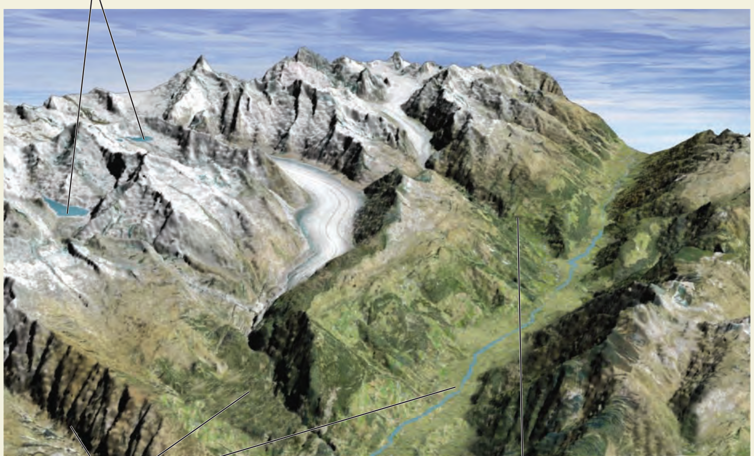
Alpine glaciers erode and shape mountains into distinctive landforms. Although larger alpine glaciers can widen and deepen valleys, their main work is to scrub existing slopes and valleys down to hard bedrock.

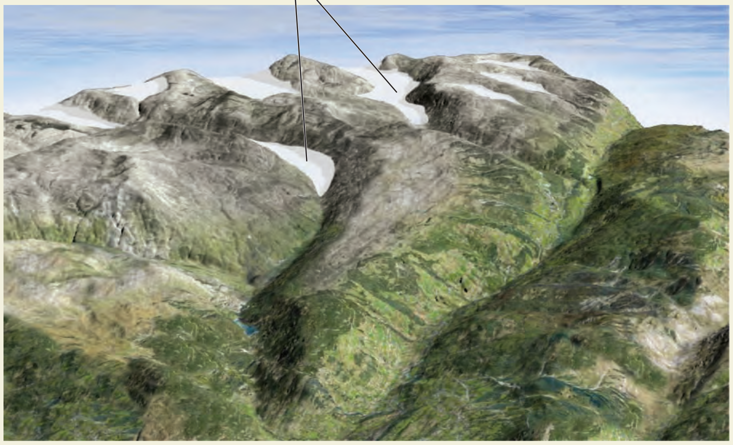


◀ **Before glaciation** This region has been sculptured entirely by weathering, mass wasting, and streams. The mountains look rugged, with steep slopes and ridges. Small valleys are steep and V-shaped, while larger valleys have narrow floodplains of alluvium and debris.

◀ **Tarn** When a glacier carves a depression into the bottom of a cirque and then melts away, a small lake called a *tarn* is formed.

▼ **Melting glaciers** As glaciers diminish, they reveal their handiwork in distinctive landforms.

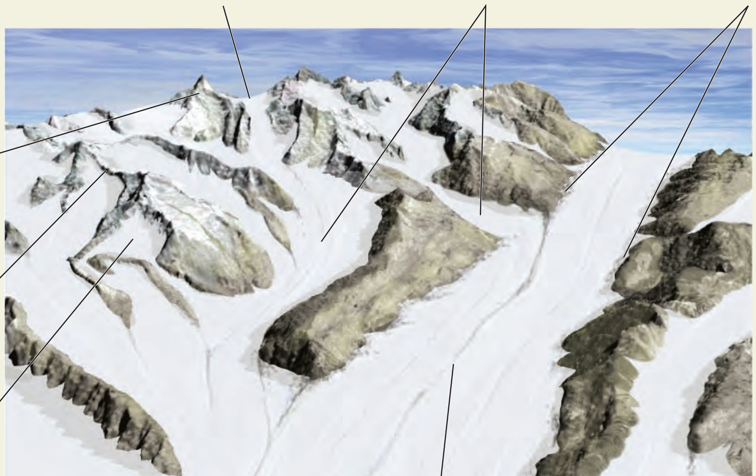




▶ **Snow accumulation** Climate change (cooling) increases snow buildup in the higher valley heads, forming *cirques*. Their cup shapes develop as regolith is stripped from slopes and bedrock is ground by ice. Slopes above the ice undergo rapid wasting from intense frost action.

▲ **Cirque** Valley heads are enlarged and hollowed out by glaciers, producing bowl-shaped *cirques*.

▲ **Horn and Arête** Intersecting cirques carve away the mountain mass, leaving peaks called *horns* and sharp ridges called *arêtes*.



▲ **Glaciation** Thousands of years of accumulating snow and ice develops these new erosional forms.

FOCUS ON REMOTE SENSING

Remote Sensing of Glaciers

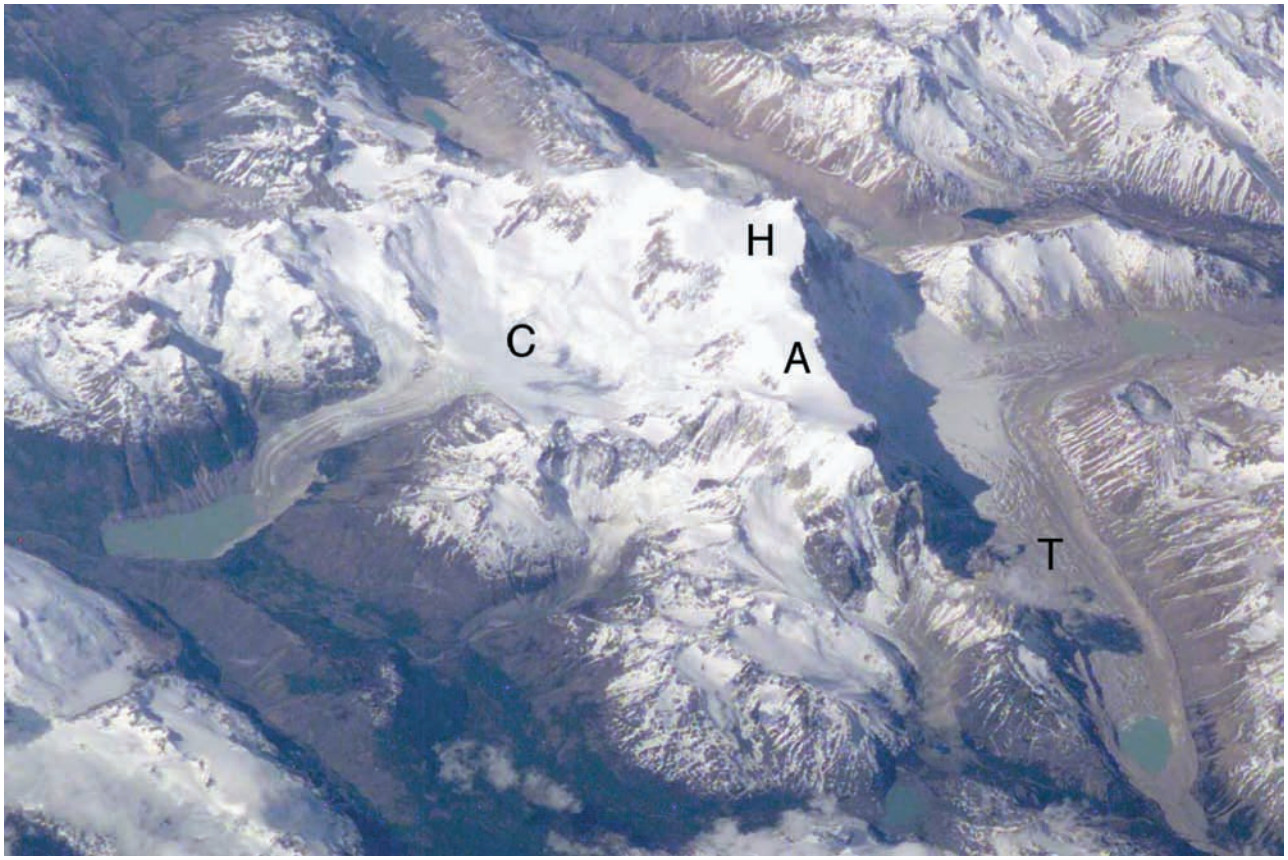
Because glaciers are often found in inaccessible terrain or in extremely cold environments, they are difficult to survey and monitor. This makes satellite remote sensing an invaluable tool for studying both continental and alpine glaciers.

Some of the world's more spectacular alpine glaciers are found in South America, along the crest of the Andes in Chile and Argentina, where mountain peaks reach as high as 3700 m (about 12,000 ft). Figure 17.8 is a true-color image of Cerro San Lorenzo (San Lorenzo Peak), acquired by astronauts aboard the International Space Station in December 2000. It shows many of the glacial features described in Figure 17.7.

Northwest of Cerro San Lorenzo lies the San Quintín glacier, shown in an ASTER image, acquired on May 2, 2000 (Figure 17.9). This color-infrared image was acquired at 15-m spatial resolution and shows the glacier in fine detail. The intense red color indicates a thick vegetation cover.

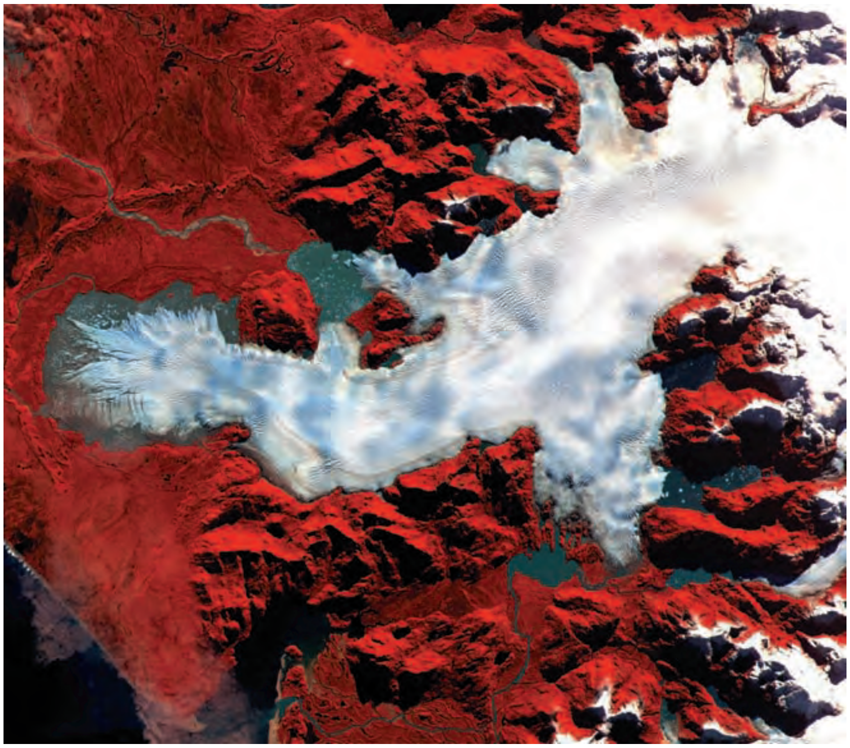
The world's largest glacier is, of course, the ice cap that covers nearly all of Antarctica. At the edges of the ice cap are *outlet glaciers*, where glacial flowinto the ocean is quite rapid. Figure 17.10 shows the Lambert Glacier, one of the largest and longest of Antarctica's outlet glaciers. From the confluence of the ice streams at the left to the tip of the Amery Ice Shelf, the glacier measures about 500 km (315 mi). The image was acquired by Canada's Radarsat radar imager.

GEODISCOVERIES Satellite Imagery and Glaciers Interactivity
Examine satellite images to identify the features of glaciers and icebergs from Iceland to Mount Kilimanjaro. View two short movies of the formation of icebergs.



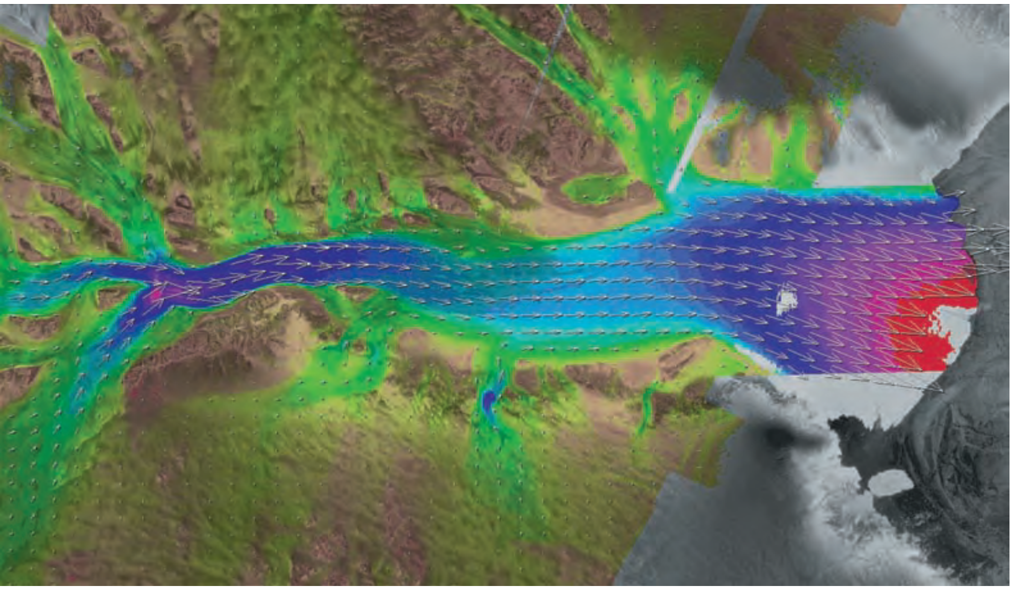
17.8 Andean alpine glacial features

This astronaut photo shows Cerro San Lorenzo, a peak along the crest of the Andes in Chile and Argentina. The peak itself is a glacial *horn* (H). Leading away from the horn to the south is a long, sharp ridge, or *arête* (A). To the left of the peak is a *cirque* (C), now only partly filled with glacial ice. These features were carved during the Ice Age, when the alpine glaciers were larger and filled the now-empty glacial troughs (T) behind the ridge to the right.



17.9 San Quintín Glacier, Chile, imaged by ASTER

This glacier is the largest outflow glacier draining the Northern Patagonia ice field. The terminal lobe of the glacier, which is about 4.7 km (2.6 mi) wide, ends in a shallow lake of sediment-laden water that drains by fine streams into the Golfo de Penas at lower left. Note the low, semicircular ridge a short distance from the lake; this is a *terminal moraine*, marking a former stand of the ice tongue. A high cloud partly obscures the southern end of the snout and nearby coastline.

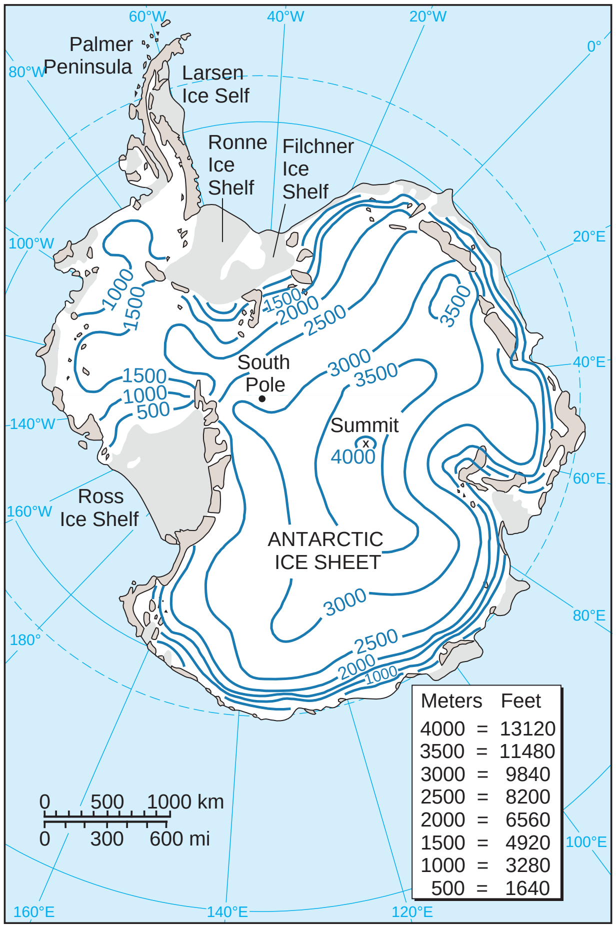


17.10 Lambert Glacier, Antarctica

The Lambert Glacier as imaged by Radarsat during the 2000 Antarctic Mapping Mission. This instrument allows the measurement of the velocity of glacier flow by comparing paired images acquired at different times (in this case, 24 days apart) using a technique called radar interferometry. Brown tones indicate little or no motion, and show both exposed mountains and stationary ice. Green, blue, and red tones indicate increasing velocity, with arrows showing direction. Glacial flow is most rapid at the left, where the flow is channeled through a narrow valley, and at the right, where the glacier spreads out and thins to feed the Amery Ice Shelf.

17.11 The Greenland Ice sheet

Contours show elevations of the ice sheet surface.



17.12 The Antarctic Ice Sheet and its ice shelves

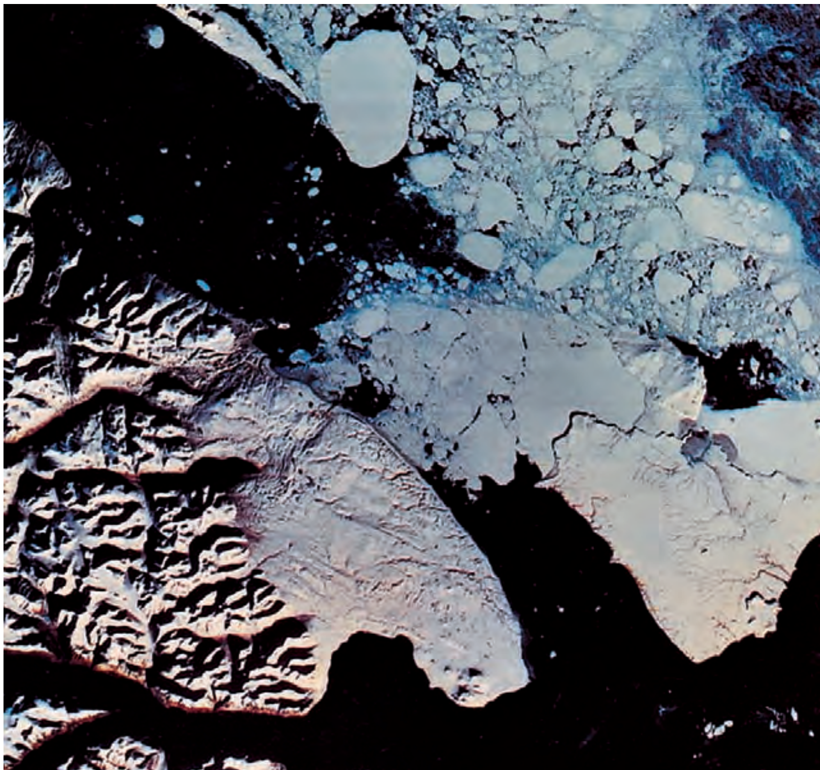
Contours show elevations of the ice sheet surface.

floating ice shelves (Figure 17.14). This process is called *calving* of the glacier. Because they are only slightly less dense than sea water, icebergs float very low in the water. About five-sixths of the bulk of an iceberg is submerged. The ice is composed of fresh water since it is formed from compacted and recrystallized snow. A major difference between sea ice and icebergs is thickness. Sea ice is always less than 5 m (16 ft) in thickness,

Sea ice is formed by freezing of ocean surface water and is rarely thicker than 5 m (16 ft). Icebergs are floating chunks of glacial ice and can be hundreds of meters thick.

17.13 Sea ice

A Landsat image of a portion of the Canadian arctic archipelago. Ice of different ages appears in different colors and textures. In the lower part of the image there is a branching glacial trough, now a water-filled fiord.



17.14 Icebergs

Adelie penguins socializing in the sun atop an iceberg in McMurdo Sound, Antarctica (National Geographic Image Collection).

generally 2–3 m (7–10 ft), whereas icebergs may be hundreds of meters thick.

GEODISCOVERIES **Calving of an Iceberg**

View the calving of an iceberg in a historic video from the last century.

LANDFORMS MADE BY ICE SHEETS

Like alpine glaciers, ice sheets are very good at stripping away loose materials and scouring bedrock. During the periods when continental ice sheets grew and spread outward over vast areas, the slowly moving ice scraped off regolith and ground away solid bedrock, leaving behind smoothly rounded rock masses. Evidence of ice abrasion—grooves and scratches left on the ground—is common throughout glaciated regions of North America. You can see signs on almost any freshly exposed hard rock surface. Sometimes the ice polishes the rock to a smooth, shining surface (Figure 17.15).

The ice sheets also excavated enormous amounts of rock at locations where the bedrock was weak and the flow of ice was channeled by a valley along the ice flow direction. Under these conditions, the ice sheet behaved like an alpine valley glacier, scooping out a deep glacial trough (Figure 17.16).

Ice sheets resemble huge conveyor belts. Anything carried on the belt is dumped off at the end, and, if not constantly removed, will pile up. Rock fragments incorporated into the ice are deposited at its outer edge as the ice evaporates or melts. We use the term **glacial drift** to refer to all the varieties of rock debris deposited by glaciers. There are two types of drift. *Stratified drift* consists of layers of sorted and stratified clays, silts, sands, or gravels. These materials were deposited by meltwater streams or in bodies of water adjacent to the ice. **Till** is

17.15 Glacial abrasion

A near-vertical rock outcrop on the side of Tracy Arm Fiord, Alaska, shows grooving and polishing from the passage of glacial ice (National Geographic Image Collection).

17.16 Finger Lakes

The Finger Lakes region of western New York is shown in this photo taken by astronauts aboard the Space Shuttle. The view is looking toward the northeast. The lakes occupy valleys that were eroded and deepened by glacial ice.

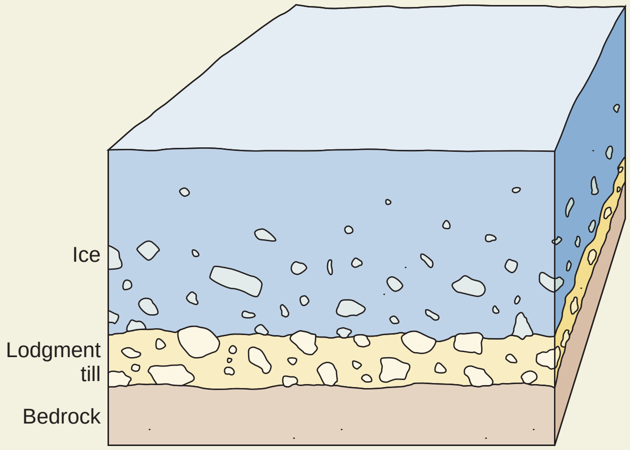
EYE ON THE LANDSCAPE **What else would the geographer see?** The Finger Lakes have been called "inland fiords" for their resemblance to the fiords of glaciated regions. The lakes were eroded from preexisting stream valleys by ice action during the multiple continental glaciations of the Ice Age. The two largest lakes in the center of the image (A) are Cayuga Lake (upper) and Seneca Lake (lower). The pattern of agricultural fields in the center and upper left part of the image (B) marks the intensive agricultural development of the Lake Erie lowlands and foothills of the Appalachian Plateau, which are mantled with productive soils of glacial origin. To the south, at the bottom of the image (C), the terrain becomes more dissected, with more pronounced valleys and ridges, as it slopes upward to the higher elevations of the plateau.

an unstratified mixture of rock fragments, ranging in size from clay to boulders, that is deposited directly from the ice without water transport (Figure 17.17). Where till forms a thin, more or less even cover, it is referred to as *ground moraine*.

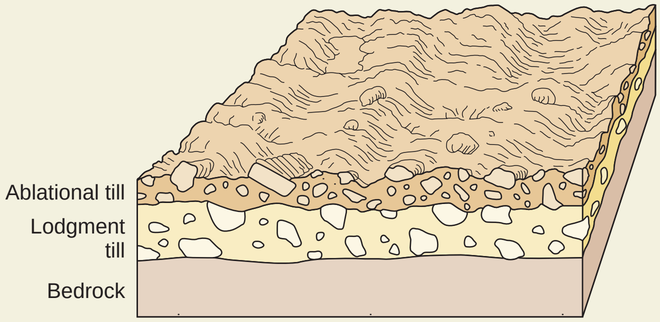
> **The term *glacial drift* describes all types of rock debris deposited in close association with glaciers. *Stratified drift* includes sediment laid by water, while *till* is deposited directly by ice.**

Over those parts of North America formerly covered by ice sheets, glacial drift thickness averages from 6 m (about 20 ft) over mountainous terrain, such as New England, to 15 m (about 50 ft) and more over the lowlands of the north-central United States. Over Iowa, drift thickness is from 45 to 60 m (about 150 to 200 ft), and over Illinois it averages more than 30 m (about 100 ft). In some places where deep stream valleys already existed before the glaciers advanced, such as in parts of Ohio, drift is much thicker.

17.17 Glacial till



▲ As ice passes over the ground, sediment and coarse rock fragments of clay-rich debris that were previously dragged forward beneath the ice are now pressed into a layer of *lodgment till*.



▲ When the overlying ice stagnates and melts, rock particles in the ice are lowered to the solid surface beneath, forming a layer of *ablational till* consisting of a mixture of sand and silt, with many angular pebbles and boulders. The layer of lense lodgment till lies below it.

Figure 17.18 describes the form and composition of deposits left by ice sheets. *Till plains*, *moraines*, and *drumlins* are formed under ice or by direct melting at the ice margin. *Kames, eskers,* and *outwash plains* are formed by fluvial action of meltwater streams.

Pluvial lakes are another type of landform created by ice sheets. During the Ice Age, some regions experienced a cooler, moister climate. In the western United States, closed basins filled with water, forming pluvial lakes. The largest of these, glacial Lake Bonneville, was about the size of Lake Michigan and occupied a vast area of western Utah. With the warmer and drier climate of the present interglacial period, these lakes shrank greatly in volume. Lake Bonneville became the present-day Great Salt Lake. Many other lakes dried up completely, forming desert playas. We can work out the history of these pluvial lakes from their ancient shorelines, some of which are as high as 300 m (about 1000 ft) above present levels.

Landforms associated with the ice are of major environmental importance. Glaciation can have both good and bad agricultural influences, depending on preglacial topography and the degree and nature of ice erosion and deposition.

In hilly or mountainous regions, such as New England, the glacial till is thinly distributed and extremely stony. The countless boulders and cobbles in the clay soil make it difficult to cultivate. Till deposits built up on steep mountain or roadside slopes pose the threat of earthflows after absorbing water from melting snows and spring rains. Crop cultivation is also hindered along moraine belts because of the steep slopes, the irregularity of the topography, and the number of boulders. But moraine belts are well suited to pastures.

Flat till plains, outwash plains, and lake plains, on the other hand, can sometimes provide very productive agricultural land. There are fertile soils on till plains and on exposed lakebeds bordering the Great Lakes. Their fertility is enhanced by a blanket of wind-deposited silt (loess) that covers these plains.

Stratified drift deposits are also very valuable. The sands and gravels from outwash plains, deltas, and eskers are used to manufacture concrete and for highway construction. And thick, stratified drift makes an excellent aquifer, providing a major source of ground water.

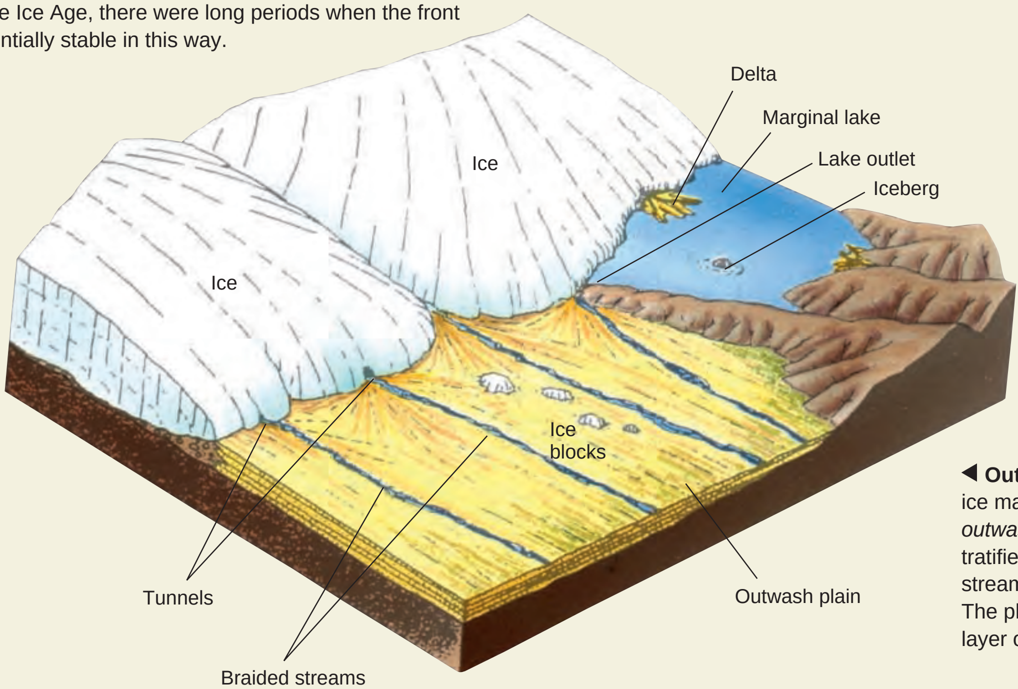
The Ice Age

Glaciation occurs when temperatures fall in regions of ample snowfall, allowing ice to accumulate and build. Although glaciation is a general term for the glacier growth and landform modification produced by glaciers, here we use it to refer to the period when continental ice sheets grow and spread outward over vast areas.

An ice age includes cycles of glaciation, deglaciation, and interglaciation. The Earth is presently in an interglaciation.

17.18 Marginal landforms produced by ice sheets

▼ **Ice sheet** When the front edge of the ice melts and evaporates at the same rate that ice is brought forward by spreading, the position of the front edge is stationary. During the Ice Age, there were long periods when the front was essentially stable in this way.



◀ **Marginal lakes** As the ice advances toward higher ground, it blocks valleys that may have opened out northward, enclosing *marginal lakes*. Streams of meltwater from the ice built glacial deltas into these marginal lakes.

◀ **Outwash plain** In front of the ice margin there is a smooth *outwash plain* that formed from tratified drift left by braided streams issuing from the ice. The plain is built of layer upon layer of sands and gravels.

▼ **Recessional moraine** The lower left portion of this aerial scene from Langdale County, Wisconsin, shows a recessional moraine covered with forest vegetation. Note the bumpy, irregular topography of sediments piled up at the former ice edge.

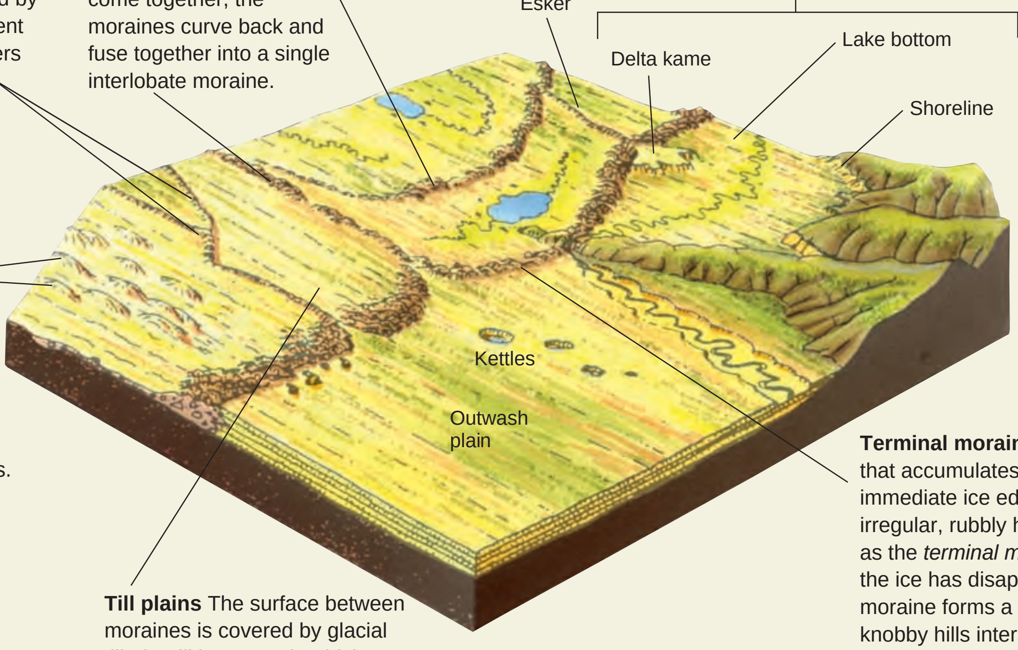
▼ **Esker** The curving ridge of sand and gravel in this photo is an *esker*, marking the bed of a river of meltwater flowing underneath a continental ice sheet near its margin. Kettle Moraine State Park Wisconsin.

Recessional moraine The ice front paused for some time along a number of positions, as it retreated, forming belts, known as *recessional moraines*. These run roughly parallel with the terminal moraine.

Marginal lake deposits When the ice withered away, the marginal lakes drained, leaving a flat floor exposed. Layers of fine clay and silt built up. These glacial lake plains often contain extensive areas of marshland.The deltas are now curiously isolated, flat-topped landforms known as *delta kames*, composed of well-washed and well-sorted sands and gravels.

Eskers Large streams carrying meltwater issue from tunnels in the ice. They form when the ice front stops moving for many kilometers back from the front. After the ice has gone, the position of a former ice tunnel is marked by a long, sinuous ridge of sediment known as an *esker*. Many eskers are several kilometers long.

Interlobate moraine Where the two ice lobes come together, the moraines curve back and fuse together into a single interlobate moraine.



Drumlins The smoothly rounded, oval hills of glacial till, which resemble the bowls of inverted teaspoons, are known as drumlins. Drumlins lie behind the terminal moraine in groups. The long axis of each drumlin parallels the direction of ice movement.

Terminal moraine Glacial till that accumulates at the immediate ice edge forms an irregular, rubbly heap known as the *terminal moraine*. After the ice has disappeared, the moraine forms a belt of knobby hills interspersed with basin-like hollows, or *kettles*, some of which hold small lakes.

Till plains The surface between moraines is covered by glacial till.The till layer can be thick and can bury the hills and valleys that existed before.

▼ **Drumlin** This small *drumlin*, located south of Sodus, New York, shows a tapered form from upper right to lower left, indicating that the ice moved in that direction (north to south).

▼ **Kame** This tree-covered hill, rising above the surrounding plain, is a *kame*—a deposit of sand and gravel built out from the front of a retreating ice sheet, possibly as a delta accumulating in a short-lived lake. As the ice melted and the lake drained, the deposit lost its lateral support and slumped down under the force of gravity forming a hill of roughly conical shape.

When the climate warms or snowfall decreases, ice sheets become thinner and cover less area. Eventually, the ice sheets may melt completely. This period is called a *deglaciation*. After a deglaciation, but before the next glaciation, there is a mild-climate period, or an **interglaciation**. The last interglaciation began about 140,000 years ago and ended between 120,000 and 110,000 years ago. A succession of alternating glaciations and interglaciations, spanning 1 to 10 million years or more, makes up an *ice age*.

The most recent ice age is but one of several ice ages the Earth has experienced in its long history. Although there is some evidence for an ice age near the start of the Proterozoic Eon, about 2.5 billion years ago, the earliest well-documented ice age took place from about 800 to 600 million years ago, near the end of that eon. That glaciation may have been quite extensive, with a "snowball Earth" that had sea ice nearly to the Equator. A minor ice age occurred in the late Ordovician Period, around 450 million years ago, and extensive polar ice caps and alpine glaciers formed twice during the Carboniferous and early Permian periods.

Throughout the past 3 million years or so, the Earth has been experiencing the **Late-Cenozoic Ice Age** (or, simply, the **Ice Age**). About 50 years ago, most geologists associated the Ice Age with the Pleistocene Epoch, which began about 1.6 million years ago. But new evidence from deep-sea sediments shows that the glaciations of the Ice Age began in late Pliocene time, perhaps 2.5 to 3.0 million years ago.

The Late-Cenozoic Ice Age is Earth's most recent ice age. It is but one of several past ice ages represented in the geologic record.

At present, we are in the middle of an interglaciation of the Ice Age, following a deglaciation that set in quite rapidly about 15,000 years ago. In the preceding glaciation, called the *Wisconsinan Glaciation*, ice sheets covered much of North America and Europe, as well as parts of northern Asia and southern South America. The maximum ice advance of the Wisconsinan Glaciation was about 18,000 years ago.

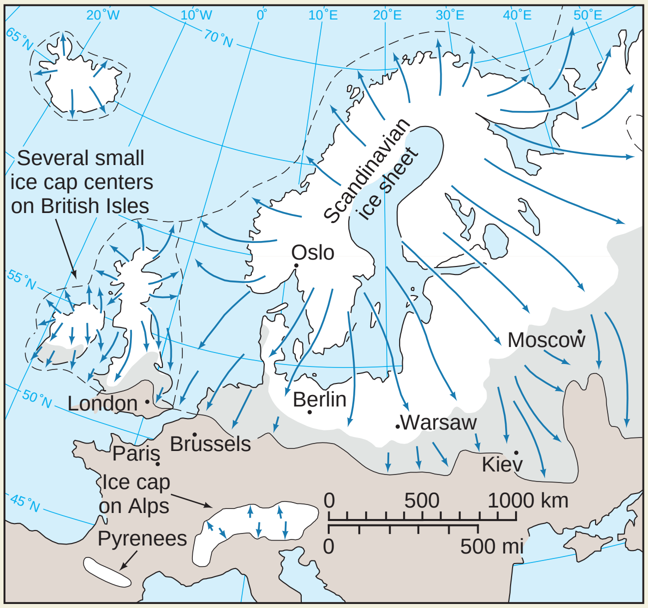
Figure 17.19 shows the maximum extent to which North America and Europe were covered during the last advance of the ice. Most of Canada was engulfed by the vast Laurentide Ice Sheet, which then spread south into the United States.

17.19 Maximum glaciation in North America and Europe

During glaciations sea level was much lower. The present coastline is shown for reference only.

Continental glaciers of the Ice Age in North America at their maximum extent reached as far south as the present Ohio and Missouri rivers.

This area in southwestern Wisconsin escaped an ice cover and is known as the Driftless Area.



▲ The Scandinavian Ice Sheet dominated northern Europe during the Ice Age glaciations. The present coastline is far inland from the coastline that prevailed during glaciations.

South America also had an ice sheet that grew from ice caps on the southern Andes Range south of about latitude 40° S and spread westward to the Pacific shore, as well as eastward to cover a broad belt of Patagonia. The South Island of New Zealand, which today has a high spine of alpine mountains with small glaciers, developed a massive ice cap in late Pleistocene time. All high mountain areas of the world developed alpine glaciers. Today, most remaining alpine glaciers are small ones.

In Europe, the Scandinavian Ice Sheet centered on the Baltic Sea, covering the Scandinavian countries, and spread south into central Germany and far eastward to cover much of Russia. The European Alps were capped by enlarged alpine glaciers. The British Isles were mostly covered by a small ice sheet that had several centers on highland areas and spread outward to coalesce with the Scandinavian Ice Sheet.

Looking carefully at the maps in Figure 17.19, you can see that the ice sheets seem to extend far out into what is now the open ocean. This is because the sea level was as much as 125 m (410 ft) lower than today, exposing large areas of the continental shelf on both sides of the Atlantic Basin. The exposed continental shelf had a vegetated landscape and was populated with animal life.

The weights of the continental ice sheets, covering vast areas with ice masses several kilometers thick, pushed down on the crust. This created depressions of hundreds of meters at some locations. When the ice melted, the crust began to rebound—and is still rebounding today in some locations.

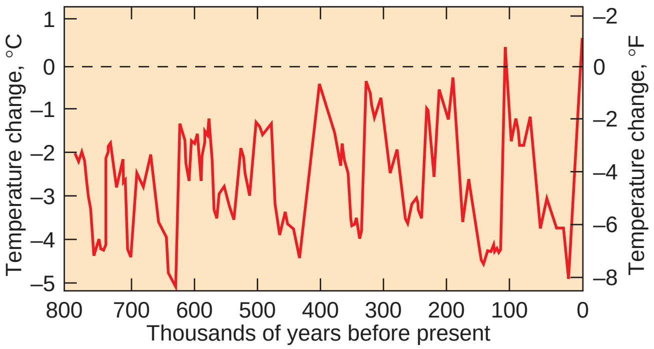
Although the largest ice sheets spread from northern hemisphere centers in Canada, Scandinavia, and Siberia, higher elevations in South America and New Zealand also developed small ice caps.

GEODISCOVERIES **Last Ice Age**

This animated map shows the retreat of continental ice sheets and coalescing alpine glaciers after the last glaciation. Watch as antarctic ice shelves and arctic sea ice also shrink.

INVESTIGATING THE ICE AGE

In the 1960s, geologists made a great scientific breakthrough that helped them study the glacial history of the Ice Age. First, they developed a technique for taking long sample cores of undisturbed fine-textured sediments of the deep ocean floor. Then they discovered how to use signs of ancient magnetism to discover how old the sediment layers were. The Earth's magnetic field experienced many sudden reversals of polarity in Cenozoic time, and the absolute ages of these reversals are known with certainty. By observing these reversals in the sediments, they were able to date the layers accurately. They also studied the composition and chemistry of the core layers, creating a record of ancient temperature cycles in the air and ocean.



17.20 Global temperatures of the Ice Age

This record of the Earth's global surface temperature, expressed as a difference from present temperature, shows *glaciations* and *interglaciations* to 800,000 years before present. Each valley represents a glacial period and each peak an interglacial. (Courtesy of Prof. Thomas Crowley, Duke University.)

Deep-sea cores reveal a long history of alternating glaciations and interglaciations going back at least 2 million years and possibly 3 million years. In late-Cenozoic time, there were more than 30 glaciations, spaced about 90,000 years apart. We don't know how much longer this sequence will continue—possibly for 1 or 2 million years, or even longer.

Figure 17.20 presents a plot of global temperature going back to about 800,000 years ago. Each valley represents a glacial period and each peak an interglacial. The figure clearly shows five distinct glaciations and four interglaciations since about 500,000 years ago. Before that time, the record shows more frequent glacial cycles that are somewhat less extreme.

POSSIBLE CAUSES OF THE ICE AGE

What caused the Earth to enter into an Ice Age? There are at least four possible explanations. The first is related to plate tectonics, the second to volcanoes, the third to changes in the Sun's energy output, and the fourth to changes in atmospheric composition.

The explanation related to plate tectonics suggests that the motions of lithospheric plates after Pangaea broke apart were responsible for the Ice Age. In Permian time, only the northern tip of the Eurasian continent projected into the polar zone. But as the Atlantic Basin opened up, North America moved westward and poleward to a position opposite Eurasia, while Greenland took up a position between North America and Europe.

The plate motions brought an enormous area of land to a high latitude, surrounding the polar ocean. This reduced, and at times totally cut off, the flow of warm ocean currents into the polar ocean, encouraging ice sheets to grow. The polar ocean would have been ice-covered for much of the time. At the same time, the average air temperatures in high latitudes would have lowered enough for ice sheets to grow on the encircling continents. In addition, Antarctica moved southward during the breakup of Pangaea and took up a position over the South Pole, where it was ideally placed to develop a large ice sheet. Some scientists have also proposed that the uplift of the Himalayan Plateau—caused by the collision of the Austral-Indian and Eurasian plates—modified weather patterns and triggered the Ice Age.

Volcanic activity has also been suggested as a possible cause of the Ice Age. Eruptions produce dust veils that linger in the stratosphere and block solar radiation (Figure 17.21). Perhaps an increase in volcanic activity on a global scale in late-Cenozoic time temporarily cooled near-surface air temperatures, somehow triggering the start of the Ice Age. The geologic record does confirm that there were periods of high levels of volcanic activity in the Miocene and Pliocene epochs, but no triggering mechanism has been demonstrated.

17.21 Volcanic eruption

Large volcanic eruptions can generate plumes of dust and gas that penetrate the stratosphere, creating persistent aerosols that can block sunlight and cool the climate. Karymsky volcano, Kamchatka Peninsula, Russia (National Geographic Image Collection).

17.22 Solar output

One possible cause of the Late-Cenozoic Ice Age is a reduction in solar output (National Geographic Image Collection).

Four factors have been proposed to explain why the Earth has entered the Late-Cenozoic Ice Age: a change in the placement of the continents, increased volcanic activity, a reduction in solar energy output, and a change in atmospheric composition.

The third proposed cause of the Ice Age is a slow decrease in the Sun's energy output over the last several million years (Figure 17.22). This could form part of a slow cycle of increase and decrease over many millions of years. As yet, we don't have enough data to identify whether this mechanism was responsible. But research on this topic is being stepped up as satellites give us new knowledge of the Sun and its changing surface.

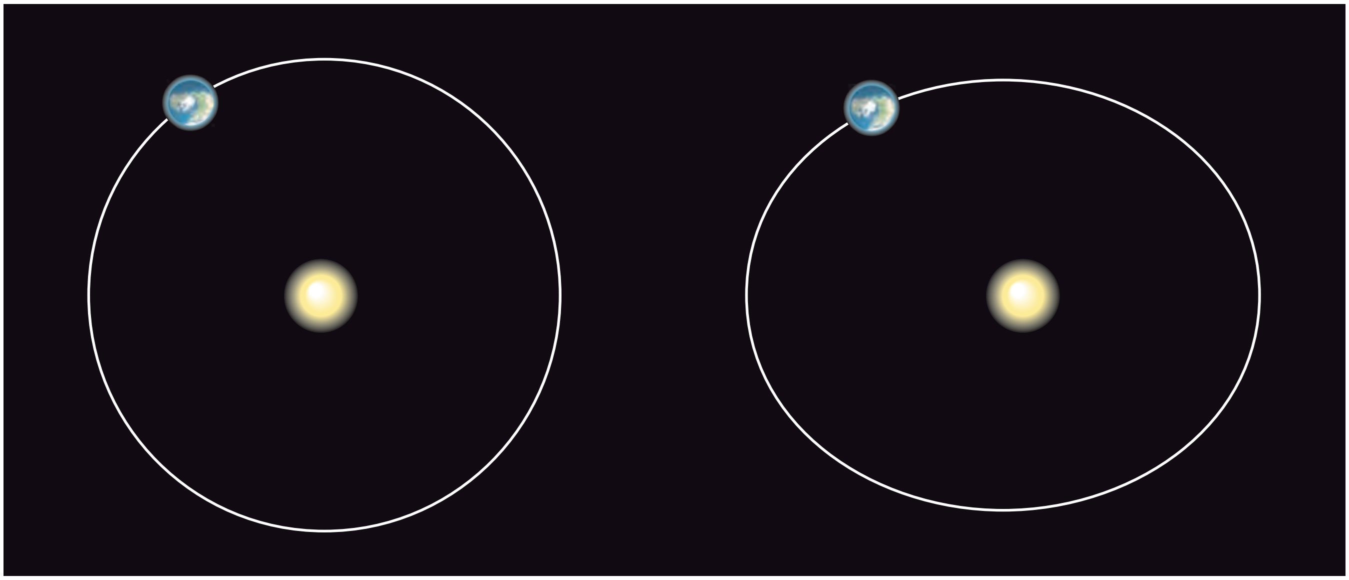
The last cause is a change in atmospheric composition. We have seen how greenhouse gases act to warm the Earth, and a reduction in greenhouse gases could cause an Ice Age. However, the concentration of greenhouse gases is determined by a complicated process of interaction and feedbacks between biological and physical processes and can change on a rapid time scale. Although there is some evidence that greenhouse gas levels have fallen at the start of ice ages and increased at their end, it's not certain just how or why such changes might have taken place.

For now, most scientists seem to agree that tectonic plate movements that affect oceanic and atmospheric circulation are at least necessary, if not sufficient, for an ice age to occur.

POSSIBLE CAUSES OF GLACIATION CYCLES

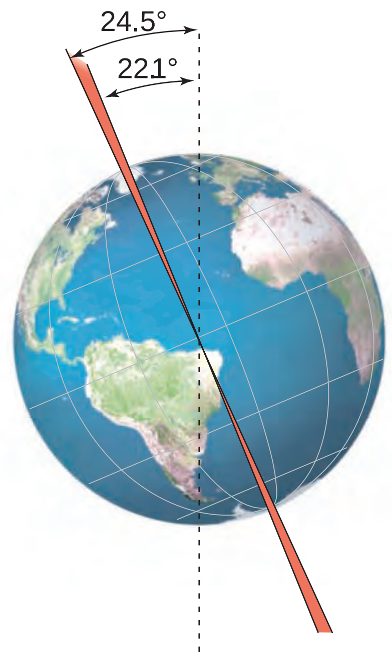
What timing and triggering mechanisms are responsible for the many cycles of glaciation and interglaciation that the Earth is experiencing during the present Ice Age? Although many causes for glacial cycles have been proposed, in this book we'll just discuss one major contender, called the **astronomical hypothesis**. It has been under consideration for about 40 years and is now widely accepted.

The astronomical hypothesis is based on the motion of the Earth in its orbit around the Sun—which is now well established (Figure 17.23). The Earth's orbit around the Sun is an ellipse, not a circle. We call the point in



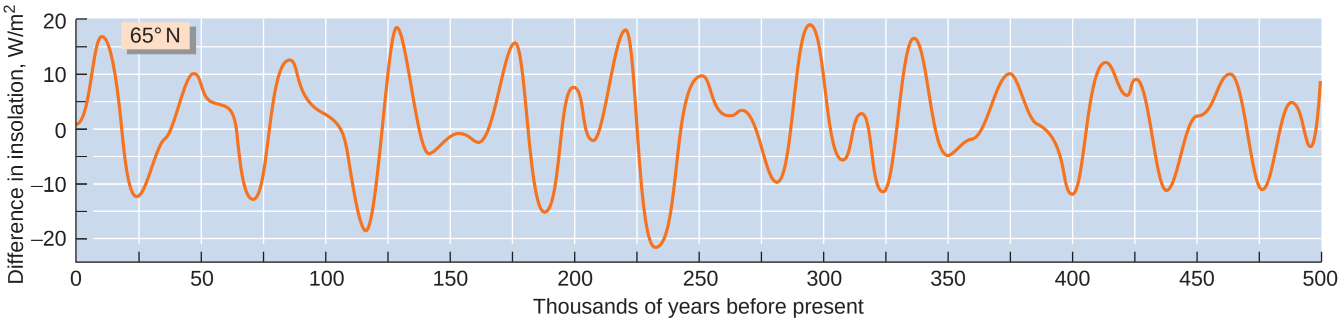
▲ The shape of the Earthís orbit around the Sun varies from nearly circular to slightly elliptical with a period of about 108,000 years.

▲ The Earthís axis of rotation slowly revolves, tracing a circle over a period of about 26,000 years.



▲ As the axis of rotation moves along the circle, it also varies its angle slightly from 221° to 24.5° with a period of about 41,000 years.

17.23 The astronomical hypothesis for cycles of glaciation



17.24 The Milankovitch curve

The vertical axis shows fluctuations in summer daily insolation at lat. 65° N for the last 500,000 years. These are calculated from mathematical models of the change in Earth–Sun distance and change in axial tilt with time. The zero value represents the present value.

the orbit nearest the Sun the *perihelion*, and the point farthest from the Sun the *aphelion*. Today, the Earth is at perihelion around January 3 and aphelion around July 4. But astronomers have observed that the orbit slowly rotates on a 108,000-year cycle, so the absolute time of perihelion and aphelion shifts by a very small amount each year. In addition, the orbit's shape varies on a cycle of 92,000 years, becoming more and less elliptical. These cycles change the Earth–Sun distance and therefore the amount of solar energy the Earth receives at each point during the year.

The Earth's axis of rotation also experiences cyclic motions. The tilt angle of the axis varies from about 22 to 24 degrees on a 41,000-year cycle. The axis also "wobbles" on a 26,000-year cycle, moving in a slow circular motion much like a spinning top or toy gyroscope.

These cycles in axial rotation and solar revolution mean that the annual insolation experienced at each latitude changes from year to year. Figure 17.24 shows a graph of summer insolation received at 65° N latitude for the last 500,000 years as calculated from these cycles. The graph is known as the *Milankovitch curve*, named for Milutin Milankovitch, the astronomer who first calculated it in 1938.

Looking at the figure, you can see that the dominant cycle of the curve has a period of about 40,000 years. But notice that every second or third peak seems to be higher. Dating methods using ancient ice cores and deep lake sediment cores tell us that the peaks at about 12,000, 130,000, 220,000, 285,000, and 380,000 years ago correspond with the rapid melting of ice sheets and the onset of deglaciations. Most scientists studying climate change during the Ice Age now agree that these cyclic insolation changes explain the cycles of glaciation within the Ice Age.

According to the astronomical hypothesis, the timing of glaciations and interglaciations is determined by variations in insolation produced by minor cycles in the Earth's orbit and the Earth's axial rotation.

HOLOCENE ENVIRONMENTS

About 10,000 years have elapsed since the Wisconsinan Glaciation ended. We call that time period the **Holocene Epoch**. It began with a rapid warming of ocean surface temperatures. Continental climate zones then quickly shifted poleward, and plants recolonized the glaciated areas.

There were three major climatic periods during the Holocene Epoch leading up to the last 2000 years. These periods are inferred from studies of fossil pollen and spores preserved in glacial bogs, which show changes in vegetation cover over time (Figure 17.25). The earliest of the three is the *Boreal stage*, characterized by boreal forest vegetation in midlatitude regions. There followed a general warming until the *Atlantic stage*, with temperatures somewhat warmer than today, was reached about 8000 years ago (–8000 years). Next came a period of temperatures that were below average—the *Subboreal stage*. This stage spanned the age range –5000 to –2000 years.

We can describe the climate of the past 2000 years on a finer scale, thanks to historical records and more detailed evidence. A secondary warm period occurred in the period A.D. 1000 to 1200 (–1000 to –800 years). This warm episode was followed by the Little Ice Age, A.D. 1450–1850 (–550 to –150 years), when valley glaciers made new advances and extended to lower elevations.

Global temperatures have been slowly warming within the last century and are now starting to warm even more rapidly due to the release of greenhouse gases by human activity. As we saw in our opening section, *Eye on Global Change • Ice Sheets, Sea Ice, and Global Warming*, global warming is bringing major change to glaciers and sea ice. This is but one effect of the global climate change now being brought about by human activities. There will be many others.

GEODISCOVERIES Web Quiz

Take a quick quiz on the key concepts of this chapter.

17.25 Pollen grains

Pollen grains of different species have distinct sizes and shapes. Where they are well preserved in a sample of ice-age sediment, it is possible to determine the composition of the vegetation cover.

A Look Ahead

Our chapter has focused on glaciers and the processes that construct glacial landforms, showing how flowing ice and meltwater leave distinctive signatures on the landscape. The group of chapters we have now completed has reviewed landform-making agents and processes that operate on the surface of the continents. These have ranged from mass wasting to fluvial action, waves, wind, and glaciers. The great variety and complexity of landforms we have described are not difficult to understand when each agent is examined in turn.

This chapter completes our presentation of physical geography, which has covered topics from weather and climate to biogeography and landforms. As you observe and experience the world around you, you should now better understand your environment and the processes that are constantly shaping it.

Human activity has changed the Earth in many ways over the last few millennia, and human impact will increase in the future. We hope that the background and context on the workings of the Earth and the environment that you have gained from the book will be valuable as you face the challenges of world citizenship in the twenty-first century.

GEODISCOVERIES **Web Links**

This chapter's web links are rich in photos of glaciers and glacial landforms from Alaska to Antarctica. Go exploring!

IN REVIEW GLACIAL LANDFORMS AND THE ICE AGE

- Global warming is increasing the amount of snow accumulation on ice sheets, but is also increasing the melting and thinning of ice shelves and the edges of ice sheets.
- Although the East Antarctic Ice Sheet is holding its own, the West Antarctic Ice Sheet is losing ice mass. The Greenland ice cap is also losing ice mass as well. These losses are contributing to sea-level rise.
- There is a possibility that the West Antarctic Ice Sheet could collapse, raising sea level by several meters within a few hundred years.
- Arctic sea ice is thinning rapidly and decreasing in summer extent due to climate warming.
- Glaciers affect global climate by reflecting solar radiation back to space. When glaciers grow and recede, sea level falls and rises.
- **Glaciers** form when snow accumulates to a great depth, creating a mass of ice that is plastic in lower layers and flows outward or downhill from a center in response to gravity. Glaciers exist as **alpine glaciers** and as **ice sheets**.
- As they move, glaciers pick up and carry loose soil, regolith, and sediment. They also erode bedrock by

abrasion and *plucking*. The materials moved by the ice form depositional landforms when the ice melts.

- *Alpine glaciers* develop in *cirques* in high mountain locations. Alpine glaciers flow downvalley on steep slopes, picking up rock debris and depositing it in *lateral* and *terminal* **moraines**.
- By removal of loose soil and debris, alpine glaciers carve **glacial troughs** that are distinctive features of glaciated mountain regions. They become **fiords** if later submerged by rising sea level.
- Alpine glaciers are often inaccessible, but are easily monitored by remote sensing. Images show the extent and locations of glaciers, and some types of data can show the velocity and direction of flowing ice.
- *Ice sheets* are huge masses of ice that cover vast areas. They are present today in Greenland and Antarctica.
- The Antarctic Ice Sheet includes **ice shelves**—great plates of floating glacial ice.
- **Sea ice** is formed by direct freezing of ocean water and accumulation of snow. It can form *pack ice*, which completely covers the surface, or break into *ice floes* with *leads* of open water.
- **Icebergs** form when glacial ice flowing into an ocean breaks into great chunks and floats free. Most of the ice mass lies below the sea surface.
- Moving ice sheets create many types of landforms. Bedrock is grooved, scratched, and polished. Where rocks are weak, long valleys can be excavated to depths of hundreds of meters.
- The melting of glacial ice deposits **glacial drift**, which may be stratified by water flow or deposited directly as **till**. *Moraines* accumulate at ice edges.
- *Outwash plains* are built up by meltwater streams. Meltwater streams also build *glacial deltas* into lakes formed at the ice margin and line lake bottoms with clay and silt. Stream tunnels within the ice leave stream deposits as *eskers*.
- Till may be spread smooth and thick under an ice sheet, leaving a *till plain*. This may be studded with elongated till mounds, termed *drumlins*. When the lakes drain, these features remain.
- *Pluvial lakes* formed during the cooler, wetter climate of the Ice Age. These lakes are now much smaller or represented by playas.
- An ice age includes alternating periods of **glaciation**, *deglaciation*, and **interglaciation**.
- During the past 2 to 3 million years, the Earth has experienced the **Late-Cenozoic Ice Age**. During this ice age, continental ice sheets have grown and melted as many as 30 times.
- The most recent glaciation is the *Wisconsinan Glaciation*, in which ice sheets covered much of North America and Europe, as well as parts of northern Asia and southern South America.
- Factors proposed to have initiated the Ice Age include a change in the global position of continents, an increase in volcanism, a reduction in the Sun's energy output, and a change in atmospheric composition.
- Individual cycles of glaciation seem strongly related to cyclic changes in Earth–Sun distance and axial tilt. This is called the **astronomical hypothesis** and was developed by the astronomer Milutin Milankovitch.
- The Holocene Epoch spans the end of the Wisconsinan Glaciation to the present. So far, this epoch includes cool, warm, and cool stages before A.D. 1000. Since then, we have experienced warm, cool, and warm periods.

KEY TERMS

glacier, p. 000
alpine glacier, p. 000
ice sheet, p. 000
moraine, p. 000
glacial trough, p. 000
fiord, p. 000
ice shelves, p. 000
sea ice, p. 000
icebergs, p. 000
glacial drift, p. 000
till, p. 000
glaciation, p. 000
interglaciation, p. 000
Late-Cenozoic Ice Age, p. 000
astronomical hypothesis, p. 000
Holocene Epoch, p. 000

REVIEW QUESTIONS

1. How is global warming affecting the Earth's ice sheets?
2. Why is the West Antarctic Ice Sheet considered unstable?
3. What is the effect of global warming on arctic sea ice?
4. Why are glaciers important to the global climate system? How do they affect sea level?
5. How does a glacier form? Why does it move?
6. Compare alpine glaciers to ice sheets. Where are they found?
7. Explain how glacial action erodes bedrock. What two processes are involved?
8. Explain how alpine glaciers create the following landforms: *cirques*, *arêtes*, *horns*, *cols*, *moraines*, and *tarns*.

9. What is a glacial trough, and how is it formed? How does a *hanging valley* come about? How is a glacial trough related to a fiord?
10. How is remote sensing used to study glaciers?
11. Where are the Earth's great ice sheets found? What is an ice shelf? Where are ice shelves found?
12. Contrast *sea ice* and *icebergs*, including the processes by which they form.
13. Define the term *glacial drift*. Identify two basic kinds of glacial drift.
14. What are *moraines*? How are they formed? What types of moraines are there?
15. Identify the landforms and deposits associated with stream action at or near the front of an ice sheet.
16. Identify the landforms and deposits associated with deposition underneath a moving ice sheet.
17. Identify the landforms and deposits associated with lakes that form at ice sheet margins.
18. Define the terms *glaciation, deglaciation*, and *interglaciation*.
19. Identify the Late-Cenozoic Ice Age. When did it begin? Identify the most recent glaciation of the Ice Ago. When did it end?
20. What areas were covered with ice sheets by the last glaciation? How was sea level affected?
21. Identify and describe four possible causes of the Ice Age.
22. What causes the glacial cycles observed within the Ice Age? What astronomical motions are involved?
23. What is the Milankovitch curve? What does it show about warm and cold periods during the last 500,000 years?
24. How has climate changed during the Holocene Epoch? What periods are recognized, and what are their characteristics?

VISUALIZING EXERCISES

1. What are some typical features of an alpine glacier? Sketch a cross section along the length of an alpine glacier and label it.
2. Refer to Figure 17.12, which shows the Antarctic continent and its ice cap. Identify the Ross, Filchner, and Larsen ice shelves. Use the scale to measure the approximate area of each in square kilometers or miles. Consulting an atlas or almanac, identify the state or province of the United States or Canada that is nearest in area to each.

ESSAY QUESTIONS

1. Imagine that you are planning a car trip to the Canadian Rockies. What glacial landforms would you expect to find there? Where would you look for them?
2. At some time during the latter part of the Pliocene Epoch, the Earth entered an ice age. Describe the nature of this ice age and the cycles that occur within it. What explanations are proposed for causing an ice age and its cycles? What cycles have been observed since the last ice sheets retreated?

Appendix 1
Climate Definitions and Boundaries

The following table summarizes the definitions and boundaries of climates and climate subtypes based on the soil-water balance, as described in Chapter 14 and shown on the world climate map, Figure 7.10.

Ep	Water need (potential evapotranspiration)
D	Soil-water shortage (deficit)
R	Water surplus (runoff)
S	Storage (limited to 300 mm)

GROUP I: LOW-LATITUDE CLIMATES

1. **Wet equatorial climate** ①
   Ep ≥ 100 mm in every month, and
   S ≥ 200 mm in 10 or more months.
2. **Monsoon and trade-wind coastal climate** ②
   Ep ≥ 40 mm in every month, or
   Ep > 1300 mm annual total, or both, and
   S ≥ 200 mm in 6, 7, 8, or 9 consecutive months, or, if
   S > 200 mm in 10 or more months, then Ep ≤ 100 mm in 5 or more consecutive months.
3. **Wet-dry tropical climate** ③
   D ≥ 200 mm, and
   R ≥ 100 mm, and
   Ep ≥ 1300 mm annual total, or Ep ≥ 40 mm in every month, or both, and
   S ≥ 200 mm in 5 months or fewer, or minimum monthly S < 30 mm.
4. **Dry tropical climate** ④
   D ≥ 150 mm, and
   R = 0, and
   Ep ≥ 1300 mm annual total, or Ep ≥ 40 mm in every month, or both.
   Subtypes of dry climates (④, ⑤, ⑦, and ⑨)
   s Semiarid subtype (Steppe subtype) At least 1 month with S > 20 mm.
   a Desert subtype
   No month with S > 20 mm.

GROUP II: MIDLATITUDE CLIMATES

5. **Dry subtropical climate** ⑤
   D ≥ 150 mm, and
   R = 0, and Ep < 1300 mm annual total, and
   Ep ≥ 8 mm in every month, and
   Ep < 40 mm in 1 month.
   (Subtypes ⑤a and ⑤s as defined under ④.)
6. **Moist subtropical climate** ⑥
   D < 150 mm when R = 0, and
   Ep < 40 mm in at least 1 month, and
   Ep ≥ 8 mm in every month.
7. **Mediterranean climate** ⑦
   D ≥ 150 mm, and
   R ≥ 0, and
   Ep ≥ 8 mm in every month, and storage index > 75%, or P/Ea × 100 < 40%. (Subtypes ⑦a and ⑦s as defined under ④.)
8. **Marine west-coast climate** ⑧
   D < 150 mm, and
   Ep < 800 mm annual total, and
   Ep ≥ 8 mm in every month.
9. **Dry midlatitude climate** ⑨
   D ≥ 150 mm, and
   R = 0, and
   Ep ≤ 7 mm in at least 1 month, and
   Ep > 525 mm annual total.
   (Subtypes ⑨a and ⑨s as defined under ④.)
10. **Moist continental climate** ⑩
    D < 150 mm when R = 0, and
    Ep ≤ 7 mm in at least 1 month, and
    Ep > 525 mm annual total.

GROUP III: HIGH-LATITUDE CLIMATES

11. **Boreal forest climate** ⑪
    525 mm > Ep > 350 mm annual total, and
    Ep = 0 in fewer than 8 consecutive months.
12. **Tundra climate** ⑫
    Ep < 350 mm annual total, and
    Ep = 0 in 8 or more consecutive months.
13. **Ice sheet climate** ⑬
    Ep = 0 in all months.

Appendix 2
Conversion Factors

Metric to English

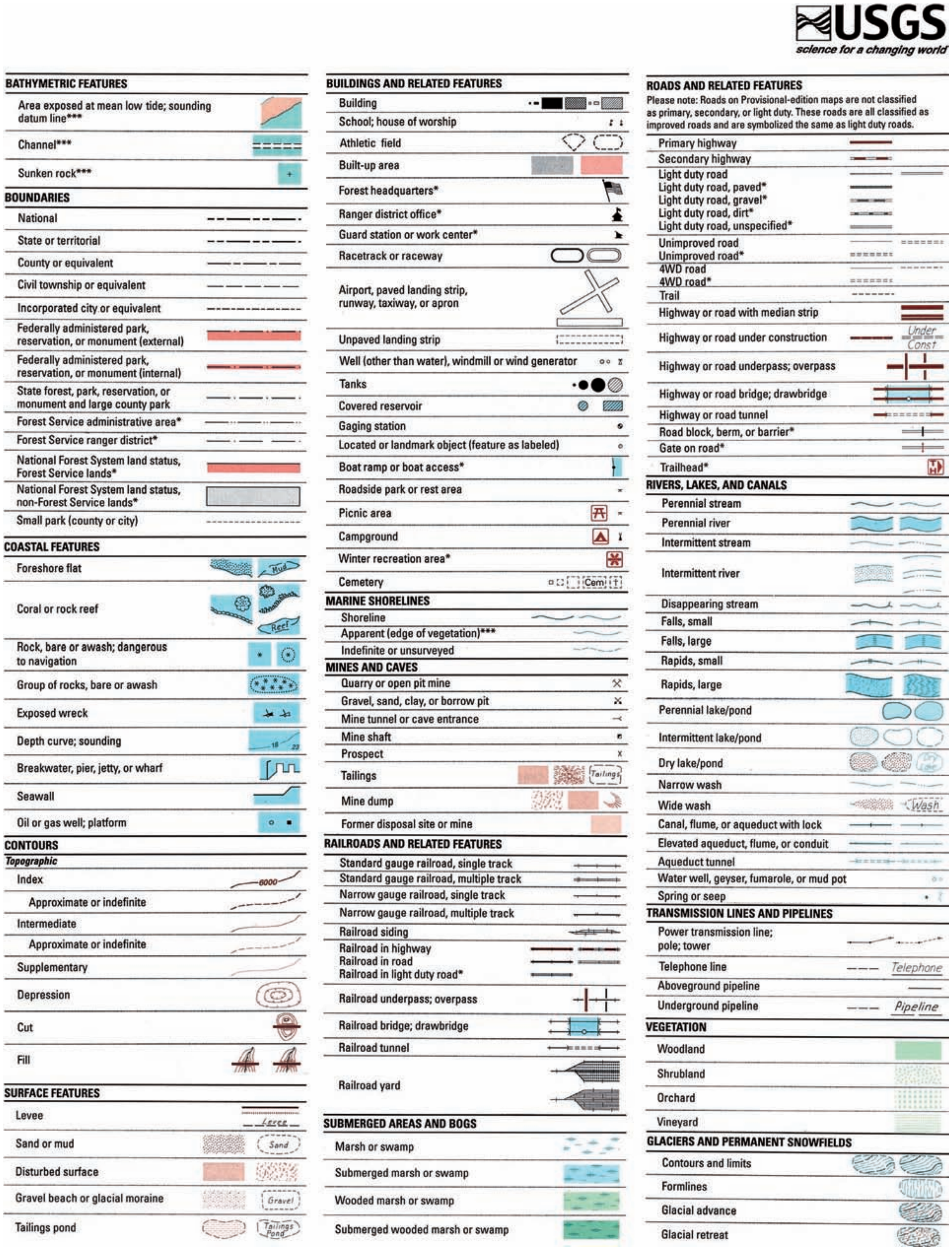
Metric Measure	Multiply by*	English Measure
LENGTH		
Millimeters (mm)	0.0394	Inches (in.)
Centimeters (cm)	0.394	Inches (in.)
Meters (m)	3.28	Feet (ft)
Kilometers (km)	0.621	Miles (mi)
AREA		
Square centimeters (cm^2)	0.155	Square inches (in^2)
Square meters (m^2)	10.8	Square feet (ft^2)
Square meters (m^2)	1.12	Square yards (yd^2)
Square kilometers (km^2)	0.386	Square miles (mi^2)
Hectares (ha)	2.47	Acres
VOLUME		
Cubic centimeters (cm^3)	0.0610	Cubic inches (in^3)
Cubic meters (m^3)	35.3	Cubic feet (ft^3)
Cubic meters (m^3)	1.31	Cubic yards (yd^3)
Milliliters (ml)	0.0338	Fluid ounces (fl oz)
Liters (l)	1.06	Quarts (qt)
Liters (l)	0.264	Gallons (gal)
MASS		
Grams (g)	0.0353	Ounces (oz)
Kilograms (kg)	2.20	Pounds (lb)
Kilograms (kg)	0.00110	Tons (2000 lb)
Tonnes (t)	1.10	Tons (2000 lb)

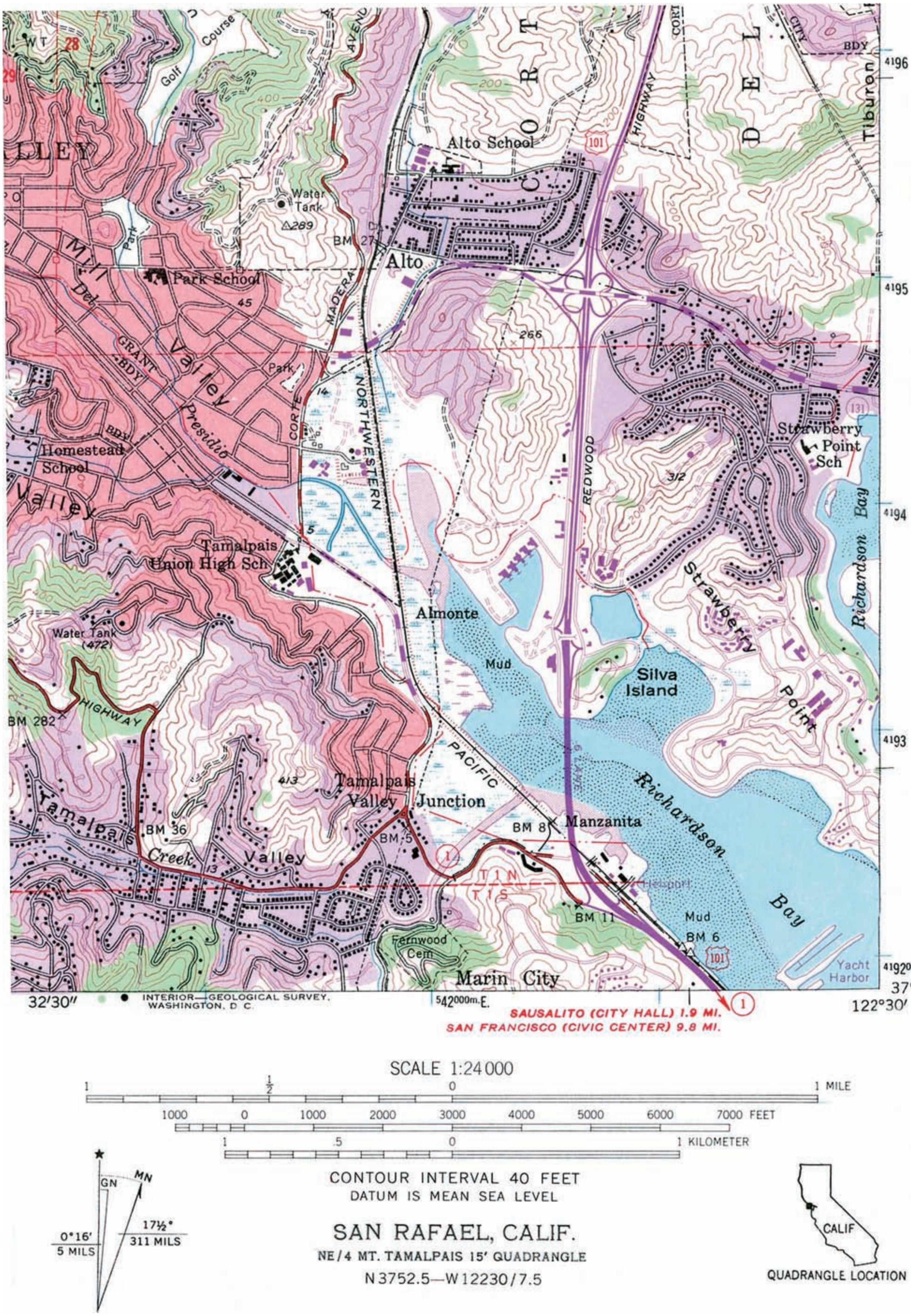
English to Metric

English Measure	Multiply by*	Metric Measure
LENGTH		
Inches (in.)	2.54	Centimeters (cm)
Feet (ft)	0.305	Meters (m)
Yards (yd)	0.914	Meters (m)
Miles (mi)	1.61	Kilometers (km)
AREA		
Square inches (in^2)	6.45	Square centimeters (cm^2)
Square feet (ft^2)	0.0929	Square meters (m^2)
Square yards (yd^2)	0.836	Square meters (m^2)
Square miles (mi^2)	2.59	Square kilometers (km^2)
Acres	0.405	Hectares (ha)
VOLUME		
Cubic inches (in^3)	16.4	Cubic centimeters (cm^3)
Cubic feet (ft^3)	0.0283	Cubic meters (m^3)
Cubic yards (yd^3)	0.765	Cubic meters (m^3)
Fluid ounces (fl oz)	29.6	Milliliters (ml)
Pints (pt)	0.473	Liters (l)
Quarts (qt)	0.946	Liters (l)
Gallons (gal)	3.79	Liters (l)
MASS		
Ounces (oz)	28.4	Grams (g)
Pounds (lb)	0.454	Kilograms (kg)
Tons (2000 lb)	907	Kilograms (kg)
Tons (2000 lb)	0.907	Tonnes (t)

*Conversion factors shown to 3 decimal digit precision.

Appendix 3
Topographic Map Symbols




Alto School
Alto
Water Tank
BM 27
Park School
Mill Valley
Del Presidio
Valley
Homestead School
Tamalpais Union High Sch
Almonte
Water Tank (472)
BM 282
HIGHWAY
NORTHWESTERN
PACIFIC
REDWOOD
HIGHWAY
Strawberry Point Sch
Strawberry Point
Silva Island
Mud
Richardson Bay
Tamalpais Valley Junction
Manzanita
BM 8
BM 36
BM 5
Tamalpais Creek Valley
BM 11
BM 6
Fernwood Cem
Marin City
Yacht Harbor
Tiburon
Golf Course
T 1 N
T 1 S
4196
4195
4194
4193
4192000m.N.
37°52′30″
32′30″
542000m.E.
122°30′
INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.
SAUSALITO (CITY HALL) 1.9 MI.
SAN FRANCISCO (CIVIC CENTER) 9.8 MI.
SCALE 1:24 000
1 ½ 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER
CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL
SAN RAFAEL, CALIF.
NE/4 MT. TAMALPAIS 15′ QUADRANGLE
N3752.5—W12230/7.5
GN
MN
0°16′
5 MILS
17½°
311 MILS
CALIF
QUADRANGLE LOCATION

Glossary

This glossary contains definitions of terms shown in the text in italics or boldface.

A

A horizon mineral horizon of the soil, overlying the E and B horizons.

ablation wastage of glacial ice by melting and evaporation.

ablation till heterogeneous mixture of rock fragments released by the melting in place of stagnant glacial ice. (See also *till*.)

abrasion erosion of bedrock of a stream channel by impact of particles carried in a stream and by rolling of larger rock fragments over the streambed; abrasion is also an activity of glacial ice, waves, and wind.

abrasion platform sloping, nearly flat bedrock surface extending out from the foot of a marine cliff under the shallow water of breaker zone.

absorption (of radiation) transfer of electromagnetic energy into heat energy within a gas or liquid through which the radiation is passing or at the surface of a solid struck by the radiation.

abyssal hills small hills rising to heights from a few tens of meters to a few hundred meters above the deep ocean floor.

abyssal plain large expanse of very smooth, flat ocean floor found at depths of 4600 to 5500 m (15,000 to 18,000 ft).

accelerated erosion soil erosion occurring at a rate much faster than soil horizons can be formed from the parent regolith.

accretion of lithosphere production of new oceanic lithosphere at an active spreading plate boundary by the rise and solidification of magma of basaltic composition.

accretionary prism mass of deformed trench sediments and ocean-floor sediments accumulated in wedge-like slices on the underside of the overlying plate above a plate undergoing subduction.

acid action solution of minerals by acids occurring in soil and ground water.

acid deposition the deposition of acid raindrops and/or dry acidic dust particles on vegetation and ground surfaces.

acid mine drainage sulfuric acid effluent from coal mines, mine tailings, or spoil ridges made by strip mining.

acid rain rainwater having an abnormally low pH, between 2 and 5, as a result of air pollution by sulfur oxides and nitrogen oxides.

active continental margins continental margins that coincide with tectonically active plate boundaries. (See also *continental margins, passive continental margins*.)

active layer shallow surface layer subject to seasonal thawing in permafrost regions.

active pool type of pool in the biogeochemical cycle in which the materials are in forms and places easily accessible to life processes. (See also *storage pool*.)

active systems remote sensing systems that emit a beam of wave energy at a source and measure the intensity of that energy reflected back to the source.

actual evapotranspiration (water use) Actual rate of evapotranspiration at a given time and place.

adiabatic lapse rate (See *dry adiabatic lapse rate, moist adiabatic lapse rate*.)

adiabatic principle the physical principle that a gas cools as it expands and warms as it is compressed, provided that no heat flows into or out of the gas during the process.

adiabatic process change of temperature within a gas because of compression or expansion, without gain or loss of heat from the outside.

advection fog fog produced by condensation within a moist basal air layer moving over a cold land or water surface.

aerosols tiny particles present in the atmosphere, so small and light that the slightest movements of air keep them aloft.

aggradation raising of stream channel altitude by continued deposition of bed load.

air a mixture of gases that surrounds the Earth.

air mass extensive body of air within which upward gradients of temperature and moisture are fairly uniform over a large area.

air-mass thunderstorm thunderstorm arising from daytime heating of the land surface, usually characterized by isolated cumulus and cumulonimbus clouds.

air pollutant an unwanted substance injected into the atmosphere from the Earth's surface by either natural or human activities; includes aerosols, gases, and particulates.

air temperature temperature of air, normally observed by a thermometer under standard conditions of shelter and height above the ground.

albedo proportion or percentage of downwelling solar radiation reflected upward from a surface.

albic horizon pale, often sandy soil horizon from which clay and free iron oxides have been removed. Found in the profile of the Spodosols.

Alfisols soil order consisting of soils of humid and subhumid climates, with high base status and an argillic horizon.

allele specific version of a particular gene.

allelopathy interaction among species in which a plant secretes substances into the soil that are toxic to other organisms.

allopatric speciation type of speciation in which populations are geographically isolated and gene flow between the populations does not take place.

alluvial fan gently sloping, conical accumulation of coarse alluvium deposited by a braided stream undergoing aggradation below the point of emergence of the channel from a narrow gorge or canyon.

alluvial meanders sinuous bends of a graded stream flowing in the alluvial deposit of a floodplain.

alluvial river stream of low gradient flowing on thick deposits of alluvium and experiencing approximately annual overbank flooding of the adjacent floodplain.

alluvial terrace bench-like landform carved in alluvium by a stream during degradation.

alluvium any stream-laid sediment deposit found in a stream channel and in low parts of a stream valley subject to flooding.

alpine chains high mountain ranges that are narrow belts of tectonic activity severely deformed by folding and thrusting in comparatively recent geologic time.

alpine debris avalanche debris flood of steep mountain slopes, often laden with tree trunks, limbs, and large boulders.

alpine glacier long, narrow, mountain glacier on a steep downgrade.

alpine permafrost permafrost occurring at high altitudes equatorward of the normal limit of permafrost.

alpine tundra a plant formation class within the tundra biome, found at high altitudes above the limit of tree growth.

altocumulus cloud type in which patchy clouds or rolls are found near the middle of the troposphere.

altostratus cloud type in which sheets or layers of clouds are found near the middle of the troposphere.

amphibole group silicate minerals rich in calcium, magnesium, and iron, dark in color, high in density, and classed as mafic minerals.

amplitude for a smooth wave-like curve, the difference in height between a crest and the adjacent trough.

andesite extrusive igneous rock of diorite composition, dominated by plagioclase feldspar; the extrusive equivalent of diorite.

Andisols a soil order that includes soils formed on volcanic ash; often enriched by organic matter, yielding a dark soil color.

anemometer weather instrument used to indicate wind speed.

aneroid barometer barometer using a mechanism consisting of a partially evacuated air chamber and a flexible diaphragm.

angle of repose natural surface inclination (dip) of a slope consisting of loose, coarse, well-sorted rock or mineral fragments; for example, the slip face of a sand dune, a talus slope, or the sides of a cinder cone.

annuals plants that live only a single growing season, passing the unfavorable season as a seed or spore.

annular drainage pattern a stream network dominated by concentric (ring-like) major subsequent streams.

Antarctic Circle parallel of latitude at 66½° S.

antarctic front zone frontal zone of interaction between antarctic air masses and polar air masses.

antarctic zone latitude zone in the latitude range 60° to 75° S (more or less), centered on the Antarctic Circle, and lying between the subantarctic zone and the polar zone.

anticlinal valley valley eroded in weak strata along the central line or axis of an eroded anticline.

anticline upfold of strata or other layered rock in an arch-like structure; a class of folds. (See also *syncline*.)

anticyclone center of high atmospheric pressure.

anvil cloud anvil-shaped cloud extending downwind from the top of mature thunderstorms.

aphelion point on the Earth's elliptical orbit at which the Earth is farthest from the Sun.

aquatic ecosystem ecosystem of a lake, bog, pond, river, estuary, or other body of water.

Aquepts suborder of the soil order Inceptisols; includes Inceptisols of wet places, seasonally saturated with water.

aquiclude rock mass or layer that impedes or prevents the movement of ground water.

aquifer rock mass or layer that readily transmits and holds ground water.

arc curved line that forms a portion of a circle.

arc-continent collision collision of a volcanic arc with continental lithosphere along a subduction boundary.

Arctic Circle parallel of latitude at 66½° N.

arctic front zone frontal zone of interaction between arctic air masses and polar air masses.

arctic tundra a plant formation class within the tundra biome, consisting of low, mostly herbaceous plants, but with some very small stunted trees, associated with the tundra climate ⑫.

arctic zone latitude zone in the latitude range 60° to 75° N (more or less), centered about on the Arctic Circle, and lying between the subarctic zone and the polar zone.

arête sharp, knife-like divide or crest formed between two cirques by alpine glaciation.

argillic horizon soil horizon, usually the B horizon, in which clay minerals have accumulated by illuviation.

arid (dry climate subtype) subtype of the dry climates that is extremely dry and supports little or no vegetation cover.

Aridisols soil order consisting of soils of dry climates, with or without argillic horizons, and with accumulations of carbonates or soluble salts.

artesian well drilled well in which water rises under hydraulic pressure above the level of the surrounding water table and may reach the surface.

aspect compass orientation of a slope as an inclined element of the ground surface.

association plant-animal community type identified by the typical organisms that are likely to be found together.

asthenosphere soft layer of the upper mantle, beneath the rigid lithosphere.

astronomical hypothesis explanation for glaciations and interglaciations making use of cyclic variations in solar energy received by the Earth at higher latitudes.

Atlantic stage second climatic period within the Holocene epoch, somewhat warmer than today.

atmosphere envelope of gases surrounding the Earth, held by gravity.

atmospheric pressure pressure exerted by the atmosphere because of the force of gravity acting on the overlying column of air.

atoll circular or closed-loop coral reef enclosing an open lagoon with no island inside.

atomic mass number total number of protons and neutrons within the nucleus of an atom.

atomic number number of protons within the nucleus of an atom; determines element name and chemical properties of the atom.

autogenic succession form of ecological succession that is self-producing—that is, results from the actions of plants and animals themselves.

autumnal equinox September equinox in the northern hemisphere.

average deviation difference between a single value and the mean of all values, taken without respect to sign.

axial rift narrow, trench-like depression situated along the center line of the midoceanic ridge and identified with active seafloor spreading.

axis of rotation center line around which a body revolves, as the Earth's axis of rotation.

B

B horizon mineral soil horizon located beneath the A horizon, and usually characterized by a gain of mineral matter (such as clay minerals and oxides of aluminum and iron) and organic matter (humus).

backswamp area of low, swampy ground on the floodplain of an alluvial river between the natural levee and the bluffs.

backwash return flow of swash water under influence of gravity.

badlands rugged land surface of steep slopes, resembling miniature mountains, developed on weak clay formations or clay-rich regolith by fluvial erosion too rapid to permit plant growth and soil formation.

bar (marine or coastal) (See *sandbar.*)

bar (pressure) unit of pressure equal to 105 Pa (pascals); approximately equal to the pressure of the Earth's atmosphere at sea level.

barchan dune sand dune of crescentic base outline with a sharp crest and a steep lee slip face, with crescent points (horns) pointing downwind; also known as a crescent dune.

barometer instrument for measurement of atmospheric pressure.

barrier (to dispersal) a zone or region that a species is unable to colonize or perhaps even occupy for a short time, thus halting diffusion.

barrier island long narrow island, built largely of beach sand and dune sand, parallel with the mainland and separated from it by a lagoon.

barrier reef coral reef separated from mainland shoreline by a lagoon.

barrier-island coast coastline with broad zone of shallow water offshore (a lagoon) shut off from the ocean by a barrier island.

basalt extrusive igneous rock of gabbro composition; occurs as lava.

base flow that portion of the discharge of a stream contributed by ground water seepage.

base level lower limiting surface or level that can ultimately be attained by a stream under conditions of stability of the Earth's crust and sea level; an imaginary surface equivalent to sea level projected inland.

base status of soils quality of a soil as measured by the presence or absence of clay minerals capable of holding large numbers of bases. Soils of high base status are rich in base-holding clay minerals; soils of low base status are deficient in such minerals.

bases certain positively charged ions in the soil that are also plant nutrients; the most important are calcium, magnesium, potassium, and sodium.

batholith large, deep-seated body of intrusive igneous rock, usually with an area of surface exposure greater than 100 km^2 (40 mi^2).

bauxite mixture of several clay minerals, consisting largely of aluminum oxide and water with impurities; a principal ore of aluminum.

bay a body of water sheltered from strong wave action by the configuration of the coast.

beach thick, wedge-shaped accumulation of sand, gravel, or cobbles in the zone of breaking waves.

beach drift transport of sand on a beach parallel with a shoreline by a succession of landward and seaward water movements at times when swash approaches obliquely.

bearing direction angle between a line of interest and a reference line, which is usually a line pointing north.

bed load that portion of the stream load moving close to the streambed by rolling and sliding.

bedrock solid rock in place with respect to the surrounding and underlying rock and relatively unchanged by weathering processes.

bedrock slump landslide of bedrock in which most of the bedrock remains more or less intact as it moves.

bioclimatic frontier geographic boundary corresponding with a critical limiting level of climate stress beyond which a species cannot survive.

biodiversity the variety of biological life on Earth or within a region.

biogas mixture of methane and carbon dioxide generated by action of anaerobic bacteria in animal and human wastes enclosed in a digesting chamber.

biogeochemical cycle total system of pathways by which a particular type of matter (a given element, compound, or ion, for example) moves through the Earth's ecosystem or biosphere; also called a material cycle or nutrient cycle.

biogeographic region region in which the same or closely related plants and animals tend to be found together.

biogeography the study of the distributions of organisms at varying spatial and temporal scales, as well as the processes that produce these distribution patterns.

biomass dry weight of living organic matter in an ecosystem within a designated surface area; units are kilograms of organic matter per square meter.

biome largest recognizable subdivision of terrestrial ecosystems, including the total assemblage of plant and animal life interacting within the life layer.

biosphere all living organisms of the Earth and the environments with which they interact.

biota plants and animals, referred to collectively; a list of plants and animals found at a location or in a region.

bitumen combustible mixture of hydrocarbons that is highly viscous and will flow only when heated; considered a form of petroleum.

bituminous sand (See *bitumen.*)

blackbody ideal object or surface that is a perfect radiator and absorber of energy; absorbs all radiation it intercepts and emits radiation perfectly according to physical theory.

block mountains class of mountains produced by block faulting and usually bounded by normal faults.

block separation separation of individual joint blocks during the process of physical weathering.

blowout shallow depression produced by continued deflation.

bluffs steeply rising ground slopes marking the outer limits of a floodplain.

bog a shallow depression filled with organic matter, for example, a glacial lake or pond basin filled with peat.

Boralfs suborder of the soil order Alfisols; includes Alfisols of boreal forests or high mountains.

boreal forest variety of needleleaf forest found in the boreal forest climate ⑪ regions of North America and Eurasia.

boreal forest climate ⑪ cold climate of the subarctic zone in the northern hemisphere with long, extremely severe winters and several consecutive months of zero potential evapotranspiration (water need).

Boreal stage first climatic period within the Holocene epoch with boreal forest in midlatitude regions.

Borolls suborder of the soil order Mollisols; includes Mollisols of cold-winter semiarid plants (steppes) or high mountains.

braided stream stream with shallow channel in coarse alluvium carrying multiple threads of fast flow that subdivide and rejoin repeatedly and continually shift in position.

breaker sudden collapse of a steepened water wave as it approaches the shoreline.

broadleaf deciduous forest type consisting of broadleaf trees that shed their leaves in the cold or dry season. (See also *midlatitude deciduous forest.*)

broadleaf evergreen forest forest type consisting of broadleaf evergreen trees. (See also *low-latitude rainforest.*)

budget in flow systems, an accounting of energy and matter flows that enter, move within, and leave a system.

bush-fallow farming agricultural system practiced in the African savanna woodland in which trees are cut and burned to provide cultivation plots.

butte prominent, steep-sided hill or peak, often representing the final remnant of a resistant layer in a region of flat-lying strata.

C

C horizon soil horizon lying beneath the B horizon, consisting of sediment or regolith that is the parent material of the soil.

calcification accumulation of calcium carbonate in a soil, usually occurring in the B or C horizons.

calcite mineral having the composition calcium carbonate.

calcium carbonate compound consisting of calcium (Ca) and carbonate (CO_3) ions, formula $CaCO_3$, occurring naturally as the mineral calcite.

caldera large, steep-sided circular depression resulting from the explosion and subsidence of a stratovolcano.

calving shedding of ice into a water body by the terminus of a *glacier.*

Cambrian period Geologic period in which fossils first become abundant, from about 542–488 million years ago.

canyon (See *gorge.*)

capillary action process by which capillary tension draws water into a small opening, such as a soil pore or a rock joint.

capillary tension a cohesive force among surface molecules of a liquid that gives a droplet its rounded shape.

carbohydrate class of organic compounds consisting of the elements carbon, hydrogen, and oxygen.

carbon cycle biogeochemical cycle in which carbon moves through the biosphere; includes both gaseous cycles and sedimentary cycles.

carbon dioxide the chemical compound CO_2, formed of oxygen and carbon; normally a gas present in low concentration in the atmosphere; an important greenhouse gas.

carbon fixation (See *photosynthesis.*)

carbonates (carbonate minerals, carbonate rocks) minerals that are carbonate compounds of calcium or magnesium or both, that is, calcium carbonate or magnesium carbonate. (See also *calcite.*)

carbonic acid a weak acid created when CO_2 gas dissolves in water.

carbonic acid action chemical reaction of carbonic acid in rainwater, soil water, and ground water with minerals; most strongly affects carbonate minerals and rocks, such as limestone and marble; an activity of chemical weathering.

cartography the science and art of making maps.

Celsius scale temperature scale in which the freezing point of water is 0° and the boiling point is 100°, measured at sea level.

Cenozoic Era last (youngest) of the eras of geologic time.

channel (See *stream channel.*)

chaparral sclerophyll scrub and dwarf forest plant formation class found throughout the coastal mountain ranges and hills of central and Southern California.

chemical energy energy stored within an organic molecule and capable of being transformed into heat during metabolism.

chemical weathering chemical change in rock-forming minerals through exposure to atmospheric conditions in the presence of water; mainly involving oxidation, hydrolysis, carbonic acid action, or direct solution.

chemically precipitated sediment sediment consisting of mineral matter precipitated from a water solution in which the matter has been transported in the dissolved state as ions.

chert sedimentary rock composed largely of silicon dioxide and various impurities, in the form of nodules and layers, often occurring with limestone layers.

chinook wind a local wind occurring at certain times to the lee of the Rocky Mountains; a very dry wind with a high capacity to evaporate snow.

chlorofluorocarbons (CFCs) synthetic chemical compounds containing chlorine, fluorine, and carbon atoms that are widely used as coolant fluids in refrigeration systems.

choropleth map a map that identifies spatial information by categories.

cinder cone conical hill built of coarse tephra ejected from a narrow volcanic vent; a type of volcano.

circle of illumination great circle that divides the globe at all times into a sunlit hemisphere and a shadowed hemisphere.

circum-Pacific belt chains of andesite volcanoes making up mountain belts and island arcs surrounding the Pacific Ocean Basin.

cirque bowl-shaped depression carved in rock by glacial processes and holding the firn of the upper end of an alpine glacier.

cirrocumulus cloud type in which thin cloud patches are found in the upper troposphere.

cirrostratus cloud type in which thin, smooth layers of clouds are found in the upper troposphere.

cirrus cloud cloud composed of small ice crystals, typically found in upper troposphere.

clast rock or mineral fragment broken from a parent rock source.

clastic sediment sediment consisting of particles broken from a parent rock source.

clay sediment particles smaller than 0.004 mm in diameter.

clay minerals class of minerals produced by alteration of silicate minerals, having plastic properties when moist.

claystone sedimentary rock formed by lithification of clay and lacking fissile structure.

cliff sheer, near-vertical rock wall formed from flat-lying resistant layered rocks, usually sandstone, limestone, or lava flows; may refer to any near-vertical rock wall. (See also *marine cliff.*)

climate generalized statement of the prevailing weather conditions at a given place, based on statistics of a long period of record and including mean values, departures from those means, and the probabilities associated with those departures.

climatic frontier a geographical boundary that marks the limit of survival of a plant species subjected to climatic stress.

climatology the science that describes and explains the variability in space and time of the heat and moisture states of the Earth's surface, especially its land surfaces.

climax stable community of plants and animals reached at the end point of ecological succession.

climograph a graph on which two or more climatic variables, such as monthly mean temperature and monthly mean precipitation, are plotted for each month of the year.

cloud forest a type of low evergreen rainforest that occurs high on mountain slopes, where clouds and fog are frequent.

clouds dense concentrations of suspended water or ice particles in the diameter range 20 to 50 μm. (See also *cumuliform clouds, stratiform clouds.*)

coal rock consisting of hydrocarbon compounds, formed of compacted, lithified, and altered accumulations of plant remains (peat).

coarse textured (rock) having mineral crystals sufficiently large that they are at least visible to the naked eye or with low magnification.

coast (See *coastline.*)

coastal and marine geography the study of the geomorphic processes that shape shores and coastlines and their application to coastal development and marine resource utilization.

coastal blowout dune high sand dune of the parabolic dunes class formed adjacent to a beach, usually with a deep deflation hollow (blowout) enclosed within the dune ridge.

coastal foredunes belt of irregularly shaped sand dunes found landward of a sand beach.

coastal forest subtype of needleleaf evergreen forest found in the humid coastal zone of the northwestern United States and western Canada.

coastal plain coastal belt, emerged from beneath the sea as a former continental shelf, underlain by strata with gentle dip seaward.

coastline (coast) zone in which coastal processes operate or have a strong influence.

cognitive representation in the representation perspective of geography, mental mapping of spatial relationships as they are experienced by humans.

col natural pass or low notch in an arête between opposed cirques.

cold air outbreak tongue of cold polar air moving from the midlatitudes into the very low latitudes. (See also *northers, nortes, pamperos.*)

cold front moving weather front along which a cold air mass moves underneath a warm air mass, causing the latter to be lifted.

cold-blooded animal animal whose body temperature passively follows the temperature of the environment.

cold-core ring circular eddy of cold water, surrounded by warm water and lying adjacent to a warm, poleward-moving ocean current, such as the Gulf Stream. (See also *warm-core ring.*)

colloids particles of extremely small size, capable of remaining indefinitely in suspension in water. May be mineral or organic in nature.

colluvium deposit of sediment or rock particles accumulating from overland flow at the base of a slope and originating from higher slopes where sheet erosion is in progress. (See also *alluvium.*)

community an assemblage of organisms that live in a particular habitat and interact with one another.

competition form of interaction among plant or animal species in which both draw resources from the same pool.

component in flow systems, a part of the system, such as a pathway, connection, or flow of matter or energy.

composite volcano volcano composed of layers of ash and lava. (See also *stratovolcano.*)

compression (tectonic) squeezing together, as horizontal compression of crustal layers by tectonic processes.

condensation process of change of matter in the gaseous state (water vapor) to the liquid state (liquid water) or solid state (ice).

condensation nucleus a tiny bit of solid matter (aerosol) in the atmosphere on which water vapor condenses to form a tiny water droplet.

conditionally stable air air mass in which the environmental lapse rate is less than the dry adiabatic rate but greater than the moist adiabatic lapse rate.

conduction of heat transmission of sensible heat through matter by transfer of energy from one atom or molecule to the next in the direction of decreasing temperature.

cone of depression conical configuration of the lowered water table around a well from which water is being rapidly withdrawn.

conformal projection map projection that preserves without shearing the true shape or outline of any small surface feature of the Earth.

conglomerate a sedimentary rock composed of pebbles in a matrix of finer rock particles.

conic projections a group of map projections in which the geographic grid is transformed to lie on the surface of a developed cone.

consequent stream stream that takes its course down the slope of an initial landform, such as a newly emerged coastal plain or a volcano.

consumers animals in the food chain that live on organic matter formed by primary producers or by other consumers. (See also *primary consumers, secondary consumers.*)

consumption (of a lithospheric plate) destruction or disappearance of a subducting lithospheric plate in the asthenosphere, in part by melting of the upper surface, but largely by softening because of heating to the temperature of the surrounding mantle rock.

continental collision event in plate tectonics in which subduction brings two segments of the continental lithosphere into contact, leading to formation of a continental suture.

continental crust crust of the continents, of felsic composition in the upper part; thicker and less dense than oceanic crust.

continental drift hypothesis, introduced by Alfred Wegener and others early in the 1900s, of the breakup of a parent continent, Pangaea, starting near the close of the Mesozoic era, and resulting in the present arrangement of continental shields and intervening ocean-basin floors.

continental lithosphere lithosphere bearing continental crust of felsic igneous rock.

continental margins (1) topographic: one of three major divisions of the ocean basins, being the zones directly adjacent to the continent and including the continental shelf, continental slope, and continental rise. (2) tectonic: marginal belt of continental crust and lithosphere that is in contact with oceanic crust and lithosphere, with or without an active plate boundary being present at the contact. (See also *active continental margins, passive continental margins.*)

continental rise gently sloping seafloor lying at the foot of the continental slope and leading gradually into the abyssal plain.

continental rupture crustal spreading apart affecting the continental lithosphere, so as to cause a rift valley to appear and to widen, eventually creating a new belt of oceanic lithosphere.

continental scale scale of observation at which we recognize continents and other large Earth surface features, such as ocean currents.

continental shelf shallow, gently sloping belt of seafloor adjacent to the continental shoreline and terminating at its outer edge in the continental slope.

continental shields ancient crustal rock masses of the continents, largely igneous rock and metamorphic rock, and mostly of Precambrian age.

continental slope steeply descending belt of seafloor between the continental shelf and the continental rise.

continental suture long, narrow zone of crustal deformation, including underthrusting and intense folding, produced by a continental collision. Examples: Himalayan Range, European Alps.

continuous permafrost permafrost that underlies more than 90 percent of the surface area of a region.

convection (atmospheric) air motion consisting of strong updrafts taking place within a convection cell.

convection cell individual column of strong updrafts produced by atmospheric convection.

convection current in plate tectonics, a stream of upwelling mantle rock that rises steadily beneath a spreading plate boundary.

convection loop circuit of moving fluid, such as air or water, created by unequal heating of the fluid.

convective precipitation a form of precipitation induced when warm, moist air is heated at the ground surface, rises, cools, and condenses to form water droplets, raindrops, and eventually, rainfall.

convergence horizontal motion of air creating a net inflow; causes a rising motion when occurring at the surface or a sinking motion when occurring aloft.

converging boundary boundary between two crustal plates along which subduction is occurring and lithosphere is being consumed.

Coordinated Universal Time legal standard time, administered by the Bureau International de l'Heure, Paris.

coral reef rock-like accumulation of carbonates secreted by corals and algae in shallow water along a marine shoreline.

coral-reef coast coast built out by accumulations of limestone in coral reefs.

core of Earth spherical central mass of the Earth composed largely of iron and consisting of an outer liquid zone and an interior solid zone.

Coriolis effect effect of the Earth's rotation tending to turn the direction of motion of any object or fluid toward the right in the northern hemisphere and to the left in the southern hemisphere.

Coriolis force the Coriolis effect, treated as a force perpendicular to the direction of motion that increases with the speed of motion but decreases with latitude.

corrosion erosion of bedrock of a stream channel (or other rock surface) by chemical reactions between solutions in stream water and mineral surfaces.

cosmopolitan species species that are found very widely.

counterradiation longwave radiation of atmosphere directed downward to the Earth's surface.

covered shields areas of continental shields in which the ancient rocks are covered beneath a thin layer of sedimentary strata.

crater central summit depression associated with the principal vent of a volcano.

crescent dune (See *barchan dune.*)

crest in describing water waves, the highest point of the wave form.

crevasse gaping crack in the brittle surface ice of a glacier.

crude oil liquid fraction of petroleum.

crust of Earth outermost solid shell or layer of the Earth, composed largely of silicate minerals.

Cryaquepts great group within the soil suborder of Aquepts; includes Aquepts of cold-climate regions and particularly the tundra climate ⑫.

cryoturbation movement of mineral particles of any size by freezing and thawing of ice.

cuesta erosional landform developed on resistant strata having low to moderate dip and taking the form of an asymmetrical low ridge or hill belt with one side a steep slope and the other a gentle slope; usually associated with a coastal plain.

cultural energy energy in forms exclusive of solar energy of photosynthesis that is expended on the production of raw food or feed crops in agricultural ecosystems.

cumuliform clouds clouds of globular shape, often with extended vertical development.

cumulonimbus cloud large, dense cumuliform cloud yielding precipitation.

cumulus cloud type consisting of low-lying, white cloud masses of globular shape well separated from one another.

cutoff cutting-through of a narrow neck of land, so as to bypass the streamflow in an alluvial meander and cause it to be abandoned.

cycle in flow systems, a closed flow system of matter. Example: biogeochemical cycle.

cycle of rock change total cycle of changes in which rock of any one of the three major rock classes—igneous rock, sedimentary rock, metamorphic rock—is transformed into rock of one of the other classes.

cyclone center of low atmospheric pressure. (See also *tropical cyclone, wave cyclone.*)

cyclonic precipitation a form of precipitation that occurs as warm moist air is lifted by air motion occurring in a cyclone.

cyclonic storm intense weather disturbance within a moving cyclone generating strong winds, cloudiness, and precipitation.

cylindric projections group of map projections in which the geographic grid is transformed to lie on the surface of a developed cylinder.

D

data acquisition component component of a geographic information system in which data are gathered together for input to the system.

data management component component of a geographic information system that creates, stores, retrieves, and modifies data layers and spatial objects.

daughter product new isotope created by decay of an unstable isotope.

daylight that period of the day during which the Sun is above the horizon at a particular location.

daylight saving time time system under which time is advanced by one hour with respect to the standard time of the prevailing standard meridian.

debris flood (debris flow) stream-like flow of muddy water heavily charged with sediment of a wide range of size grades, including boulders, generated by sporadic torrential rains on steep mountain watersheds.

decalcification removal of calcium carbonate from a soil horizon as carbonic acid reacts with carbonate mineral matter.

December solstice solstice occurring on December 21 or 22, when the subsolar point is at 23½° S.

deciduous plant tree or shrub that sheds its leaves seasonally.

declination of Sun latitude at which the Sun is directly overhead; varies from –23½° (23½° S lat.) to +23½° N lat.

décollement detachment and extensive sliding of a rock layer, usually sedimentary, over a near-horizontal basal rock surface; a special form of low-angle thrust faulting.

decomposers organisms that feed on dead organisms from all levels of the food chain; most are microorganisms and bacteria that feed on decaying organic matter.

deep-sea cone a fan-shaped accumulation of undersea sediment on the continental rise produced by sediment-rich currents flowing down the continental slope.

deficit (soil-water shortage) in the soil-water budget, the difference between water use and water need; the quantity of irrigation water required to achieve maximum growth of agricultural crops.

deflation lifting and transport in turbulent suspension by wind of loose particles of soil or regolith from dry ground surfaces.

deglaciation widespread recession of ice sheets during a period of warming global climate, leading to an interglaciation. (See also *glaciation, interglaciation.*)

degradation lowering or downcutting of a stream channel by stream erosion in alluvium or bedrock.

degree of arc measurement of the angle associated with an arc, in degrees.

delta sediment deposit built by a stream entering a body of standing water and formed of the stream load.

delta coast coast bordered by a delta.

delta kame flat-topped hill of stratified drift representing a glacial delta constructed adjacent to an ice sheet in a marginal glacial lake.

dendritic drainage pattern drainage pattern of tree-like branched form, in which the smaller streams take a wide variety of directions and show no parallelism or dominant trend.

denitrification biochemical process in which nitrogen in forms usable to plants is converted into molecular nitrogen in the gaseous form and returned to the atmosphere—a process that is part of the nitrogen cycle.

density of matter quantity of mass per unit of volume, stated in kg/m^3.

denudation total action of all processes whereby the exposed rocks of the continents are worn down and the resulting sediments are transported to the sea by the fluid agents; also includes weathering and mass wasting.

deposition (atmosphere) the change of state of a substance from a gas (water vapor) to a solid (ice); in the science of meteorology, the term sublimation is used to describe both this process and the change of state from solid to vapor. (See also *sublimation.*)

deposition (of sediment) (See *stream deposition.*)

depositional landforms landforms made by deposition of sediment.

desert biome biome of the dry climates consisting of thinly dispersed plants that may be shrubs, grasses, or perennial herbs, but lacking in trees.

desert pavement surface layer of closely fitted pebbles or coarse sand from which finer particles have been removed.

desertification (See *land degradation.*)

detritus decaying organic matter on which decomposers feed.

dew point (See *dew-point temperature.*)

dew-point lapse rate rate at which the dew point of an air mass decreases with elevation; typical value is 1.8°C/1000 m (1.0°F/1000 ft).

dew-point temperature temperature of an air mass at which the air holds its full capacity of water vapor.

diagnostic horizons soil horizons, rigorously defined, that are used as diagnostic criteria in classifying soils.

differential GPS method of application of GPS that reduces position error by using two receivers simultaneously.

diffuse radiation solar radiation that has been scattered (deflected or reflected) by minute dust particles or cloud particles in the atmosphere.

diffuse reflection solar radiation scattered back to space by the Earth's atmosphere.

diffusion in biogeography, the slow extension of the range of a species by normal processes of dispersal.

digital image numeric representation of a picture consisting of a collection of numeric brightness values (pixels) arrayed in a fine grid pattern.

dike thin layer of intrusive igneous rock, often near-vertical or with steep dip, occupying a widened fracture in the surrounding rock and typically cutting across older rock planes.

diorite intrusive igneous rock consisting dominantly of plagioclase feldspar and pyroxene; a felsic igneous rock.

dip acute angle between an inclined natural rock plane or surface and an imaginary horizontal plane of reference; always measured perpendicular to the strike. Also a verb, meaning to incline toward.

diploid having two sets of chromosomes, one from each parent organism.

discharge volume of flow moving through a given cross section of a stream in a given unit of time; commonly given in m^3/s (ft^3/s).

discontinuous permafrost permafrost that underlies from 10 to 90 percent of the surface of a region.

disjunction geographic distribution pattern of species in which one or more closely related species are found in widely separated regions.

dispersal in biogeography, the capacity of a species to move from a location of birth or origin to new sites.

dissipating stage stage of air-mass thunderstorm development in which strong downdrafts throughout the air column inhibit the convection and latent heat release needed to sustain the thunderstorm.

distributary branching stream channel that crosses a delta to discharge into open water.

diurnal adjective meaning "daily."

divergence horizontal motion of air creating a net outflow; causes a rising motion from below when occurring aloft.

doldrums belt of calms and variable winds occurring at times along the equatorial trough.

dolomite carbonate mineral or sedimentary rock having the composition calcium magnesium carbonate.

dome (See *sedimentary dome.*)

drainage basin total land surface occupied by a drainage system, bounded by a drainage divide.

drainage divide imaginary line following a crest of high land such that overland flow on opposite sides of the line enters different streams.

drainage pattern the plan of a network of interconnected stream channels.

drainage system a branched network of stream channels and adjacent land slopes, bounded by a drainage divide and converging to a single channel at the outlet.

drainage winds winds, usually cold, that flow from higher to lower regions under the direct influence of gravity.

drawdown (of a well) difference in height between base of cone of depression and original water table surface.

drought occurrence of substantially lower-than-average precipitation in a season that normally has ample precipitation for the support of food-producing plants.

drumlin hill of glacial till, oval or elliptical in basal outline and with smoothly rounded summit, formed by plastering of till beneath moving, debris-laden glacial ice.

dry adiabatic lapse rate rate at which rising air is cooled by expansion when no condensation is occurring; 10°C per 1000 m (5.5°F per 1000 ft).

dry desert plant formation class in the desert biome consisting of widely dispersed xerophytic plants that may be small, hard-leaved or spiny shrubs, succulent plants (cacti), or hard grasses.

dry lake shallow basin covered with salt deposits formed when stream input to the basin is subjected to severe evaporation; may also form by evaporation of a saline lake when climate changes. (See also *salt flat.*)

dry line boundary separating hot, dry air from warm, moist air along which thunderstorms tend to form.

dry midlatitude climate ⑨ dry climate of the midlatitude zone with a strong annual cycle of potential evapotranspiration (water need) and cold winters.

dry subtropical climate ⑤ dry climate of the subtropical zone, transitional between the dry tropical climate ④ and the dry midlatitude climate ⑨.

dry tropical climate ④ climate of the tropical zone with large total annual potential evapotranspiration (water need).

dune (See *sand dune.*)

dust bowl western Great Plains of the United States, which suffered severe wind deflation and soil drifting during the drought years of the middle 1930s.

dust storm heavy concentration of dust in a turbulent air mass, often associated with a cold front.

E

E horizon soil mineral horizon lying below the A horizon and characterized by the loss of clay minerals and oxides of iron and aluminum; it may show a concentration of quartz grains and is often pale in color.

Earth's crust (See *crust of Earth.*)

earth hummock low mound of vegetation-covered earth found in permafrost terrain, formed by cycles of ground ice growth and melting. (See also *mud hummock.*)

Earth visualization tool web-based system for displaying images and spatial information about the Earth's surface; example: Google Earth.

earthflow moderately rapid downhill flowage of masses of water-saturated soil, regolith, or weak shale, typically forming a step-like terrace at the top and a bulging toe at the base.

earthquake a trembling or shaking of the ground produced by the passage of seismic waves.

earthquake focus point within the Earth at which the energy of an earthquake is first released by rupture and from which seismic waves emanate.

easterly wave weak, slowly moving trough of low pressure within the belt of tropical easterlies; causes a weather disturbance with rain showers.

ebb current oceanward flow of tidal current in a bay or tidal stream.

ecological biogeography branch of biogeography focusing on how distribution patterns of organisms are related to their environment.

ecological niche functional role played by an organism in an ecosystem; how it obtains energy and how it influences other organisms and its environment.

ecological succession time-succession (sequence) of distinctive plant and animal communities occurring within a given area of newly formed land or land cleared of plant cover by burning, clearcutting, or other agents.

ecology science of interactions between life-forms and their environment; the science of ecosystems.

ecosystem group of organisms and the environment with which the organisms interact.

edaphic factors factors relating to soil that influence a terrestrial ecosystem.

El Niño episodic cessation of the typical upwelling of cold deep water off the coast of Peru; literally, "The Christ Child," for its occurrence in the Christmas season once every few years.

electromagnetic radiation (electromagnetic energy) wave-like form of energy radiated by any substance possessing heat; it travels through space at the speed of light.

electromagnetic spectrum the total wavelength range of electromagnetic energy.

eluviation soil-forming process consisting of the downward transport of fine particles, particularly soil colloids (both mineral and organic), carrying them out of an upper soil horizon.

emergence exposure of submarine landforms by a lowering of sea level or a rise of the crust, or both.

emissivity ratio of the actual energy emitted by an object or substance to that of a blackbody at the same temperature.

endemic species a species found only in one region or location.

endogenic processes internal Earth processes that create landforms, such as tectonics and volcanism.

energy the capacity to do work, that is, to bring about a change in the state or motion of matter.

energy balance (global) balance between shortwave solar radiation received by the Earth-atmosphere system and radiation lost to space by shortwave reflection and longwave radiation from the Earth-atmosphere system.

energy balance (of a surface) balance between the flows of energy reaching a surface and the flows of energy leaving it.

energy flow system open system that receives an input of energy, undergoes internal energy flow, energy transformation, and energy storage, and has an energy output.

enhanced Fujita intensity scale a measure of tornado intensity, based on damage to structures and surrounding vegetation, introduced in 2007 as an improvement to the original Fujita intensity scale.

Entisols soil order consisting of mineral soils lacking soil horizons that would persist after normal plowing.

entrenched meanders winding, sinuous valley produced by degradation of a stream with trenching into the bedrock by downcutting.

environmental temperature lapse rate rate of temperature decrease upward through the troposphere; standard value is 6.4 °C/km (3°F/1000 ft).

eolian landforms landforms, such as dunes or loess deposits, formed by wind transport of sediment.

eon largest unit of geologic time, including hundreds of millions of years; subdivided into eras.

epipedon soil horizon that forms at the surface.

epiphytes plants that live above ground level out of contact with the soil, usually growing on the limbs of trees or shrubs; also called air plants.

epoch a unit of geologic time; units to tens of millions of years in length; a subdivision of the period time unit.

equal-area projections class of map projections on which any given area of the Earth's surface is shown to correct relative areal extent, regardless of position on the globe.

Equator parallel of latitude occupying a position midway between the Earth's poles of rotation; the largest of the parallels, designated as latitude 0°.

equatorial current westward-flowing ocean current in the belt of the trade winds.

equatorial easterlies upper-level easterly airflow over the equatorial zone.

equatorial rainforest plant formation class within the forest biome, consisting of tall, closely set broadleaf trees of evergreen or semideciduous habit.

equatorial trough atmospheric low-pressure trough centered more or less over the Equator and situated between the two belts of trade winds.

equatorial zone latitude zone lying between lat. 10° S and 10° N (more or less) and centered on the Equator.

equilibrium in flow systems, a state of balance in which flow rates remain unchanged.

equinox instant in time when the subsolar point falls on the Earth's Equator and the circle of illumination passes through both poles.

era major unit of geologic time tens or hundreds of millions of years in length; subdivided into periods.

erg large expanse of active sand dunes in the Sahara Desert of North Africa.

erosional landforms class of the sequential landforms shaped by the removal of regolith or bedrock by agents of erosion. Examples: gorge, glacial cirque, marine cliff.

esker narrow, often sinuous embankment of coarse gravel and boulders deposited in the bed of a meltwater stream enclosed in a tunnel within stagnant ice of an ice sheet.

estuary bay that receives fresh water from a river mouth and salt water from the ocean.

Eurasian-Indonesian belt mountain arc system extending from southern Europe across southern Asia and Indonesia.

eustatic referring to a true change in sea level, as opposed to a local change created by upward or downward tectonic motion of land.

eutrophication excessive growth of algae and other related organisms in a stream or lake as a result of the input of large amounts of nutrient ions, especially phosphate and nitrate.

evaporation process in which water in liquid state or solid state passes into the vapor state.

evaporites class of chemically precipitated sediment and sedimentary rock composed of soluble salts deposited from saltwater bodies.

evapotranspiration combined water loss to the atmosphere by evaporation from the soil and transpiration from plants.

evergreen plant tree or shrub that holds most of its green leaves or needles throughout the year.

evolution the creation of the diversity of life-forms through the process of natural selection.

exfoliation process of removal of overlying rock load from bedrock by processes of denudation, accompanied by expansion and often leading to the development of sheeting structure.

exfoliation dome smoothly rounded rock knob or hilltop bearing rock sheets or shells produced by spontaneous expansion accompanying unloading.

exogenic processes landform-making processes that are active at the Earth's surface, such as erosion by water, waves and currents, glacial ice, and wind.

exotic river stream that flows across a region of dry climate and derives its discharge from adjacent uplands where a water surplus exists.

exponential growth increase in number or value over time in which the increase is a constant proportion or percentage within each time unit.

exposed shields areas of continental shields in which the ancient basement rock, usually of Precambrian age, is exposed to the surface.

extension (tectonic) drawing apart of crustal layers by tectonic activity resulting in faulting.

extinction the event that the number of organisms of a species shrinks to zero so that the species no longer exists.

extratropical cyclone (See *midlatitude cyclone*.)

extrusion release of molten rock magma at the surface, as in a flow of lava or shower of volcanic ash.

extrusive igneous rock rock produced by the solidification of lava or ejected fragments of igneous rock (tephra).

F

Fahrenheit scale temperature scale in which the freezing point of water is 32° and the boiling point is 212°.

fair-weather system a traveling anticyclone in which the descent of air suppresses clouds and precipitation and the weather is typically fair.

fallout gravity fall of atmospheric particles of particulates reaching the ground.

fault sharp break in rock with a displacement (slippage) of the block on one side with respect to an adjacent block. (See also *normal fault, overthrust fault, strike-slip fault, transform fault.*)

fault coast coast formed when a shoreline comes to rest against a fault scarp.

fault creep more or less continuous slippage on a fault plane, relieving some of the accumulated strain.

fault plane surface of slippage between two Earth blocks moving relative to each other during faulting.

fault scarp cliff-like surface feature produced by faulting and exposing the fault plane; commonly associated with a normal fault.

fault-line scarp erosion scarp developed on an inactive fault line.

feedback in flow systems, a linkage between flow paths such that the flow in one pathway acts either to reduce or increase the flow in another pathway.

feldspar group of silicate minerals consisting of silicate of aluminum and one or more of the metals potassium, sodium, or calcium. (See also *plagioclase feldspar, potash feldspar.*)

felsenmeer expanse of large blocks of rock produced by joint block separation and shattering by frost action at high altitudes or in high latitudes; from the German for "rock sea."

felsic igneous rock igneous rock dominantly composed of felsic minerals.

felsic minerals (felsic mineral group) quartz and feldspars treated as a mineral group of light color and relatively low density. (See also *mafic minerals.*)

fetch distance that wind blows over water to create a train of water waves.

fine textured (rock) having mineral crystals too small to be seen by eye or with low magnification.

fiord narrow, deep ocean embayment partially filling a glacial trough.

fiord coast deeply embayed, rugged coast formed by partial submergence of glacial troughs.

firn granular old snow forming a surface layer in the zone of accumulation of a glacier.

fissile adjective describing a rock, usually shale, that readily splits up into small flakes or scales.

flash flood flood in which heavy rainfall causes a stream or river to rise very rapidly.

flocculation the clotting together of colloidal mineral particles to form larger particles; it occurs when a colloidal suspension in fresh water mixes with sea water.

flood streamflow at a stream stage so high that it cannot be accommodated within the stream channel and must spread over the banks to inundate the adjacent floodplain.

flood basalts large-scale outpourings of basalt lava to produce thick accumulations of basalt over large areas.

flood current landward flow of a tidal current.

flood stage designated stream-surface level for a particular point on a stream, above which overbank flooding occurs.

floodplain belt of low, flat ground, present on one or both sides of a stream channel, subject to inundation by a flood about once annually and underlain by alluvium.

flow system a physical system in which matter, energy, or both move through time from one location to another.

fluid substance that flows readily when subjected to unbalanced stresses; may exist as a gas or a liquid.

fluid agents fluids that erode, transport, and deposit mineral matter and organic matter; they are running water, waves and currents, glacial ice, and wind.

fluvial landforms landforms shaped by running water.

fluvial processes geomorphic processes in which running water is the dominant fluid agent, acting as overland flow and streamflow.

focus (See *earthquake focus.*)

fog cloud layer in contact with land or sea surface, or very close to that surface. (See also *advection fog, radiation fog.*)

folding process by which folds are produced; a form of tectonic activity.

folds wave-like corrugations of strata (or other layered rock masses) as a result of crustal compression.

food web (food chain) organization of an ecosystem into steps or levels through which energy flows as the organisms at each level consume energy stored in the bodies of organisms of the next lower level.

forb broad-leaved herb, as distinguished from the grasses.

forearc trough in plate tectonics, a shallow trough between a tectonic arc and a continent; accumulates sediment in a basin-like structure.

foredunes ridge of irregular sand dunes typically found adjacent to beaches on low-lying coasts and bearing a partial cover of plants.

foreland folds folds produced by continental collision in strata of a passive continental margin.

forest assemblage of trees growing close together, their crowns forming a layer of foliage that largely shades the ground.

forest biome biome that includes all regions of forest over the lands of the Earth.

formation classes subdivisions within a biome based on the size, shape, and structure of the plants that dominate the vegetation.

fossil fuels naturally occurring hydrocarbon compounds that represent the altered remains of organic materials enclosed in rock; examples are coal, petroleum (crude oil), and natural gas.

fractional scale (See *scale fraction.*)

freezing change from liquid state to solid state accompanied by release of latent heat, becoming sensible heat.

freezing front location at which freezing is occurring in the active layer of permafrost during the annual freeze-over; fronts may move downward from the top or upward from the bottom.

fringing reef coral reef directly attached to land with no intervening lagoon of open water.

front surface of contact between two unlike air masses. (See also *cold front, occluded front, polar front, warm front.*)

frost action rock breakup by forces accompanying the freezing of water.

Fujita intensity scale scale used to rate the intensity of a tornado by examining the damage caused to different types of structures.

G

gabbro intrusive igneous rock consisting largely of pyroxene and plagioclase feldspar, with variable amounts of olivine; a mafic igneous rock.

gamma radiation high-energy electromagnetic radiation of wavelength shorter than 0.005 nm; can be hazardous to health.

gas (gaseous state) fluid of very low density (as compared with a liquid of the same chemical composition) that expands to fill uniformly any small container and is readily compressed.

gaseous cycle type of biogeochemical cycle in which an element or compound is converted into gaseous form, diffuses through the atmosphere, and passes rapidly over land or sea where it is reused in the biosphere.

Gelisols soil order of cold regions, including soils underlain by permafrost with organic and mineral materials churned by frost action.

gene flow speciation process in which evolving populations exchange alleles as individuals move among populations.

geoid shape of the Earth's surface coinciding with mean sea level at any point.

genetic drift speciation process in which chance mutations change the genetic composition of a breeding population until it diverges from other populations.

genotype the gene set of an individual organism or species.

genus a collection of closely related species that share a similar genetic evolutionary history.

geographic cycle cycle of stages of landscape evolution from rugged peaks to a flat lowland; described by geographer W. M. Davis. (See also *mature stage, old age, rejuvenation, youthful stage.*)

geographic grid complete network of parallels and meridians on the surface of the globe, used to fix the locations of surface points.

geographic information system (GIS) a system for acquiring, processing, storing, querying, creating, and displaying spatial data; in the representation perspective of geography, the use of GISs to represent and manipulate spatial data.

geographic isolation speciation process in which a breeding population is split into parts by an emerging geographic barrier, such as an uplifting mountain range or a changing climate.

geography the study of the evolving character and organization of the Earth's surface.

geography of soils the study of the distribution of soil types and properties and the processes of soil formation.

geologic norm stable natural condition in a moist climate in which slow soil erosion is paced by maintenance of soil horizons bearing a plant community in an equilibrium state.

geology science of the solid Earth, including the Earth's origin and history, materials comprising the Earth, and the processes acting within the Earth and on its surface.

geomorphic factors landform factors influencing ecosystems, such as slope steepness, slope aspect, and relief.

geomorphology science of Earth surface processes and landforms, including their history and processes of origin.

geostationary orbit satellite orbit in which the satellite remains nearly fixed in space above a single point on the Equator, maintaining a constant view of the same portion of the Earth.

geostrophic wind wind at high levels above the Earth's surface blowing parallel with a system of straight, parallel isobars.

geyser periodic jet-like emission of hot water and steam from a narrow vent at a geothermal locality.

glacial abrasion abrasion by a moving glacier of the bedrock floor beneath it.

glacial delta delta built by meltwater streams of a glacier into standing water of a marginal glacial lake.

glacial drift general term for all varieties and forms of rock debris deposited in close association with ice sheets of the Pleistocene epoch.

glacial plucking removal of masses of bedrock from beneath an alpine glacier or ice sheets as ice moves forward suddenly.

glacial trough deep, steep-sided rock trench of U-shaped cross section formed by alpine glacier erosion.

glaciation (1) general term for the total process of glacier growth and landform modification by glaciers. (2) single episode or time period in which ice sheets formed, spread, and disappeared.

glacier large natural accumulation of land ice affected by present or past flowage. (See also *alpine glacier*.)

Global Positioning System (GPS) system of satellites and ground instruments that locates the global position of an observer.

global radiation balance the energy flow process by which the Earth absorbs shortwave solar radiation and emits longwave radiation; in the long run, the two flows must balance.

global scale scale at which we are concerned with the Earth as a whole, for example, in considering Earth–Sun relationships.

glowing avalanche cloud of white-hot gas and fine ash released by a volcanic eruption. Also termed glowing cloud.

gneiss variety of metamorphic rock showing banding and commonly rich in quartz and feldspar.

GOES Geostationary Operational Environmental Satellites, a series of Earth-imaging satellites used to monitor atmospheric and surface conditions primarily for weather forecasting.

Gondwana a supercontinent of the Permian period including much of the regions that are now South America, Africa, Antarctica, Australia, New Zealand, Madagascar, and peninsular India.

Goode projection an equal-area map projection, often used to display areal thematic information, such as climate or soil type.

gorge (canyon) steep-sided bedrock valley with a narrow floor limited to the width of a stream channel.

graben trench-like depression representing the surface of a crustal block dropped down between two opposed, inward-facing normal faults. (See also *rift valley*.)

graded profile smoothly descending profile displayed by a graded stream.

graded stream stream (or stream channel) with stream gradient so adjusted as to achieve a balanced state in which average bed load transport is matched to average bed load input; an average condition over periods of many years' duration.

gradient degree of slope, as the gradient of a river or a flowing glacier.

granite intrusive igneous rock consisting largely of quartz, potash feldspar, and plagioclase feldspar, with minor amounts of biotite and hornblende; a felsic igneous rock.

granitic rock general term for rock of the upper layer of the continental crust, composed largely of felsic igneous and metamorphic rock; rock of composition similar to that of granite.

granular disintegration grain-by-grain breakup of the outer surface of coarse-grained rock, yielding sand and gravel and leaving behind rounded boulders.

graphic scale map scale as shown by a line divided into equal parts.

grassland biome biome consisting largely or entirely of herbs, which may include grasses, grass-like plants, and forbs.

graupel suspended ice pellets formed when supercooled water drops freeze around a central ice crystal.

gravel rock particles larger than 2 mm in size.

gravitation mutual attraction between any two masses.

gravity gravitational attraction of the Earth on any small mass near the Earth's surface. (See also *gravitation*.)

gravity gliding the sliding of a thrust sheet away from the center of an orogen under the force of gravity.

great circle circle formed by passing a plane through the exact center of a perfect sphere; the largest circle that can be drawn on the surface of a sphere.

greenhouse effect accumulation of heat in the lower atmosphere through the absorption of longwave radiation from the Earth's surface.

greenhouse gases atmospheric gases such as CO_2, CH_4, N_2O, and chlorofluorocarbons (CFCs) that absorb outgoing longwave radiation, contributing to the greenhouse effect.

Greenwich meridian meridian passing through the old Royal Observatory at Greenwich, England; taken as 0° longitude. (See also *prime meridian*.)

groin wall or embankment built out into the water at right angles to the shoreline.

gross photosynthesis total amount of carbohydrate produced by photosynthesis by a given organism or group of organisms in a given unit of time.

ground ice frozen water within the pores of soils and regolith or as free bodies or lenses of solid ice.

ground moraine moraine formed of till distributed beneath a large expanse of land surface covered at one time by an ice sheet.

ground water subsurface water occupying the saturated zone and moving under the force of gravity.

growth rate (of a population) rate at which a population grows or shrinks with time; usually expressed as a percent or proportion of increase or decrease in a given unit of time.

gullies deep, V-shaped trenches carved by newly formed streams in rapid headward growth during advanced stages of accelerated soil erosion.

gust front downdraft spreading outwards in front of a severe thunderstorm, creating strong wind gusts. (See also *roll cloud*.)

guyot sunken remnant of a volcanic island.

gyres large circular ocean current systems centered on the oceanic subtropical high-pressure cells.

H

habitat subdivision of the environment according to the needs and preferences of organisms or groups of organisms.

Hadley cell atmospheric circulation cell in low latitudes involving rising air over the equatorial trough and sinking air over the subtropical high-pressure belts.

hail form of precipitation consisting of pellets or spheres of ice with a concentric layered structure.

hairpin dune type of parabolic dune with long, parallel sides.

half-life time required for an initial quantity at time-zero to be reduced by one-half in an exponential decay system.

hanging valley stream valley truncated by glacial erosion at its intersection with a larger valley filled with ice.

hazards assessment a field of study blending physical and human geography to focus on the perception of risk of natural hazards and on developing public policy to mitigate that risk.

haze minor concentration of pollutants or natural forms of aerosols in the atmosphere causing a reduction in visibility.

heat (See *latent heat, sensible heat*.)

heat index measure of apparent temperature based on actual air temperature and relative humidity, designed to account for inability to remove heat through perspiration.

heat island persistent region of higher air temperatures centered over a city.

hemisphere half of a sphere; that portion of the Earth's surface found between the Equator and a pole.

herb tender plant, lacking woody stems, usually small or low; may be annual or perennial.

herbivory form of interaction among species in which an animal (herbivore) grazes on herbaceous plants.

heterosphere region of the atmosphere above about 100 km in which gas molecules tend to become increasingly sorted into layers by molecular weight and electric charge.

hibernation dormant state of some vertebrate animals during the winter season.

high base status (See *base status of soils*.)

high-latitude climates group of climates in the subarctic zone, arctic zone, and polar zone, dominated by arctic air masses and polar air masses.

high-level temperature inversion condition in which a high-level layer of warm air overlies a layer of cooler air, reversing the normal trend of cooling with altitude.

high-pressure cell center of high barometric pressure; an anticyclone.

historical biogeography branch of biogeography focusing on how spatial patterns of organisms arise over space and through time.

Histosols soil order consisting of soils with a thick upper layer of organic matter.

hogbacks sharp-crested, often sawtooth ridges formed of the upturned edge of a resistant rock layer of sandstone, limestone, or lava.

Holocene epoch last epoch of geologic time, commencing about 10,000 years ago; it followed the Pleistocene epoch and includes the present.

homosphere the lower portion of the atmosphere, below about 100 km altitude, in which atmospheric gases are uniformly mixed.

horn sharp peak in glaciated landscape formed by glacial erosion of intersection cirques.

horse latitudes subtropical high-pressure belt of the North Atlantic Ocean, coincident with the central region of the Azores high; a belt of weak, variable winds and frequent calms.

horst crustal block uplifted between two normal faults.

hot springs springs discharging heated ground water at a temperature close to the boiling point; found in geothermal areas and thought to be related to a magma body at depth.

hotspot (biogeography) geographic region of high biodiversity.

hotspot (plate tectonics) center of intrusive igneous and volcanic activity thought to be located over a rising mantle plume.

human geography the part of systematic geography that deals with social, economic and behavioral processes that differentiate places.

human habitat the lands of the Earth that support human life.

human-influenced vegetation vegetation that has been influenced in some way by human activity, for example, through cultivation, grazing, timber cutting, or urbanization.

humidity general term for the amount of water vapor present in the air. (See also *relative humidity, specific humidity*.)

humification pedogenic process of transformation of plant tissues into humus.

humus dark brown to black organic matter on or in the soil, consisting of fragmented plant tissues partly digested by organisms.

hurricane tropical cyclone of the western North Atlantic and Caribbean Sea.

hydraulic action stream erosion by impact force of the flowing water on the bed and banks of the stream channel.

hydrograph graphic presentation of the variation in stream discharge with elapsed time, based on data of stream gauging at a given station on a stream.

hydrologic cycle total plan of movement, exchange, and storage of the Earth's free water in gaseous state, liquid state, and solid state.

hydrology science of the Earth's water and its motions through the hydrologic cycle.

hydrolysis chemical union of water molecules with minerals to form different, more stable mineral compounds.

hydrosphere total water realm of the Earth's surface zone, including the oceans, surface waters of the lands, ground water, and water held in the atmosphere.

hygrometer instrument that measures the water vapor content of the atmosphere; some types measure relative humidity directly.

I

ice age span of geologic time, usually on the order of one to three million years, or longer, in which glaciations alternate with interglaciations repeatedly in rhythm with cyclic global climate changes. (See also *glaciation, interglaciation*.)

Ice Age (Late-Cenozoic Ice Age) the present ice age, which began in late Pliocene time, perhaps 2.5 to 3 million years ago.

ice floe a sheet of floating ice.

ice lens more or less horizontal layer of segregated ice formed by capillary movement of soil water toward a freezing front.

ice lobes (glacial lobes) broad tongue-like extensions of an ice sheet resulting from more rapid ice motion where terrain was more favorable.

ice sheet large thick plate of glacial ice moving outward in all directions from a central region of accumulation.

ice sheet climate ⑬ severely cold climate, found on the Greenland and Antarctic ice sheets, with potential evapotranspiration (water need) effectively zero throughout the year.

ice shelf thick plate of floating glacial ice attached to an ice sheet and fed by the ice sheet and by snow accumulation.

ice storm occurrence of heavy glaze of ice on solid surfaces.

ice stream tongue of rapidly flowing ice within a continental ice sheet.

ice wedge vertical, wall-like body of ground ice, often tapering downward, occupying a shrinkage crack in silt of permafrost areas.

ice-wedge polygons polygonal networks of ice wedges.

iceberg mass of glacial ice floating in the ocean, derived from a glacier that extends into tidal water.

igneous rock rock solidified from a high-temperature molten state; rock formed by cooling of magma. (See also *extrusive igneous rock, felsic igneous rock, intrusive igneous rock, mafic igneous rock, ultramafic igneous rock.*)

illuviation accumulation in a lower soil horizon (typically, the B horizon) of materials brought down from a higher horizon; a soil-forming process.

image processing mathematical manipulation of digital images, for example, to enhance contrast or edges.

Inceptisols soil order consisting of soils having weakly developed soil horizons and containing weatherable minerals.

induced deflation loss of soil by wind erosion that is triggered by human activity such as cultivation or overgrazing.

induced mass wasting mass wasting that is induced by human activity, such as creation of waste soil and rock piles or undercutting of slopes in construction.

infiltration absorption and downward movement of precipitation into the soil and regolith.

infrared imagery images formed by infrared radiation emanating from the ground surface as recorded by a remote sensor.

infrared radiation electromagnetic energy in the wavelength range of 0.7 to about 200 μm.

initial landforms landforms produced directly by internal Earth processes of volcanism and tectonic activity. Examples: volcano, fault scarp.

inner lowland on a coastal plain, a shallow valley lying between the first cuesta and the area of older rock (oldland).

input flow of matter or energy into a system.

insolation interception of solar energy (shortwave radiation) by an exposed surface.

inspiral horizontal inward spiral or motion, such as that found in a cyclone.

interglaciation within an ice age, a time interval of mild global climate in which continental ice sheets were largely absent or were limited to the Greenland and Antarctic ice sheets; the interval between two glaciations. (See also *deglaciation, glaciation.*)

interlobate moraine moraine formed between two adjacent lobes of an ice sheet.

International Date Line the 180° meridian of longitude, together with deviations east and west of that meridian, forming the time boundary between adjacent standard time zones that are 12 hours fast and 12 hours slow with respect to Greenwich standard time.

interrupted projection projection subdivided into a number of sectors (gores), each of which is centered on a different central meridian.

intertropical convergence zone (ITCZ) zone of convergence of air masses of tropical easterlies (trade winds) along the axis of the equatorial trough.

intrusion body of igneous rock injected as magma into preexisting crustal rock; example: dike or sill.

intrusive igneous rock igneous rock body produced by solidification of magma beneath the surface, surrounded by preexisting rock.

inversion (See *temperature inversion.*)

ion atom or group of atoms bearing an electrical charge as the result of a gain or loss of one or more electrons.

island arcs curved lines of volcanic islands associated with active subduction zones along the boundaries of lithospheric plates.

isobars lines on map passing through all points having the same atmospheric pressure.

isohyet line on a map drawn through all points having the same numerical value of precipitation.

isopleth line on a map or globe drawn through all points having the same value of a selected property or entity.

isostasy principle describing the flotation of the lithosphere, which is less dense, on the plastic asthenosphere, which is more dense.

isostatic compensation crustal rise or sinking in response to unloading by denudation or loading by sediment deposition, following the principle of isostasy.

isostatic rebound local crustal rise after the melting of ice sheets, following the principle of isostasy.

isotherm line on a map drawn through all points having the same air temperature.

isotope form of an element with a unique atomic mass number.

J

jet streak localized region of very high winds embedded within a jet stream.

jet stream high-speed airflow in narrow bands within the upper-air westerlies and along certain other global latitude zones at high levels.

jet stream disturbance broad, wave-like undulation in the jet stream. (See also *Rossby waves.*)

joint block separation (See *block separation.*)

joints fractures within bedrock, usually occurring in parallel and intersecting sets of planes.

joule unit of work or energy in the metric system; symbol, J.

June solstice solstice occurring on June 21 or 22, when the subsolar point is located at 23½° N.

K

karst landscape or topography dominated by surface features of limestone solution and underlain by a limestone cavern system.

Kelvin scale (K) temperature scale on which the starting point is absolute zero, equivalent to −273°C.

kinetic energy form of energy represented by matter (mass) in motion.

knob and kettle terrain of numerous small knobs of glacial drift and deep depressions usually situated along the moraine belt of a former ice sheet.

knot measure of speed used in marine and aeronautical applications equal to one nautical mile per hour (1 kt = 0.514 m/s = 1.15 mi/hr).

L

lag time interval of time between occurrence of precipitation and peak discharge of a stream.

lagoon shallow body of open water lying between a barrier island or a barrier reef and the mainland.

lahar rapid downslope or downvalley movement of a tongue-like mass of water-saturated tephra (volcanic ash) originating high up on a steep-sided volcanic cone; a variety of mudflow.

lake body of standing water that is enclosed on all sides by land.

laminar flow smooth, even flow of a fluid shearing in thin layers without turbulence.

land breeze local wind blowing from land to water during the night.

land degradation degradation of the quality of plant cover and soil as a result of overuse by humans and their domesticated animals, especially during periods of drought.

land mass large area of continental crust lying above sea level (base level) and thus available for removal by denudation.

land-mass rejuvenation episode of rapid fluvial denudation set off by a rapid crustal rise, increasing the available land mass.

landforms configurations of the land surface taking distinctive forms and produced by natural processes. Examples: hill, valley, plateau. (See also *depositional landforms, erosional landforms, initial landforms, sequential landforms.*)

Landsat series of Earth-imaging NASA satellites, 1972–present.

landslide rapid sliding of large masses of bedrock on steep mountain slopes or from high cliffs.

lapse rate rate at which temperature decreases with increasing altitude. (See also *dry adiabatic lapse rate, environmental temperature lapse rate, moist adiabatic lapse rate.*)

large-scale map map with fractional scale greater than 1:100,000; usually shows a small area.

Late-Cenozoic Ice Age the series of glaciations, deglaciations, and interglaciations experienced during the late Cenozoic era.

latent heat heat absorbed and held in storage in a gas or liquid during the processes of evaporation, or melting, or sublimation; distinguished from sensible heat.

latent heat transfer flow of latent heat that results when water absorbs heat to change from a liquid or solid to a gas and then later releases that heat to new surroundings by condensation or deposition.

lateral moraine moraine forming an embankment between the ice of an alpine glacier and the adjacent valley wall.

laterite rock-like layer rich in sesquioxides and iron, including the minerals bauxite and limonite, found in low latitudes in association with Ultisols and Oxisols.

latitude arc of a meridian between the Equator and a given point on the globe.

Laurasia a supercontinent of the Permian period, including much of the region that is now North America and western Eurasia.

lava magma emerging on the Earth's solid surface, exposed to air or water.

leaching pedogenic process in which material is lost from the soil by downward washing out and removal by percolating surplus soil water.

leads narrow strips of open ocean water between ice floes.

lee-side trough low-pressure region found on the downwind (lee) side of a mountain chain, which can subsequently generate midlatitude cyclones.

level of condensation elevation at which an upward-moving parcel of moist air cools to the dew point and condensation begins to occur.

liana woody vine supported on the trunk or branches of a tree.

lichens plant forms in which algae and fungi live together (in a symbiotic relationship) to create a single structure; they typically form tough, leathery coatings or crusts attached to rocks and tree trunks.

life cycle continuous progression of stages in a growth or development process, such as that of a living organism.

life layer shallow surface zone containing the biosphere; a zone of interaction between atmosphere and land surface, and between atmosphere and ocean surface.

life zones series of vegetation zones describing vegetation types that are encountered with increasing elevation, especially in the southwestern United States.

life-form characteristic physical structure, size, and shape of a plant or of an assemblage of plants.

lightning an electric arc passing between differently charged parts of a cloud mass or between the cloud and the ground.

limestone nonclastic sedimentary rock in which calcite is the predominant mineral, and with varying minor amounts of other minerals and clay.

limestone caverns interconnected subterranean cavities formed in limestone by carbonic acid action occurring in slowly moving ground water.

limnology study of the physical, chemical, and biological processes of lakes.

limonite mineral or group of minerals consisting largely of iron oxide and water, produced by chemical weathering of other iron-bearing minerals.

line type of spatial object in a geographic information system that has starting and ending nodes; may be directional.

liquid fluid that maintains a free upper surface and is only very slightly compressible, as compared with a gas.

lithosphere strong, brittle outermost rock layer of the Earth, lying above the asthenosphere.

lithospheric plate segment of lithosphere moving as a unit, in contact with adjacent lithospheric plates along plate boundaries.

littoral drift transport of sediment parallel with the shoreline by the combined action of beach drift and longshore current transport.

loam soil-texture class in which no one of the three size grades (sand, silt, clay) dominates over the other two.

local scale scale of observation of the Earth in which local processes and phenomena are observed.

local winds general term for winds generated as direct or immediate effects of the local terrain.

lodgment till heterogeneous mixture of rock fragments deposited beneath moving glacial ice. (See also *till.*)

loess accumulation of yellowish to buff-colored, fine-grained sediment, largely of silt grade, on upland surfaces after transport in the air in turbulent suspension (i.e., carried in a dust storm).

logistic growth growth according to a mathematical model in which the growth rate eventually decreases to near zero.

longitude arc of a parallel between the prime meridian and a given point on the globe.

longitudinal dunes class of sand dunes in which the dune ridges are oriented parallel with the prevailing wind.

longshore current current in the breaker zone, running parallel with the shoreline and set up by the oblique approach of waves.

longshore drift littoral drift caused by action of a longshore current.

longwave radiation electromagnetic energy emitted by the Earth, largely in the range from 3 to 50 μm.

low base status (See *base status of soils*.)

low-angle overthrust fault overthrust fault in which the fault plane or fault surface has a low angle of dip or may be horizontal.

low-latitude climates group of climates of the equatorial zone and tropical zone dominated by the subtropical high-pressure belt and the equatorial trough.

low-latitude rainforest evergreen broadleaf forest of the wet equatorial and tropical climate zones.

low-latitude rainforest environment low-latitude environment of warm temperatures and abundant precipitation that characterizes rainforest in the wet equatorial ① and monsoon and trade-wind coastal ② climates.

low-level temperature inversion atmospheric condition in which temperature near the ground increases, rather than decreases, with elevation.

low-pressure trough weak, elongated cyclone of clouds and showers resulting from surface convergence generated by divergence aloft.

lowlands (1) broad, open valleys between two cuestas of a coastal plain; (2) any low area of land surface.

M

mafic igneous rock igneous rock dominantly composed of mafic minerals.

mafic minerals (mafic mineral group) minerals, largely silicate minerals, rich in magnesium and iron, dark in color, and of relatively greater density.

magma mobile, high-temperature molten state of rock, usually of silicate mineral composition and with dissolved gases.

manipulation and analysis component component of a geographic information system that responds to spatial queries and creates new data layers.

mantle rock layer or shell of the Earth beneath the crust and surrounding the core, composed of ultramafic igneous rock of silicate mineral composition.

mantle plume a column-like rising of heated mantle rock, thought to be the cause of a hotspot in the overlying lithospheric plate.

map a paper representation of space showing point, line, or area data.

map projection any orderly system of parallels and meridians drawn on a flat surface to represent the Earth's curved surface.

marble variety of metamorphic rock derived from limestone or dolomite by recrystallization under pressure.

March equinox equinox occurring on March 20 or 21.

marine cliff rock cliff shaped and maintained by the undermining action of breaking waves.

marine scarp steep seaward slope in poorly consolidated alluvium, glacial drift, or other forms of regolith, produced along a coastline by the undermining action of waves.

marine terrace former abrasion platform elevated to become a step-like coastal landform.

marine west-coast climate ⑧ cool moist climate of west coasts in the midlatitude zone, usually with a substantial annual water surplus and a distinct winter precipitation maximum.

mass number (See *atomic mass number*.)

mass wasting spontaneous downhill movement of soil, regolith, and bedrock under the influence of gravity, rather than by the action of fluid agents.

massive icy beds layers of ice-rich sediment, found in permafrost regions, formed by upwelling ground water that flows to a freezing front.

material cycle a closed matter flow system in which matter flows endlessly, powered by energy inputs (See also *biogeochemical cycle*.)

mathematical and statistical models in the representation perspective of geography, the use of mathematical and statistical models to predict spatial phenomena.

mathematical modeling using variables and equations to represent real processes and systems.

matter physical substance that has mass and density.

matter flow system total system of pathways by which a particular type of matter (a given element, compound, or ion, for example) moves through the Earth's ecosystem or biosphere.

mature stage in Davis's geographic cycle, a stage of erosion with rounded hills and gentle slopes.

mean annual temperature mean of mean daily air temperature for a given year or succession of years.

mean daily air temperature sum of daily maximum and minimum air temperature readings divided by two.

mean monthly temperature mean of mean daily air temperature means for a given calendar month.

mean velocity mean, or average, speed of flow of water through an entire stream cross section.

meanders (See *alluvial meanders*.)

mechanical energy energy of motion or position; includes kinetic energy and potential energy.

mechanical weathering (See *physical weathering*.)

medial moraine long, narrow deposit of fragments on the surface of a glacier; created by the merging of lateral moraines when two glaciers join into a single stream of ice flow.

Mediterranean climate ⑦ climate type of the subtropical zone, characterized by the alternation of a very dry summer and a mild, rainy winter.

melting change from solid state to liquid state, accompanied by absorption of sensible heat to become latent heat.

Mercator projection conformal map projection with horizontal parallels and vertical meridians and with map scale rapidly increasing with increase in latitude.

mercury barometer barometer using the Torricelli principle, in which atmospheric pressure counterbalances a column of mercury in a tube.

meridian of longitude north–south line on the surface of the global oblate ellipsoid, connecting the North Pole and South Pole.

meridional transport flow of energy (heat) or matter (water) across the parallels of latitude, either poleward or equatorward.

mesa table-topped plateau of comparatively small extent bounded by cliffs and occurring in a region of flat-lying strata.

mesocyclone a vertical column of cyclonically rotating air that develops in the updraft of a severe thunderstorm cell.

mesopause upper limit of the mesosphere.

mesoscale convective system a relatively long-lived, large, and intense convective cell or cluster of cells characterized by exceptionally strong updrafts.

mesosphere atmospheric layer of upwardly diminishing temperature, situated above the stratopause and below the mesopause.

Mesozoic era second of three geologic eras following Precambrian time.

metamorphic rock rock altered in physical structure and/or chemical (mineral) composition by action of heat, pressure, shearing stress, or infusion of elements, all taking place at substantial depth beneath the surface.

meteorology science of the atmosphere; particularly the physics of the lower or inner atmosphere.

methane gaseous chemical compound of carbon and hydrogen, CH_4, emitted into the atmosphere by natural and human processes; an important greenhouse gas.

mica group aluminum-silicate mineral group of complex chemical formula having perfect cleavage into thin sheets.

microburst brief onset of intense winds close to the ground beneath the downdraft zone of a thunderstorm cell.

microcontinent fragment of continental crust and its lithosphere of subcontinental dimensions that is embedded in an expanse of oceanic lithosphere.

micrometer metric unit of length equal to one-millionth of a meter (0.000001 m); abbreviated μm.

microwaves waves of the electromagnetic radiation spectrum in the wavelength band from about 0.03 cm to about 1 cm.

middle-infrared radiation electromagnetic radiation of wavelengths 3 to 6 μm.

midlatitude climates group of climates of the midlatitude zone and subtropical zone, located in the polar front zone and dominated by both tropical air masses and polar air masses.

midlatitude cyclone traveling cyclone of the midlatitudes involving interaction of cold and warm air masses along sharply defined fronts.

midlatitude deciduous forest plant formation class within the forest biome dominated by tall, broadleaf deciduous trees, found mostly in the moist continental climate ⑩ and marine west-coast climate ⑧.

midlatitude zones latitude zones occupying the latitude range 35° to 55° N and S (more or less) and lying between the subtropical zones and the subarctic (subantarctic) zones.

midoceanic ridge one of three major divisions of the ocean basins, being the central belt of submarine mountain topography with a characteristic axial rift.

Milankovitch curve graph of summer insolation at 65° N calculated from cycles in the Earth's axial rotation and solar revolution over the last 500,000 years.

millibar unit of atmospheric pressure; one-thousandth of a bar; 100 Pa.

mineral naturally occurring inorganic substance, usually having a definite chemical composition and a characteristic atomic structure. (See also *felsic minerals, mafic minerals, silicate minerals.*)

mineral alteration chemical change of minerals to more stable compounds on exposure to atmospheric conditions; same as chemical weathering.

mineral matter (soils) component of soil consisting of weathered or unweathered mineral grains.

mineral oxides (soils) secondary minerals found in soils in which original minerals have been altered by chemical combination with oxygen.

minute (of arc) 1/60 of a degree.

mistral wind local drainage wind of cold air affecting the Rhône Valley of southern France.

MODIS Moderate Resolution Imaging Spectroradiometer, a satellite-borne NASA Earth-imaging instrument.

Moho contact surface between the Earth's crust and mantle; a contraction of Mohorovičić, the name of the seismologist who discovered this feature

moist adiabatic lapse rate reduced adiabatic lapse rate when condensation is taking place in rising air; value ranges between 4 and 9°C per 1000 m (2.2 and 4.9°F per 1000 ft).

moist continental climate ⑩ moist climate of the midlatitude zone with strongly defined winter and summer seasons, adequate precipitation throughout the year, and a substantial annual water surplus.

moist subtropical climate ⑥ moist climate of the subtropical zone, characterized by a moderate to large annual water surplus and a strongly seasonal cycle of potential evapotranspiration (water need).

mollic epipedon relatively thick, dark-colored surface soil horizon, containing substantial amounts of organic matter (humus) and usually rich in bases.

Mollisols soil order consisting of soils with a mollic horizon and high base status.

monadnock prominent, isolated mountain or large hill rising conspicuously above a surrounding peneplain and composed of a rock more resistant than that underlying the peneplain; a landform of denudation in moist climates.

monsoon and trade-wind coastal climate ② moist climate of low latitudes showing a strong rainfall peak in the season of high Sun and a short period of reduced rainfall.

monsoon forest formation class within the forest biome consisting in part of deciduous trees adapted to a long dry season in the wet–dry tropical climate ③.

monsoon system system of low-level winds blowing into a continent in summer and out of it in winter, controlled by atmospheric pressure systems developed seasonally over the continent.

montane forest plant formation class of the forest biome found in cool upland environments of the tropical zone and equatorial zone.

moraine accumulation of rock debris carried by an alpine glacier or an ice sheet and deposited by the ice to become a depositional landform. (See also *lateral moraine, terminal moraine.*)

morphology the outward form and appearance of individual organisms or species.

mountain arc curving section of an alpine chain occurring on a converging boundary between two crustal plates.

mountain roots erosional remnants of deep portions of ancient continental sutures that were once alpine chains.

mountain winds daytime movements of air up the gradient of valleys and mountain slopes; alternating with nocturnal valley winds.

mucks organic soils largely composed of fine, black, sticky organic matter.

mud sediment consisting of a mixture of clay and silt with water, often with minor amounts of sand and sometimes with organic matter.

mud hummock low mound of earth found in permafrost terrain, formed by cycles of ground ice growth and melting, with center of bare ground; vegetation may occur at edges. (See also *earth hummock.*)

mudflow a form of mass wasting consisting of the downslope flowage of a mixture of water and mineral fragments (soil, regolith, disintegrated bedrock), usually following a natural drainage line or stream channel.

mudstone sedimentary rock formed by the lithification of mud.

multipurpose map map containing several different types of information.

multispectral image image consisting of two or more images, each of which is taken from a different portion of the spectrum (e.g., blue, green, red, infrared).

multispectral scanner remote sensing instrument, flown on an aircraft or spacecraft, that simultaneously collects multiple digital images (multispectral images) of the ground. Typically, images are collected in four or more spectral bands.

mutation change in genetic material of a reproductive cell.

N

nappe overturned recumbent fold of strata, usually associated with thrust sheets in a collision orogen.

natural bridge natural rock arch spanning a stream channel, formed by cutoff of an entrenched meander bend.

natural flow systems flow systems of energy or naturally occurring substances that are powered largely or completely by natural power sources.

natural gas naturally occurring mixture of hydrocarbon compounds (principally methane) in the gaseous state held within certain porous rocks.

natural levee belt of higher ground paralleling a meandering alluvial river on both sides of the stream channel and built up by deposition of fine sediment during periods of overbank flooding.

natural selection selection of organisms by environment in a process similar to selection of plants or animals for breeding by agriculturalists.

natural vegetation stable, mature plant cover characteristic of a given area of land surface largely free from the influences and impacts of human activities.

near-infrared radiation electromagnetic radiation in the wavelength range 0.7 to 1.2 μm; plant leaves reflect near-infrared light strongly.

needleleaf evergreen forest needleleaf forest composed of evergreen tree species, such as spruce, fir, and pine.

needleleaf forest plant formation class within the forest biome, consisting largely of needleleaf trees. (See also *boreal forest.*)

needleleaf tree tree with long, thin or flat leaves, such as pine, fir, larch, or spruce.

negative exponential mathematical form of a curve that smoothly decreases to approach a steady value, usually zero.

negative feedback in flow systems, a linkage between flow paths such that the flow in one pathway acts to reduce the flow in another pathway. (See also *feedback, positive feedback.*)

net photosynthesis carbohydrate production remaining in an organism after respiration has broken down sufficient carbohydrate to power the metabolism of the organism.

net primary production rate at which carbohydrate is accumulated in the tissues of plants within a given ecosystem; units are kilograms of dry organic matter per year per square meter of surface area.

net radiation difference in intensity between all incoming energy (positive quantity) and all outgoing energy (negative quantity) carried by both shortwave radiation and longwave radiation.

neutron atomic particle contained within the nucleus of an atom; similar in mass to a proton, but without a magnetic charge.

nimbostratus cloud type in which sheets or layers of clouds are found near the bottom of the troposphere, accompanied by precipitation.

nimbus any cloud type in which precipitation is occurring

nitrogen cycle biogeochemical cycle in which nitrogen moves through the biosphere by the processes of nitrogen fixation and denitrification.

nitrogen fixation chemical process of conversion of gaseous molecular nitrogen of the atmosphere into compounds or ions that can be directly utilized by plants; a process carried out within the nitrogen cycle by certain microorganisms.

nitrous oxide gas emitted to the atmosphere, N_2O, from both human and natural activity; an important greenhouse gas.

node point marking the end of a line or the intersection of lines as spatial objects in a geographic information system

noon (See *solar noon.*)

noon angle (of the Sun) angle of the Sun above the horizon at its highest point during the day.

normal fault variety of fault in which the fault plane inclines (dips) toward the downthrown block and a major component of the motion is vertical.

nortes strong, northeasterly winds that usually accompany the intrusion of cold cP air from the north; found in subtropical regions of North America.

northers (See *nortes.*)

North Pole point at which the northern end of the Earth's axis of rotation intersects the Earth's surface.

northeast trade winds surface winds of low latitudes that blow steadily from the northeast. (See also *trade winds.*)

nuclei (atmospheric) minute particles of solid matter suspended in the atmosphere and serving as cores for condensation of water or ice.

nutrient cycle (See *biogeochemical cycle.)*

O

O1 horizon surface soil horizon containing decaying organic matter that is recognizable as leaves, twigs, or other organic structures.

Oa horizon soil horizon below the O1 horizon containing decaying organic matter that is too decomposed to recognize as specific plant parts, such as leaves or twigs.

oasis desert area where ground water is tapped for crop irrigation and human needs.

oblate ellipsoid geometric solid resembling a flattened sphere, with polar axis shorter than the equatorial diameter.

occluded front weather front along which a moving cold front has overtaken a warm front, forcing the warm air mass aloft.

ocean basin floors one of the major divisions of the ocean basins, comprising the deep portions consisting of abyssal plains and low hills.

ocean current persistent, dominantly horizontal flow of ocean water.

ocean tide periodic rise and fall of the ocean level induced by gravitational attraction between the Earth and Moon in combination with Earth rotation.

oceanic crust crust of basaltic composition beneath the ocean floors, capping oceanic lithosphere. (See also *continental crust.*)

oceanic lithosphere lithosphere bearing oceanic crust.

oceanic trench narrow, deep depression in the seafloor representing the line of subduction of an oceanic lithospheric plate beneath the margin of a continental lithospheric plate; often associated with an island arc.

old age in Davis's geographic cycle, a stage of erosion with a low, undulating landscape drained by slow and sluggish streams.

oldland in the landscape of a recently emerged coastal plain, the region of older rock at the inner contact with newer sediments.

oil sand (See *bituminous sand*.)

old-field succession form of secondary succession typical of an abandoned field, such as might be found in eastern or central North America.

olivine silicate mineral with magnesium and iron but no aluminum, usually olive-green or grayish-green; a mafic mineral.

open flow system system of interconnected flow paths of energy and/or matter with a boundary through which that energy and/or matter can enter and leave the system.

organic matter (soils) material in soil that was originally produced by plants or animals and has been subjected to decay.

organic sediment sediment consisting of the organic remains of plants or animals.

orogen the mass of tectonically deformed rocks and related igneous rocks produced during an orogeny.

orogeny major episode of tectonic activity resulting in strata being deformed by folding and faulting.

orographic pertaining to mountains.

orographic precipitation precipitation induced by the forced rise of moist air over a mountain barrier.

oscillatory wave type of wave that generates an oscillating motion of mass as the wave passes through the medium; water waves are of this type.

outcrop surface exposure of bedrock.

output the flow of matter or energy out of a system.

outspiral horizontal outward spiral or motion, such as that found in an anticyclone.

outwash glacial deposit of stratified drift left by braided streams issuing from the front of a glacier.

outwash plain flat, gently sloping plain built up of sand and gravel by the aggradation of meltwater streams in front of the margin of an ice sheet.

overburden strata overlying a layer or stratum of interest, as overburden above a coal seam.

overland flow motion of a surface layer of water over a sloping ground surface at times when the infiltration rate is exceeded by the precipitation rate; a form of runoff.

overthrust fault fault characterized by the overriding of one crustal block (or thrust sheet) over another along a gently inclined fault plane; associated with crustal compression.

ox-bow lake crescent-shaped lake representing the abandoned channel left by the cutoff of an alluvial meander.

oxidation chemical union of free oxygen with metallic elements in minerals.

oxide chemical compound containing oxygen; in soils, iron oxides and aluminum oxides are examples.

Oxisols soil order consisting of very old, highly weathered soils of low latitudes, with an oxic horizon and low base status.

oxygen cycle biogeochemical cycle in which oxygen moves through the biosphere in both gaseous and sedimentary forms.

ozone a form of oxygen with a molecule consisting of three atoms of oxygen, O_3.

ozone layer layer in the stratosphere, mostly in the altitude range 20 to 35 km (12 to 31 mi), in which a concentration of ozone is produced by the action of solar ultraviolet radiation.

P

Pacific Decadal Oscillation (PDO) slowly varying change in sea-surface temperatures and sea-level pressures of the north Pacific.

pack ice floating sea ice that completely covers the sea surface.

Paleozoic era first of three geologic eras comprising the Phanerozoic era.

pamperos strong, southerly or southwesterly winds found in Argentina and Uruguay that usually accompany the intrusion of cold mP air from the south.

Pangaea hypothetical parent continent, enduring until near the close of the Mesozoic era, consisting of the continental shields of Laurasia and Gondwana joined into a single unit.

parabolic dunes isolated low sand dunes of parabolic outline, with points directed into the prevailing wind.

parallel of latitude east-west circle on the Earth's surface, lying in a plane parallel with the Equator and at right angles to the axis of rotation.

parasitism form of negative interaction between species in which a small species (parasite) feeds on a larger one (host) without necessarily killing it.

parent material inorganic, mineral base from which the soil is formed; usually consists of regolith.

particulates solid and liquid particles capable of being suspended for long periods in the atmosphere.

pascal metric unit of pressure, defined as a force of one newton per square meter ($1\ N/m^2$); symbol, Pa; 100 Pa = 1 mb, 10^5 Pa = 1 bar.

passive continental margin continental margin lacking active plate boundaries at the contact of continental crust with oceanic crust. (See also *active continental margins, continental margins*.)

passive systems electromagnetic remote sensing systems that measure radiant energy reflected or emitted by an object or surface.

pathway in an energy flow system, a mechanism by which matter or energy flows from one part of the system to another.

pattern in the geographical perspective, the variation in phenomena that is seen at a particular scale.

patterned ground general term for a ground surface that bears polygonal or ring-like features, including stone circles, nets, polygons, steps, and stripes; includes ice wedge polygons; typically produced by frost action in cold climates.

peat partially decomposed, compacted accumulation of plant remains occurring in a bog environment.

ped individual natural soil aggregate.

pediment gently sloping, rock-floored land surface found at the base of a mountain mass or cliff in an arid region.

pedogenic processes group of recognized basic soil-forming processes, mostly involving the gain, loss, translocation, or transformation of materials within the soil body.

pedology science of the soil as a natural surface layer capable of supporting living plants; synonymous with soil science.

peneplain land surface of low elevation and slight relief produced in the late stages of denudation of a land mass.

perched water table surface of a lens of ground water held above the main body of ground water by a discontinuous impervious layer.

percolation slow, downward flow of water by gravity through soil and subsurface layers toward the water table.

perennials plants that live for more than one growing season.

peridotite igneous rock consisting largely of olivine and pyroxene; an ultramafic igneous rock occurring as a pluton, also thought to compose much of the upper mantle.

periglacial in an environment of intense frost action, located in cold-climate regions or near the margins of alpine glaciers or large ice sheets.

periglacial system a distinctive set of landforms and land-forming processes that are created by intense frost action.

perihelion point on the Earth's elliptical orbit at which the Earth is nearest to the Sun.

period (geologic time) unit of geologic time; about tens of millions of years in length; subdivided into epochs.

permafrost soil, regolith, and bedrock at a temperature below 0°C (32°F), found in cold climates of arctic, subarctic, and alpine regions.

permafrost table in permafrost, the upper surface of perennially frozen ground; lower surface of the active layer.

petroleum (crude oil) natural liquid mixture of many complex hydrocarbon compounds of organic origin, found in accumulations (oil pools) within certain sedimentary rocks.

pH measure of the concentration of hydrogen ions in a solution; acid solutions have pH values less than 7, and basic solutions have pH values greater than 7.

phenotype the morphological expression of the genotype of an individual. It includes all the physical aspects of its structure that are readily perceivable.

photoperiod duration of daylight on a given day of the year at a given latitude.

photosynthesis production of carbohydrate by the union of water with carbon dioxide while absorbing light energy.

phreatophytes plants that draw water from the ground water table beneath alluvium of dry stream channels and valley floors in desert regions.

phylum highest division of higher plant and animal life.

physical geography the part of systematic geography that deals with the natural processes occurring at the Earth's surface that provide the physical setting for human activities; includes the broad fields of climatology, geomorphology, coastal and marine geography, geography of soils, and biogeography.

physical weathering breakup of massive rock (bedrock) into small particles through the action of physical forces acting at or near the Earth's surface. (See also *weathering*.)

phytoplankton microscopic plants found largely in the uppermost layer of ocean or lake water.

pingo conspicuous conical mound or circular hill, having a core of ice, found on plains of the arctic tundra where permafrost is present.

pioneer plants plants that first invade an environment of new land or a soil that has been cleared of vegetation cover; often these are annual herbs.

pioneer stage first stage of an ecological succession.

place in geography, a location on the Earth's surface, typically a settlement or small region with unique characteristics; in the viewpoint perspective of geography, a focus on how processes are integrated at a single location or within a single region.

plagioclase feldspar aluminum-silicate mineral with sodium or calcium, or both.

plane of the ecliptic imaginary plane in which the Earth's orbit lies.

plant ecology the study of the relationships between plants and their environment.

plant nutrients ions or chemical compounds that are needed for plant growth.

plate tectonics theory of tectonic activity dealing with lithospheric plates and their activity.

plateau upland surface, more or less flat and horizontal, upheld by resistant beds of sedimentary rock or lava flows and bounded by a steep cliff.

playa flat land surface underlain by fine sediment or evaporite minerals deposited from shallow lake waters in a dry climate in the floor of a closed topographic depression.

Pleistocene epoch epoch of the Cenozoic era, often identified as the Ice Age; it preceded the Holocene epoch.

plinthite iron-rich concentrations present in some kinds of soils in deeper soil horizons and capable of hardening into rock-like material with repeated wetting and drying.

plough winds (See *straight-line winds*.)

plucking (See *glacial plucking*.)

pluton any body of intrusive igneous rock that has solidified below the surface, enclosed in preexisting rock.

pocket beach beach of crescentic outline located at a bay head.

podzol type of soil closely equivalent to Spodosol.

point spatial object in a geographic information system with no area.

point bar deposit of coarse bed-load alluvium accumulated on the inside of a growing alluvial meander.

polar easterlies system of easterly surface winds at high latitude, best developed in the southern hemisphere, over Antarctica.

polar front front lying between cold polar air masses and warm tropical air masses, often situated along a jet stream within the upper-air westerlies.

polar front jet stream jet stream found along the polar front, where cold polar air and warm tropical air are in contact.

polar front zone broad zone in midlatitudes and higher latitudes, occupied by the shifting polar front.

polar high persistent low-level center of high atmospheric pressure located over the polar zone of Antarctica.

polar outbreak tongue of cold polar air, preceded by a cold front, penetrating far into the tropical zone and often reaching the equatorial zone; it brings rain squalls and unusual cold.

polar projection map projection centered on Earth's North Pole or South Pole.

polar zones latitude zones lying between 75° and 90° N and S.

pole point at which the end of the Earth's axis of rotation intersects the Earth's surface. (See *North Pole, South Pole.*)

poleward heat transport movement of heat from equatorial and tropical regions toward the poles, occurring as latent and sensible heat transfer.

pollutants in air pollution studies, foreign matter injected into the lower atmosphere as particulates or as chemical pollutant gases.

pollution dome broad, low dome-shaped layer of polluted air, formed over an urban area at times when winds are weak or calm prevails.

pollution plume (1) the trace or path of pollutant substances, moving along the flow paths of ground water; (2) trail of polluted air carried downwind from a pollution source by strong winds.

polygon type of spatial object in a geographic information system with a closed chain of connected lines surrounding an area.

polypedon smallest distinctive geographic unit of the soil of a given area.

polyploidy mechanism of speciation in which entire chromosome sets of organisms are doubled, tripled, quadrupled, and so on.

pool in flow systems, an area or location of concentration of matter. (See also *active pool, storage pool.*)

positive feedback in flow systems, a linkage between flow paths such that the flow in one pathway acts to increase the flow in another pathway. (See also *feedback, negative feedback.)*

potash feldspar aluminum-silicate mineral with potassium the dominant metal.

potential energy energy of position; produced by gravitational attraction of the Earth's mass for a smaller mass on or near the Earth's surface.

potential evapotranspiration (water need) ideal or hypothetical rate of evapotranspiration estimated to occur from a complete canopy of green foliage of growing plants continuously supplied with all the soil water they can use; a real condition reached in those situations where precipitation is sufficiently great or irrigation water is supplied in sufficient amounts.

pothole cylindrical cavity in hard bedrock of a stream channel produced by abrasion of a rounded rock fragment rotating within the cavity.

power source flow of energy into a flow system that causes matter to move.

prairie plant formation class of the grassland biome, consisting of dominant tall grasses and subdominant forbs, widespread in subhumid continental climate regions of the subtropical zone and midlatitude zone. (See also *short-grass prairie, tall-grass prairie.)*

Precambrian time all of geologic time older than the beginning of the Cambrian period, that is, older than about 600 million years.

precipitation particles of liquid water or ice that fall from the atmosphere and may reach the ground. (See also *convective precipitation, cyclonic precipitation, orographic precipitation.*)

predation form of negative interaction among animal species in which one species (predator) kills and consumes the other (prey).

preprocessing component component of a geographic information system that prepares data for entry into the system.

pressure gradient change of atmospheric pressure measured along a line at right angles to the isobars.

pressure gradient force force acting horizontally, tending to move air in the direction of lower atmospheric pressure.

prevailing westerly winds (westerlies) surface winds blowing from a generally westerly direction in the midlatitude zone, but varying greatly in direction and intensity.

primary consumers organisms at the lowest level of the food chain that ingest primary producers or decomposers as their energy source.

primary minerals in pedology (soil science), the original, unaltered silicate minerals of igneous rocks and metamorphic rocks.

primary producers organisms that use light energy to convert carbon dioxide and water to carbohydrates through the process of photosynthesis.

primary succession ecological succession that begins on a newly constructed substrate.

prime meridian reference meridian of zero longitude; universally accepted as the Greenwich meridian.

process in the geographical perspective, how factors that affect a phenomenon act to produce a pattern at a particular scale.

product generation component component of a geographic information system that provides output products such as maps, images, or tabular reports.

progradation shoreward building of a beach, bar, or sandspit by addition of coarse sediment carried by littoral drift or brought from deeper water offshore.

proton positively charged particle within the nucleus of an atom.

pyroxene group complex aluminum-silicate minerals rich in calcium, magnesium, and iron, dark in color, high in density, classed as mafic minerals.

Q

quartz mineral of silicon dioxide composition, SiO_2.

quartzite metamorphic rock consisting largely of the mineral quartz.

quick clays clay layers that spontaneously change from a solid condition to a near-liquid condition when disturbed.

R

radar an active remote sensing system in which a pulse of electromagnetic radiation is emitted by an instrument and the strength of the echo of the pulse is recorded.

radial drainage pattern stream pattern consisting of streams radiating outward from a central peak or highland, such as a sedimentary dome or a volcano.

radiant energy transfer net flow of radiant energy between an object and its surroundings.

radiation (See *electromagnetic radiation.*)

radiation balance condition of balance between incoming energy of solar shortwave radiation and outgoing longwave radiation emitted by the Earth into space.

radiation fog fog produced by radiation cooling of the basal air layer.

radioactive decay spontaneous change in the nucleus of an atom that leads to the emission of matter and energy.

radiogenic heat heat from the Earth's interior that is slowly released by the radioactive decay of unstable isotopes.

radiometric dating a method of determining the geologic age of a rock or mineral by measuring the proportions of certain of its elements in their different isotopic forms.

rain form of precipitation consisting of falling water drops, usually 0.5 mm or larger in diameter.

rain gauge instrument used to measure the amount of rain that has fallen.

rain shadow belt of arid climate to lee of a mountain barrier, produced as a result of adiabatic warming of descending air.

rain-green vegetation vegetation that puts out green foliage in the wet season but becomes largely dormant in the dry season; found in the tropical zone, it includes the savanna biome and monsoon forest.

raised shoreline former shoreline lifted above the limit of wave action; also called an elevated shoreline.

rapids steep-gradient reaches of a stream channel in which stream velocity is high.

recessional moraine moraine produced at the ice margin during a temporary halt in the recessional phase of deglaciation.

reclamation in strip mining, the process of restoring spoil banks and ridges to a natural condition.

recombination source of variation in organisms arising from the free interchange of alleles of genes during the reproduction process.

recumbent overturned, as a folded sequence of rock layers in which the folds are doubled back on themselves.

reflection outward scattering of radiation toward space by the atmosphere and/or Earth's surface.

reg desert surface armored with a pebble layer, resulting from long-continued deflation; found in the Sahara Desert of North Africa.

regional geography that branch of geography concerned with how the Earth's surface is differentiated into unique places.

regional scale the scale of observation at which subcontinental regions are discernible.

regolith layer of mineral particles overlying the bedrock; may be derived by weathering of underlying bedrock or be transported from other locations by fluid agents. (See also *residual regolith, transported regolith.)*

rejuvenation in Davis's geographic cycle, the uplift of an old-age landscape, creating a new youthful stage of erosion.

relative humidity ratio of water vapor present in the air to the maximum quantity possible for saturated air at the same temperature.

remote sensing measurement of some property of an object or surface by means other than direct contact; usually refers to the gathering of scientific information about the Earth's surface from great heights and over broad areas, using instruments mounted on aircraft or orbiting space vehicles.

remote sensor instrument or device measuring electromagnetic radiation reflected or emitted from a target body.

removal in soil science, the set of processes that result in the removal of material from a soil horizon, such as surface erosion or leaching.

representation a perspective of geography that concerns developing and manipulating tools for the display and analysis of spatial information.

representative fraction (R.F.) (See *scale fraction.)*

residual regolith regolith formed in place by alteration of the bedrock directly beneath it.

resolution on a map, power to resolve small objects present on the ground.

respiration the oxidation of organic compounds by organisms that power bodily functions.

retrogradation cutting back (retreat) of a shoreline, beach, marine cliff, or marine scarp by wave action.

retrogressive thaw slump slump and flowage of overlying sediment occurring where erosion exposes ice-rich permafrost or massive ground ice to thawing.

reverse fault type of fault in which one fault block rides up over the other on a steep fault plane.

revolution motion of a planet in its orbit around the Sun, or of a planetary satellite around a planet.

rhyolite extrusive igneous rock of granite composition; it occurs as lava or tephra.

ria coastal embayment or estuary.

ria coast deeply embayed coast formed by partial submergence of a land mass previously shaped by fluvial denudation.

Richter scale scale of magnitude numbers describing the quantity of energy released by an earthquake.

ridge-and-valley landscape assemblage of landforms developed by denudation of a system of open folds of strata and consisting of long, narrow ridges and valleys arranged in parallel or zigzag patterns.

rift valley trench-like valley with steep, parallel sides; essentially a graben between two normal faults; associated with crustal spreading.

rill erosion form of accelerated erosion in which numerous, closely spaced miniature channels (rills) are scored into the surface of exposed soil or regolith.

rock natural aggregate of minerals in the solid state; usually hard and consisting of one, two, or more mineral varieties.

rock glacier (See *felsenmeer.)*

rock sea (See *felsenmeer.)*

rock terrace terrace carved in bedrock during the degradation of a stream channel induced by the crustal rise or a fall of the sea level. (See also *alluvial terrace, marine terrace.*)

rockslide landslide of jumbled bedrock fragments.

Rodinia early supercontinent, predating Pangaea, that was fully formed about 700 million years ago.

roll cloud tube-shaped cloud whose axis is parallel to the ground, typically found above a gust front where outflowing air at the surface is in the opposite direction to the in-flowing air above it.

Rossby waves wave-like undulations in the flow of a jet stream. (See also *jet stream disturbance.)*

rotation spinning of an object around an axis.

runoff flow of water from continents to oceans by way of streamflow and ground water flow; a term in the water balance of the hydrologic cycle. In a more restricted sense, runoff refers to surface flow by overland flow and channel flow.

S

Sahel (Sahelian zones) belt of wet–dry tropical ③ and semiarid dry tropical ④ climate in Africa in which precipitation is highly variable from year to year.

salic horizon soil horizon enriched by soluble salts.

salinity degree of "saltiness" of water; refers to the abundance of such ions as sodium, calcium, potassium, chloride, fluoride, sulfate, and carbonate.

salinization precipitation of soluble salts within the soil.

salt flat shallow basin covered with salt deposits formed when stream input to the basin is evaporated to dryness from the basin of a lake; may also form by evaporation of a saline lake when climate changes. (See also *dry lake.)*

salt marsh peat-covered expanse of sediment built up to the level of high tide over a previously formed tidal mud flat.

salt-crystal growth a form of weathering in which rock is disintegrated by the expansive pressure of growing salt crystals during dry weather periods when evaporation is rapid.

saltation leaping, impacting, and rebounding of sand grains transported over a sand or pebble surface by wind.

saltwater intrusion occurs in a coastal well when an upper layer of fresh water is pumped out, leaving a saltwater layer below to feed the well.

sample standard deviation in statistics, the square root of the average squared deviation from the mean for a sample.

sample statistics numerical values that give basic information about a sample and its variability.

sand sediment particles between 0.06 and 2 mm in diameter.

sand bar hill or ridge of sand found in shallow waters, often deposited by littoral drift.

sand dune hill or ridge of loose, well-sorted sand shaped by wind and usually capable of downwind motion.

sand sea field of transverse dunes.

sandbar hill or ridge of sand found in shallow waters, often deposited by littoral drift.

sandspit narrow, finger-like embankment of sand constructed by littoral drift into the open water of a bay.

sandstone sedimentary rock consisting largely of mineral particles of sand size.

sanitary landfill facility where trash and other wastes are buried under layers of sand or soil and allowed to decompose.

Santa Ana easterly wind, often hot and dry, that blows from the interior desert region of Southern California and passes over the coastal mountain ranges to reach the Pacific Ocean.

saturated air air with a water vapor content equal to the saturation specific humidity given for the temperature and pressure of the air.

saturated zone zone beneath the land surface in which all pores of the bedrock or regolith are filled with ground water.

saturation (atmospheric) the condition in which the specific humidity of a parcel of air is equal to the saturation specific humidity.

saturation-specific humidity the maximum amount of water vapor an air parcel can contain based on its temperature and pressure.

savanna a vegetation cover of widely spaced trees with a grassland beneath.

savanna biome biome that consists of a combination of trees and grassland in various proportions.

savanna woodland plant formation class of the savanna biome consisting of a woodland of widely spaced trees and a grass layer, found throughout the wet–dry tropical climate regions in a belt adjacent to the monsoon forest and low-latitude rainforest.

scale the magnitude of a phenomenon or system, as, for example, global scale or local scale; in the viewpoint perspective of geography, a focus on examining a phenomenon at different scales.

scale fraction ratio that relates distance on the Earth's surface to distance on a map or surface of a globe.

scale of globe ratio of size of a globe to size of the Earth, where size is expressed by a measure of length or distance.

scale of map ratio of distance between two points on a map and the same two points on the ground.

scanning systems remote sensing systems that make use of a scanning beam to generate images over the frame of observation.

scarification general term for artificial excavations and other land disturbances produced for purposes of extracting or processing mineral resources.

scattering turning aside of radiation by an atmospheric molecule or particle so that the direction of the scattered ray is changed.

schist foliated metamorphic rock in which mica flakes are typically found oriented parallel with foliation surfaces.

sclerophyll forest plant formation class of the forest biome, consisting of low sclerophyll trees and often including sclerophyll woodland or scrub, associated with regions of Mediterranean climate ⑦.

sclerophyll woodland plant formation class of the forest biome composed of widely spaced sclerophyll trees and shrubs.

sclerophylls hard-leaved evergreen trees and shrubs capable of enduring a long, dry summer.

scoria lava or tephra containing numerous cavities produced by expanding gases during cooling.

scrub plant formation class or subclass consisting of shrubs and having a canopy coverage of about 50 percent.

sea arch arch-like landform of a rocky, cliffed coast created when waves erode through a narrow headland from both sides.

sea breeze local wind blowing from sea to land during the day.

sea cave cave near the base of a marine cliff, eroded by breaking waves.

sea fog fog layer formed at sea when warm moist air passes over a cool ocean current and is chilled to the condensation point.

sea ice floating ice of the oceans formed by direct freezing of ocean water.

second of arc 1/60 of a minute, or 1/3600 of a degree.

secondary consumers animals that feed on primary consumers.

secondary minerals in soil science, minerals that are stable in the surface environment, derived by mineral alteration of the primary minerals.

secondary succession ecological succession beginning on a previously vegetated area that has been recently disturbed by such agents as fire, flood, windstorm, or humans.

sediment finely divided mineral matter and organic matter derived directly or indirectly from preexisting rock and from life processes. (See also *chemically precipitated sediment, organic sediment.)*

sediment yield quantity of sediment removed by overland flow from a land surface of a given unit area in a given unit of time.

sedimentary cycle type of biogeochemical cycle in which the compound or element is released from rock by weathering, follows the movement of running water either in solution or as sediment to reach the sea, and is eventually converted into rock.

sedimentary dome up-arched strata forming a circular structure with domed summit and flanks with moderate to steep outward dip.

sedimentary rock rock formed from accumulation of sediment.

segregated ice lenses, wedges, or veins of ice occurring as free masses in soil or regolith of permafrost terrain.

seismic sea wave (See *tsunami.)*

seismic waves waves sent out during an earthquake by faulting or other crustal disturbance from an earthquake focus and propagated through the solid Earth.

semiarid (steppe) dry climate subtype subtype of the dry climates exhibiting a short wet season supporting the growth of grasses and annual plants.

semidesert plant formation class of the desert biome, consisting of xerophytic shrub vegetation with a poorly developed herbaceous lower layer; subtypes are semidesert scrub and woodland.

sensible heat heat measurable by a thermometer; an indication of the intensity of kinetic energy of molecular motion within a substance.

sensible heat transfer flow of heat from one substance to another by direct contact.

September equinox equinox occurring on September 22 or 23.

sequential landforms landforms produced by external Earth processes in the total activity of denudation. Examples: gorge, alluvial fan, floodplain.

seral stage stage in a sere.

sere in an ecological succession, the series of biotic communities that follow one another on the way to the stable stage, or climax.

sesquioxides oxides of aluminum or iron with a ratio of two atoms of aluminum or iron to three atoms of oxygen.

shale fissile, sedimentary rock of mud or clay composition, showing lamination.

shearing (of rock) slipping motion between very thin rock layers, like a deck of cards fanned with the sweep of a palm.

sheet erosion type of accelerated soil erosion in which thin layers of soil are removed without formation of rills or gullies.

sheet flow overland flow taking the form of a continuous thin film of water over a smooth surface of soil, regolith, or rock.

sheeting structure thick, subparallel layers of massive bedrock formed by spontaneous expansion accompanying unloading.

shield volcano low, often large, dome-like accumulation of basalt lava flows emerging from long radial fissures on flanks.

shoreline shifting line of contact between water and land.

short-grass prairie plant formation class in the grassland biome consisting of short grasses sparsely distributed in clumps and bunches and some shrubs, widespread in areas of semiarid climate in continental interiors of North America and Eurasia; also called steppe.

shortwave infrared radiation electromagnetic radiation in the wavelength range from 1.2 to 3.0 μm.

shortwave radiation electromagnetic energy in the range from 0.2 to 3 μm, including most of the energy spectrum of solar radiation.

shrubs woody perennial plants, usually small or low, with several low-branching stems and a foliage mass close to the ground.

silica silicon dioxide in any of several mineral forms.

silicate minerals (silicates) minerals containing silicon and oxygen atoms, linked in the crystal space lattice in units of four oxygen atoms to each silicon atom.

sill intrusive igneous rock in the form of a plate where magma was forced into a natural parting in the bedrock, such as a bedding surface in a sequence of sedimentary rocks.

silt sediment particles between 0.004 and 0.06 mm in diameter.

sinkhole surface depression in limestone, leading down into limestone caverns.

slash-and-burn agricultural system, practiced in the low-latitude rainforest, in which small areas are cleared and the trees burned, forming plots that were cultivated for several years.

slate compact, fine-grained variety of metamorphic rock, derived from shale, showing well-developed cleavage.

sleet form of precipitation consisting of ice pellets, which may be frozen raindrops.

sling psychrometer form of hygrometer consisting of a wet-bulb thermometer and a dry-bulb thermometer.

slip face steep face of an active sand dune, receiving sand by saltation over the dune crest and repeatedly sliding because of oversteepening.

slope (1) degree of inclination from the horizontal of an element of ground surface; (2) any portion or element of the Earth's solid surface.

small circle circle formed by passing a plane through a sphere without passing through the exact center.

small-scale map map with fractional scale of less than 1:100,000; usually shows a large area.

smog mixture of aerosols and chemical pollutants in the lower atmosphere, usually found over urban areas.

snow form of precipitation consisting of ice particles.

soil natural terrestrial surface layer containing living matter and supporting or capable of supporting plants.

soil colloids mineral particles of extremely small size, capable of remaining suspended indefinitely in water; typically, they have the form of thin plates or scales.

soil creep extremely slow downhill movement of soil and regolith as a result of continued agitation and disturbance of the particles by such activities as frost action, temperature changes, or wetting and drying of the soil.

soil enrichment additions of materials to the soil body; one of the pedogenic processes.

soil erosion erosional removal of material from the soil surface.

soil horizon distinctive layer of the soil, more or less horizontal, set apart from other soil zones or layers by differences in physical and chemical composition, organic content, structure, or a combination of those properties, produced by soil-forming processes.

soil orders those 11 soil classes forming the highest category in the classification of soils.

soil profile display of soil horizons on the face of a freshly cut vertical exposure through the soil.

soil science (See *pedology*.)

soil solum that part of the soil made up of the A, E, and B soil horizons; the soil zone in which living plant roots can influence the development of soil horizons.

soil structure presence, size, and form of aggregations (lumps or clusters) of soil particles.

soil texture descriptive property of the mineral portion of the soil based on varying proportions of sand, silt, and clay.

soil water water held in the soil and available to plants through their root systems; a form of subsurface water.

soil-water balance balance among the component terms of the soil-water budget; namely, precipitation, evapotranspiration, change in soil water storage, and water surplus.

soil-water belt soil layer from which plants draw soil water.

soil-water budget accounting system evaluating the daily, monthly, or yearly amounts of precipitation, evapotranspiration, soil-water storage, water deficit, and water surplus.

soil-water recharge restoration of depleted soil water by infiltration of precipitation.

soil-water shortage (See *deficit.*)

soil-water storage actual quantity of water held in the soil-water belt at any given instant; usually applied to a soil layer of given depth, such as 300 cm (about 12 in.).

solar constant intensity of solar radiation falling on a unit area of surface held at right angles to the Sun's rays at a point outside the Earth's atmosphere; equal to an energy flow of 1367 W/m^2.

solar day average time required for the Earth to complete one rotation with respect to the Sun; time elapsed between one solar noon and the next, averaged over the period of one year.

solar noon instant at which the subsolar point crosses the meridian of longitude of a given point on the Earth; instant at which the Sun's shadow points exactly due north or due south at a given location.

solids substances in the solid state; they resist changes in shape and volume, are usually capable of withstanding large unbalanced forces without yielding, but will ultimately yield by sudden breakage.

solifluction tundra (arctic) variety of earthflow in which sediments of the active layer move in a mass slowly downhill over a water-rich plastic layer occurring at the top of permafrost; produces solifluction terraces and solifluction lobes.

solifluction lobe bulging mass of saturated regolith with steep curved front moved downhill by solifluction.

solifluction terrace mass of saturated regolith formed by solifluction into a flat-topped terrace.

solution a weathering process in which minerals dissolve in water; may be enhanced by the action of carbonic acid or weak organic acids.

sorting separation of one grade size of sediment particles from another by the action of currents of air or water.

source region extensive land or ocean surface over which an air mass derives its temperature and moisture characteristics.

South Pole point at which the southern end of the Earth's axis of rotation intersects the Earth's surface.

southeast trade winds surface winds of low latitudes that blow steadily from the southeast. (See also *trade winds.*)

Southern Oscillation episodic reversal of prevailing barometric pressure differences between two regions, one centered on Darwin, Australia, in the eastern Indian Ocean, and the other on Tahiti in the western Pacific Ocean; a precursor to the occurrence of an El Niño event. (See also *El Ñino.)*

southern pine forest subtype of needleleaf forest dominated by pines and occurring in the moist subtropical climate; typically found on sandy soils of the Atlantic and Gulf Coast coastal plains.

space in the viewpoint perspective of geography, a focus on how places are interdependent.

spatial data information associated with a specific location or area of the Earth's surface.

spatial object a geographic area, line, or point to which information is attached.

speciation the process by which species are differentiated and maintained.

species a collection of individual organisms that are capable of interbreeding to produce fertile offspring.

specific heat physical constant of a material that describes the amount of heat energy in joules required to raise the temperature of one gram of the material by one Celsius degree.

specific humidity mass of water vapor contained in a unit mass of air.

spectral signature in remote sensing, the reflectance of an object or a surface type in particular spectral bands.

sphere in physical geography, a great physical realm of the Earth; atmosphere, lithosphere, hydrosphere, biosphere.

spit (See *sandspit.*)

splash erosion soil erosion caused by direct impact of falling raindrops on a wet surface of soil or regolith.

spodic horizon soil horizon containing precipitated amorphous materials composed of organic matter and sesquioxides of aluminum, with or without iron.

Spodosols soil order consisting of soils with a spodic horizon, an albic horizon, with low base status, and lacking in carbonate materials.

spoil rock waste removed in a mining operation.

spreading plate boundary lithospheric plate boundary along which two plates of oceanic lithosphere are undergoing separation, while at the same time new lithosphere is being formed by accretion. (See also *transform plate boundary.*)

squall line line of thunderstorms and strong winds that extends for several hundred kilometers (miles).

stable air mass air mass in which the environmental temperature lapse rate is less than the dry adiabatic lapse rate, inhibiting convectional uplift and mixing.

stack (marine) isolated columnar mass of bedrock left standing in front of a retreating marine cliff.

stage height of the surface of a river above its bed or a fixed level near the bed.

standard meridians standard time meridians separated by 15° of longitude and having values that are multiples of 15°. (In some cases meridians are used that are multiples of 7½°.)

standard time system time system based on the local time of a standard meridian and applied to belts of longitude extending 7½° (more or less) on either side of that meridian.

standard time zone zone of the Earth in which all locations keep the same time, according to a standard meridian within the zone.

star dune large, isolated sand dune with radial ridges culminating in a peaked summit; found in the deserts of North Africa and the Arabian Peninsula.

stationary front boundary between two differing air masses that has not moved over the last 3 to 6 hours or that has moved relatively slowly.

statistics a branch of mathematical sciences that deals with the analysis of numerical data.

steppe semiarid grassland occurring largely in dry continental interiors. (See also *short-grass prairie.*)

steppe climate (See *semiarid (steppe) dry climate subtype.*)

stone nets (See *stone polygons.*)

stone polygons linked ring-like ridges of cobbles or boulders lying at the surface of the ground in arctic and alpine tundra regions.

stone stripes stone polygons drawn out into long stripes, usually in the direction of a gentle slope.

storage capacity maximum capacity of soil to hold water against the pull of gravity.

storage pool type of pool in a biogeochemical cycle in which materials are largely inaccessible to life. (See also *active pool.*)

storage recharge restoration of stored soil water during periods when precipitation exceeds potential evapotranspiration (water need).

storage withdrawal depletion of stored soil water during periods when evapotranspiration exceeds precipitation, calculated as the difference between actual evapotranspiration (water use) and precipitation.

storm surge rapid rise of coastal water level accompanying the onshore arrival of a tropical cyclone.

strata layers of sediment or sedimentary rock in which individual beds are separated from one another along bedding planes.

straight-line winds strong surface winds blowing from a single direction, usually arising from downburst winds of thunderstorms spreading out at the surface.

strata layers of sediment or sedimentary rock in which individual beds are separated from one another along bedding planes.

stratified drift glacial drift made up of sorted and layered clay, silt, sand, or gravel deposited from meltwater in stream channels, or in marginal lakes close to the ice front.

stratiform clouds clouds of layered, blanket-like form.

stratopause upper limit of the stratosphere.

stratosphere layer of atmosphere lying directly above the troposphere.

stratovolcano volcano constructed of multiple layers of lava and tephra (volcanic ash).

stratus cloud type of the low-height family formed into a dense, dark gray layer.

stream long, narrow body of flowing water occupying a stream channel and moving to lower levels under the force of gravity. (See also *consequent stream, graded stream, subsequent stream.*)

stream capacity maximum stream load of solid matter that can be carried by a stream for a given discharge.

stream channel long, narrow, trough-like depression occupied and shaped by a stream moving to progressively lower levels.

stream deposition accumulation of transported particles on a streambed, on the adjacent floodplain, or in a body of standing water.

stream erosion progressive removal of mineral particles from the floor or sides of a stream channel by drag force of the moving water, or by abrasion, or by corrosion.

stream gradient rate of descent to lower elevations along the length of a stream channel, stated in m/km, ft/mi, degrees, or percent.

stream load solid matter carried by a stream in dissolved form (as ions), in turbulent suspension, and as bed load.

stream order ranking of streams and stream segments in a drainage system, with the smallest streams first-order.

stream profile a graph of the elevation of a stream plotted against its distance downstream.

stream transportation downvalley movement of eroded particles in a stream channel in solution, in turbulent suspension, or as bed load.

streamflow water flow in a stream channel; same as channel flow.

strike compass direction of the line of intersection of an inclined rock plane and a horizontal plane of reference. (See also *dip*.)

strike-slip fault variety of fault on which the motion is dominantly horizontal along a near-vertical fault plane.

strip mining mining method in which overburden is first removed from a seam of coal, or a sedimentary ore, allowing the coal or ore to be extracted.

structure (of a system) the pattern of the pathways and their interconnections within a flow system.

subantarctic low-pressure belt persistent belt of low atmospheric pressure centered about at lat. 65° S over the Southern Ocean.

subantarctic zone latitude zone lying between lat. 55° and 60° S (more or less) and occupying a region between the midlatitude zone and the antarctic zone.

subarctic zone latitude zone between lat. 55° and 60° N (more or less), occupying a region between the midlatitude zone and the arctic zone.

subboreal stage third climatic period within the Holocene epoch with below-average temperatures.

subduction descent of the downbent edge of a lithospheric plate into the asthenosphere so as to pass beneath the edge of the adjoining plate.

sublimation process of change of ice (solid state) to water vapor (gaseous state); in meteorology, sublimation also refers to the change of state from water vapor (liquid) to ice (solid), which is referred to as deposition in this text.

submergence inundation or partial drowning of a former land surface by a rise of sea level or a sinking of the crust, or both.

suborder a unit of soil classification representing a subdivision of the soil order.

subsea permafrost permafrost lying below sea level, found in a shallow offshore zone fringing the arctic seacoast.

subsequent stream stream that develops its course by stream erosion along a band or belt of weaker rock.

subsolar point point on the Earth's surface at which solar rays are perpendicular to the surface.

subsurface water water of the lands held in soil, regolith, or bedrock below the surface.

subtropical broadleaf evergreen forest a formation class of the forest biome composed of broadleaf evergreen trees; occurs primarily in the regions of the moist subtropical climate ⑥.

subtropical evergreen forest a subdivision of the forest biome composed of both broadleaf and needleleaf evergreen trees.

subtropical high-pressure belts belts of persistent high atmospheric pressure trending east–west and centered about on lat. 30° N and S.

subtropical jet stream jet stream of westerly winds forming at the tropopause, just above the Hadley cell.

subtropical needleleaf evergreen forest a formation class of the forest biome composed of needleleaf evergreen trees occurring in the moist subtropical climate ⑥ of the southeastern United States; also referred to as the southern pine forest.

subtropical zones latitude zones occupying the region of lat. 25° to 35° N and S (more or less) and lying between the tropical zones and the midlatitude zones.

succulents plants adapted to resist water losses by means of thickened spongy tissue in which water is stored.

summer monsoon inflow of maritime air at low levels from the Indian Ocean toward the Asiatic low-pressure center in the season of high Sun; associated with the rainy season of the wet–dry tropical climate ③ and the Asiatic monsoon climate.

summer solstice June solstice in the northern hemisphere.

summer time daylight savings time.

Sun-synchronous orbit satellite orbit in which the orbital plane remains fixed in position with respect to the Sun.

supercell thunderstorm strong, single-cell convective storm that persists for many hours and is usually accompanied by severe weather including downbursts, hail, and possible tornado formation.

supercontinent single world continent, formed when plate tectonic motions move continents together into a single, large land mass. (See also *Pangaea*.)

supercontinent cycle plate tectonic cycle in which a supercontinent breaks apart, forming smaller continents that later reform into another supercontinent.

supercooled water water existing in the liquid state at a temperature lower than the normal freezing point.

surface the very thin layer of a substance that receives and radiates energy and conducts heat to and away from the substance.

surface energy balance equation equation expressing the balance among heat flows to and from a surface.

surface water water of the lands flowing freely (as streams) or impounded (as ponds, lakes, marshes).

surges episodes of very rapid downvalley movement within an alpine glacier.

suspended load that part of the stream load carried in turbulent suspension.

suspension (See *turbulent suspension*.)

suture (See *continental suture*.)

swash surge of water up the beach slope (landward) following collapse of a breaker.

symbiosis form of positive interaction between species that is beneficial to one of the species and does not harm the other.

sympatric speciation type of speciation in which speciation occurs within a larger population.

synclinal mountain steep-sided ridge or elongate mountain developed by erosion of a syncline.

synclinal valley valley eroded on weak strata along the central trough or axis of a syncline.

syncline downfold of strata (or other layered rock) in a trough-like structure; a class of folds. (See also *anticline.*)

synthesis a perspective of geography that focuses on putting together ideas from different fields and assembling them in new ways.

system (1) a collection of things that are somehow related or organized; (2) a scheme for naming, as in a classification system; (3) a flow system of matter and energy.

systematic geography the study of the physical, economic, and social processes that differentiate the Earth's surface into places.

systems approach the study of the interconnections among natural processes by focusing on how, where, and when natural systems are linked and interconnected.

systems theory body of knowledge explaining how systems work.

T

taiga plant formation class consisting of woodland with low, widely spaced trees and a ground cover of lichens and mosses, found along the northern fringes of the region of boreal forest climate ⑪; also called cold woodland.

tailings (See *spoil.*)

talik pocket or region within permafrost that is unfrozen; ranges from small inclusions to large "holes" in permafrost under lakes.

tall-grass prairie a formation class of the grassland biome that consists of tall grasses with broad-leaved herbs.

talus accumulation of loose rock fragments derived by fall of rock from a cliff.

talus slope slope formed of talus.

tar sand (See *bitumen.*)

tarn small lake occupying a rock basin in a cirque of glacial trough.

tectonic activity process of bending (folding) and breaking (faulting) of crustal mountains, concentrated on or near active lithospheric plate boundaries.

tectonic arc long, narrow chain of islands or mountains or a narrow submarine ridge adjacent to a subduction boundary and its trench, formed by tectonic processes, such as the construction and rise of an accretionary prism.

tectonic crest ridge-like summit line of a tectonic arc associated with an accretionary prism.

tectonics branch of geology relating to tectonic activity and the features it produces. (See also *plate tectonics, tectonic activity.*)

temperature gradient rate of temperature change along a selected line or direction.

temperature inversion upward reversal of the normal environmental temperature lapse rate, so that the air temperature increases upward. (See also *high-level temperature inversion, low-level temperature inversion.*)

temperature regime distinctive type of annual temperature cycle.

tephra collective term for all size grades of solid igneous rock particles blown out under gas pressure from a volcanic vent.

terminal moraine moraine deposited as an embankment at the terminus of an alpine glacier or at the leading edge of an ice sheet.

terrane continental crustal rock unit having a distinctive set of lithologic properties, reflecting its geologic history, that distinguish it from adjacent or surrounding continental crust.

terrestrial ecosystems ecosystems of land plants and animals found on upland surfaces of the continents.

tetraploid having four sets of chromosomes instead of a normal two sets.

thematic map map showing a single type of information.

theme category or class of information displayed on a map.

thermal circulation motion of air toward a warmer region at low levels and away from the warmer region at high levels.

thermal erosion in regions of permafrost, the physical disruption of the land surface by melting of ground ice, brought about by removal of a protective organic layer.

thermal infrared a portion of the infrared radiation wavelength band, from approximately 6 to 300 μm, in which objects at temperatures encountered on the Earth's surface (including fires) emit electromagnetic radiation.

thermal pollution form of water pollution in which heated water is discharged into a stream or lake from the cooling system of a power plant or other industrial heat source.

thermistor electronic device that measures (air) temperature.

thermocline water layer of a lake or the ocean in which temperature changes rapidly in the vertical direction.

thermohaline circulation a slow flow of ocean water linking all ocean basins, driven by the sinking of cold, salty surface water at the northern edge of the Atlantic Ocean.

thermokarst in arctic environments, an uneven terrain produced by thawing of the upper layer of permafrost, with settling of sediment and related water erosion; often occurs when the natural surface cover is disturbed by fire or human activity.

thermokarst lake shallow lake formed by the thawing and settling of permafrost, usually in response to disturbance of the natural surface cover by fire or human activity.

thermometer instrument measuring temperature.

thermometer shelter louvered wooden cabinet of standard construction used to hold thermometers and other weather-monitoring equipment.

thermosiphon device that pumps heat from the ground, keeping permafrost from thawing.

thermosphere atmospheric layer of upwardly increasing temperature, lying above the mesopause.

thorntree semidesert formation class within the desert biome, transitional from grassland biome and savanna biome and consisting of xerophytic trees and shrubs.

thorntree-tall-grass savanna plant formation class, transitional between the savanna biome and the grassland biome, consisting of widely scattered trees in an open grassland.

thrust sheet sheet-like mass of rock moving forward over a low-angle overthrust fault.

thunderstorm intense, local convectional storm associated with a cumulonimbus cloud and yielding heavy precipitation, also with lightning and thunder, and sometimes the fall of hail.

tidal current current set in motion by the ocean tide.

tidal inlet narrow opening in a barrier island or baymouth bar through which tidal currents flow.

tide (See *ocean tide.*)

tide curve graphical presentation of the rhythmic rise and fall of ocean water because of ocean tides.

till heterogeneous mixture of rock fragments ranging in size from clay to boulders, deposited beneath moving glacial ice or directly from the melting in place of stagnant glacial ice.

till plain undulating, plain-like land surface underlain by glacial till.

time cycle in flow systems, a regular alternation of flow rates with time.

time zones zones or belts of given east–west (longitudinal) extent within which standard time is applied according to a uniform system.

topographic contour isopleth of uniform elevation appearing on a map.

tornado small, very intense wind vortex with extremely low air pressure in center, formed beneath a dense cumulonimbus cloud in proximity to a cold front.

trade winds (trades) surface winds in low latitudes, representing the low-level airflow within the tropical easterlies.

transcurrent fault fault on which the relative motion is dominantly horizontal, in the direction of the strike of the fault; also called a strike-slip fault.

transform fault special case of a strike-slip fault making up the boundary of two moving lithospheric plates; usually found along an offset of the midoceanic ridge where seafloor spreading is in progress.

transform plate boundary lithospheric plate boundary along which two plates are in contact on a transform fault; the relative motion is that of a strike-slip fault.

transform scar linear topographic feature of the ocean floor taking the form of an irregular scarp or ridge and originating at the offset axial rift of the midoceanic ridge; it represents a former transform fault but is no longer a plate boundary.

transformation (soils) a class of soil-forming processes that transform materials within the soil body; examples include mineral alteration and humification.

translocation a soil-forming process in which materials are moved within the soil body, usually from one horizon to another.

transpiration evaporative loss of water to the atmosphere from leaf pores of plants.

transportation (See *stream transportation.*)

transported regolith regolith formed of mineral matter carried by fluid agents from a distant source and deposited on the bedrock or on older regolith; examples: floodplain silt, lake clay, beach sand.

transverse dunes field of wave-like sand dunes with crests running at right angles to the direction of the prevailing wind.

traveling anticyclone center of high pressure and outspiraling winds that travels over the Earth's surface; often associated with clear, dry weather.

traveling cyclone center of low pressure and inspiraling winds that travels over the Earth's surface; includes wave cyclones, tropical cyclones, and tornadoes.

travertine carbonate mineral matter, usually calcite, accumulating on limestone cavern surfaces situated in the unsaturated zone.

tree large erect woody perennial plant typically having a single main trunk, few branches in the lower part, and a branching crown.

trellis drainage pattern drainage pattern characterized by a dominant parallel set of major subsequent streams, joined at right angles by numerous short tributaries; typical of coastal plains and belts of eroded folds.

TRMM Tropical Rainfall Measuring Mission, American-Japanese Earth-observation satellite mission to measure and map rainfall in the tropical and equatorial zones.

Tropic of Cancer parallel of latitude at 23½° N.

Tropic of Capricorn parallel of latitude at 23½° S.

tropical cyclone intense traveling cyclone of tropical and subtropical latitudes, accompanied by high winds and heavy rainfall.

tropical depression tropical cyclone with a closed low and wind speeds lower than 17 m/s (38 mi/hr).

tropical desert desert within the tropical zone, near the Tropic of Cancer or Capricorn.

tropical easterlies low-latitude wind system of persistent airflow from east to west between the two subtropical high-pressure belts.

tropical easterly jet stream upper-air jet stream of seasonal occurrence, running east to west at very high altitudes over Southeast Asia.

tropical high-pressure belt a high-pressure belt occurring in tropical latitudes at a high level in the troposphere; extends downward and poleward to form the subtropical high-pressure belt, located at the surface.

tropical storm tropical cyclone with a closed low and wind speeds between 17 to 33 m/s (38 to 74 mi/hr).

tropical zones latitude zones centered on the Tropic of Cancer and the Tropic of Capricorn, within the latitude ranges 10° to 25° N and 10° to 25° S, respectively.

tropical-zone rainforest plant formation class within the forest biome similar to equatorial rainforest, but occurring farther poleward in tropical regions.

tropopause boundary between troposphere and stratosphere.

tropophyte plant that sheds its leaves and enters a dormant state during a dry or cold season when little soil water is available.

troposphere lowermost layer of the atmosphere in which air temperature falls steadily with increasing altitude.

trough in describing water waves, the lowest part of the wave form.

tsunami train of sea waves set off by an earthquake (or other seafloor disturbance) traveling over the ocean surface.

tundra (See *arctic tundra.*)

tundra biome biome of the cold regions of arctic tundra and alpine tundra, consisting of grasses, grass-like plants, flowering herbs, dwarf shrubs, mosses, and lichens.

tundra climate ⑫ cold climate of the arctic zone with eight or more consecutive months of zero potential evapotranspiration (water need).

turbulence in fluid flow, the motion of individual water particles in complex eddies, superimposed on the average downstream flow path.

turbulent flow mode of fluid flow in which individual fluid particles (molecules) move in complex eddies, superimposed on the average downstream flow path.

turbulent suspension stream transportation in which particles of sediment are held in the body of the stream by turbulent eddies. (Also applies to wind transportation.)

twilight solar radiation from below the horizon that is scattered toward the ground by the atmosphere to provide illumination after the Sun has set or before it has risen.

typhoon tropical cyclone of the western North Pacific and coastal waters of Southeast Asia.

U

Udalfs suborder of the soil order Alfisols; includes Alfisols of moist regions, usually in the midlatitude zone, with deciduous forest as the natural vegetation.

Udolls suborder of the soil order Mollisols; includes Mollisols of the moist soil-water regime in the midlatitude zone and with no horizon of calcium carbonate accumulation.

Ultisols soil order consisting of soils of warm soil temperatures with an argillic horizon and low base status.

ultramafic igneous rock igneous rock composed almost entirely of mafic minerals, usually olivine or pyroxene group.

ultraviolet radiation electromagnetic energy in the wavelength range of 0.2 to 0.4 μm.

unloading (See *exfoliation.*)

urban heat island zone of warmer temperatures in the center of a city produced by enhanced absorption of solar radiation by urban surfaces and by waste heat release.

unsaturated zone subsurface water zone in which pores are not fully saturated, except at times when infiltration is very rapid; lies above the saturated zone.

unstable air air with substantial content of water vapor, capable of breaking into spontaneous convectional activity leading to the development of heavy showers and thunderstorms.

unstable isotope elemental isotope that spontaneously decays to produce one or more new isotopes. (See also *daughter product.*)

upper-air westerlies system of westerly winds in the upper atmosphere over middle and high latitudes.

upwelling upward motion of cold, nutrient-rich ocean waters, often associated with cool equatorward currents occurring along continental margins.

urban heat island zone of warmer temperatures in the center of a city produced by enhanced absorption of solar radiation by urban surfaces and by waste heat release.

Ustalfs suborder of the soil order Alfisols; includes Alfisols of semiarid and seasonally dry climates in which the soil is dry for a long period in most years.

Ustolls suborder of the soil order Mollisols; includes Mollisols of the semiarid climate in the midlatitude zone, with a horizon of calcium carbonate accumulation.

V

valley winds air movement at night down the gradient of valleys and the enclosing mountainsides; alternating with daytime mountain winds.

variation in the study of evolution, natural differences arising between parents and offspring as a result of mutation and recombination.

varve annual layer of sediment on the bottom of a lake or the ocean marked by a change in color or texture of the sediment.

veins small, irregular, branching network of intrusive rock within a preexisting rock mass.

verbal description in the representation perspective of geography, the use of written or oral text to describe geographic phenomena.

vernal equinox March equinox in the northern hemisphere.

Vertisols soil order consisting of soils of the subtropical zone and the tropical zone with high clay content, developing deep, wide cracks when dry, and showing evidence of movement between aggregates.

viewpoint a unique perspective of geography that considers where and how phenomena occur and how they are related to other phenomena nearby and far away.

visible light electromagnetic energy in the wavelength range of 0.4 to 0.7 μm.

visual display in the representation perspective of geography, tools such as cartography and remote sensing that display spatial information visually.

void empty region of pore space in sediment; often occupied by water or water films.

volcanic bombs boulder-sized, semisolid masses of lava that are ejected from an erupting volcano.

volcanic neck isolated, narrow steep-sided peak formed by erosion of igneous rock previously solidified in the feeder pipe of an extinct volcano.

volcanism general term for volcano building and related forms of extrusive igneous activity.

volcano conical, circular structure built by accumulation of lava flows and tephra. (See also *shield volcano, stratovolcano.*)

volcano coast coast formed by volcanoes and lava flows built partly below and partly above sea level.

W

warm front moving weather front along which a warm air mass is sliding up over a cold air mass, leading to production of stratiform clouds and precipitation.

warm-blooded animal animal that possesses one or more adaptations to maintain a constant internal temperature despite fluctuations in the environmental temperature.

warm-core ring circular eddy of warm water, surrounded by cold water and lying adjacent to a warm, poleward moving ocean current, such as the Gulf Stream. (See also *cold-core ring.*)

washout downsweeping of atmospheric particulates by precipitation.

water gap narrow transverse gorge cut across a narrow ridge by a stream, usually in a region of eroded folds.

water need (See *potential evapotranspiration.*)

water resources a field of study that couples basic study of the location, distribution, and movement of water with the utilization and quality of water for human use.

watershed (See *drainage basin.*)

water surplus water disposed of by runoff or percolation to the ground water zone after the storage capacity of the soil is full.

water table upper boundary surface of the saturated zone; the upper limit of the ground water body.

water use (See *actual evapotranspiration.*)

water vapor the gaseous state of water.

waterfall abrupt descent of a stream over a bedrock step in the stream channel.

waterlogging rise of a water table in alluvium to bring the zone of saturation into the root zone of plants.

watt unit of power equal to the quantity of work done at the rate of one joule per second; symbol, W.

wave cyclone (See *midlatitude cyclone.*)

wave height in describing water waves, the height of the wave as measured from the top of the crest to the bottom of the trough.

wave length in describing water waves, the length of the wave from crest to crest or trough to trough.

wave period in describing water waves, time in seconds between successive crests or successive troughs that pass a fixed point.

wave-cut notch rock recess at the base of a marine cliff where wave impact is concentrated.

weak equatorial low weak, slowly moving low-pressure center (cyclone) accompanied by numerous convectional showers and thunderstorms; it forms close to the intertropical convergence zone in the rainy season or summer monsoon.

weather physical state of the atmosphere at a given time and place.

weather system recurring pattern of atmospheric circulation associated with characteristic weather, such as a cyclone or anticyclone.

weathering total of all processes acting at or near the Earth's surface to cause physical disruption and chemical decomposition of rock. (See also *chemical weathering, physical weathering.*)

west-wind drift ocean drift current moving eastward in zone of prevailing westerlies.

westerlies (See *prevailing westerly winds, upper-air westerlies.*)

wet equatorial climate ① moist climate of the equatorial zone with a large annual water surplus, and with uniformly warm temperatures throughout the year.

wet-dry tropical climate ③ climate of the tropical zone characterized by a very wet season alternating with a very dry season.

wetlands land areas of poor surface drainage, such as marshes and swamps.

Wilson cycle plate tectonic cycle in which continents rupture and pull apart, forming oceans and oceanic crust, then converge and collide with accompanying subduction of oceanic crust.

wilting point quantity of stored soil water, less than which the foliage of plants not adapted to drought will wilt.

wind air motion, dominantly horizontal relative to the Earth's surface.

wind abrasion mechanical wearing action of wind-driven mineral particles striking exposed rock surfaces.

wind chill index index in °F used in the United States to express how cold the air feels to the skin when the wind is blowing.

wind shear a change in wind speed or direction with height.

wind vane weather instrument used to indicate wind direction.

window (radiation) region of the spectrum in the thermal infrared where Earth radiation escapes to space.

winter monsoon outflow of continental air at low levels from the Siberian high, passing over Southeast Asia as a dry, cool northerly wind.

winter solstice December solstice in the northern hemisphere.

Wisconsinan Glaciation last glaciation of the Pleistocene epoch.

woodland plant formation class, transitional between forest biome and savanna biome, consisting of widely spaced trees with canopy coverage between 25 and 60 percent.

X

X-rays electromagnetic radiation of wavelength 0.005 to 10 nm; may be hazardous to health.

Xeralfs suborder of the soil order Alfisols; includes Alfisols of the Mediterranean climate ⑦.

xeric animals animals adapted to dry conditions typical of a desert climate.

Xerolls suborder of the soil order Mollisols; includes Mollisols of the Mediterranean climate ⑦.

xerophytes plants adapted to a dry environment.

Y

youthful stage in Davis's geographic cycle, a stage of erosion with steep slopes and river gradients.

Z

zooplankton microscopic animals found largely in the uppermost layer of ocean or lake water.

Illustration Credits

Introduction Page 18: A. N. Strahler; Page 20 (top): U.S. Geological Survey; Page 20 (left): After J. P. Cole and C. A. M. King, *Quantitative Geography,* copyright © John Wiley & Sons, London. Used by permission; Page 21 (top): Modified from U.S. Army Corps of Engineers; Page 21 (bottom): From P. Gersmehl, *Annals of the Assoc. of Amer. Geographers*, vol. 67. Copyright © Association of American Geographers. Used by permission; Page 29 (left): © A. N. Strahler.

Chapter 1 Page 40 (top left): Courtesy Mike Sandiford, Univ. of Melbourne; Page 48 (bottom): U.S. Navy Oceanographic Office.

Chapter 2 Page 58: NASA Media Services; Page 62: After W. D. Sellers, *Physical Climatology,* University of Chicago Press. Used by permission; Page 63 (middle): From A. N. Strahler, "The Life Layer," *Journal of Geography*, vol. 69, Figure 2.4. Used by permission; Page 66: Copyright © A. N. Strahler. Used by permission; Page 67 (left): Copyright © A. N. Strahler. Used by permission; Page 70: Copyright © A .N. Strahler. Used by permission.

Chapter 3 Page 84: Mauna Loa Observatory; Page 93 (top and bottom): Courtesy NOAA; Page 104: After Hansen et al., 2000, *Proc. National Academy of Sciences*, revised 2009. Used by permission; Page 105: James Hansen/NASA Goddard Institute of Space Sciences; Page 106 (upper): IPCC, 2001. Used by permission.

Chapter 4 Page 113 (bottom): National Atmospheric Deposition Program (NRSp-3)/National Trends Network, Illinois State Water Survey; Page 116: Based on data of John R. Mather; Page 117: Data of J. von Hann, R. Süring, and J. Szava-Kovats as shown in Haurwitz and Austin, *Climatology*; Page 120: Copyright © A. N. Strahler; Page 121: Copyright © A. N. Strahler; Page 133 (upper right): R. H. Skaggs, *Proc. Assoc. American Geographers,* vol. 6, Figure 2. Used by permission; Page 137: Adapted from diagrams by Research Applications Program, National Center for Atmospheric Research, Boulder, Colorado; Page 141: Data from EPA.

Chapter 5 Page 161: Data compiled by John E. Oliver; Page 163: Data compiled by John E. Oliver; Page 164: Data compiled by John E. Oliver; Page 168 (left): Copyright © A. N. Strahler; Page 168 (upper right): After National Weather Service; Page 169: Copyright © A. N. Strahler. Used by permission; Page 173: Copyright © A. N. Strahler. Used by permission; Page 175: Copyright © A. N. Strahler; Page 175 (left): National Weather Service; Page 176: Courtesy NOAA; Page 178: From Murck, Barbara W., Brian J. Skinner, and Dana Mackenzie, *Visualizing Geology.* Copyright © 2008 John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.

Chapter 6 Page 188: Data from U.S. Dept of Commerce; Page 189: Drawn by A. N. Strahler; Page 189: Drawn by A. N. Strahler; Page 190: Drawn by A. N. Strahler; Page 199: Based on data of S. Pettersen, B. Haurwitz, and N. M. Austin, J. Namias, M. J. Rubin, and J-H. Chang; Page 200: After M. A. Garbell; Page 201: Data from H. Riehl, *Tropical Meteorology*, New York: McGraw-Hill; Page 202: Redrawn from NOAA, National Weather Service; Page 203: Courtesy NASA and National Hurricane Center. Image published on Wikipedia; Page 204: Based on data of S. Pettersen, B. Haurwitz and N. M. Austin, J. Namias, M. J. Rubin, and J-H. Chang; Page 208: NASA.

Chapter 7 Page 219 (bottom): Courtesy of Sharon E. Nicholson, Department of Meteorology, Florida State University, Tallahassee; Page 223: From Strahler, Alan and Arthur Strahler, *Physical Geography: Science and Systems of the Human Environment,* 3rd ed. Copyright © 2005 John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc; Page 226–227: Simplified and modified from Plate 3, "World Climatology," Volume I, *The Times Atlas,* Editor John Bartholomew, The Times Publishing Company, Ltd., London, 1958; Page 230: Compiled by A. N. Strahler from station data.

Chapter 8 Page 267 (top): Data from UN/IPCC; Page 270: Food chain after R. L. Smith, *Ecology and Field Biology,* Harper and Row, New York; Page 272 (bottom): Data of Stofelt, in A.C. Leopold, *Plant Growth and Development*, McGraw-Hill, New York; Page 273: Compiled by the National Science Board, National Science Foundation; Page 277: After P. Dansereau; Page 284: After D.I. Rasmussen, *Ecological Monographs*, vol. 11, 1941, p. 23; Page 291: From J. H. Brown and M. V. Lomolino, *Biogeography,* second ed., 1998, Sinaeur, Sunderland, Massachusetts. Used by permission; Page 293: From H. J .B. Birks, *J. Biogeography,* vol. 16, pp. 503–540; Page 296: From J.H. Brown and M.V. Limolino, *Biogeography,* second ed., 1998, Sinauer, Sunderland, MA. Used by permission; Page 297 (upper): After Goode, 1974; Page 297 (lower): After Wallace, 1876; Page 298: Data from Nature Conservancy; Page 299: Conservation International.

Chapter 9 Page 308 (left): Global Forest Watch, WRI; Page 309 (right): USDA Global Desertification Vulnerability Map; Page 312–313: Based on maps of S. R. Eyre, 1968; Page 315: After J. S. Beard, *The Natural Vegetation of Trinidad,* Clarendon Press, Oxford; Page 317: Based on maps of S. R. Eyre, 1968; Page 318: Based on maps of S. R. Eyre, 1968; Page 321: Based on maps of S. R. Eyre, 1968; Page 322: Based on maps of S. R. Eyre, 1968; Page 323: Based on maps of S. R. Eyre, 1968; Page 325: Based on maps of S. R. Eyre, 1968; Page 328: Based on maps of S. R. Eyre, 1968; Page 330: Based on maps of S. R. Eyre, 1968; Page 336–337: Mark Friedl, Damien Sulla-Menashe, Bin Tan, Boston University; Page 338: Based on data of G. A. Pearson, C. H. Merriam, and A. N. Strahler.

Chapter 10 Page 352: Copyright © A. N. Strahler. Used by permission; Page 353: After Natural Resources Conservation Service, USDA; Page 358-359: Based on data of Natural Resources Conseration Service, USDA.

Chapter 11 Page 381: Copyright © A. N. Strahler; Page 386: Copyright © A. N. Strahler; Page 387: Based in part on data of R. E. Murphy, P. M. Hurley, and others; Page 391: Based on diagrams by A. Heim, 1922, *Geologie der Schweiz,* vol. II-1, Tauschnitz, Leipzig; Page 392: Copyright © A. N. Strahler; Page 392: Copyright © A. N. Strahler; Page 393: NG Image Collection; Page 394: Copyright © A. N. Strahler; Page 396: From *Plate Tectonics,* Arthur N. Strahler, 1998, GeoBooks Publishing. Used by permission; Page 397: Copyright © A. N. Strahler; Page 398: From *Plate Tectonics,* Arthur N. Strahler, 1998, GeoBooks Publishing. Used by permission; Page 398: From *Plate Tectonics,* Arthur N. Strahler, 1998, GeoBooks Publishing. Used by permission; Page 399: From A. Wegener, 1915, *Die Entsechung der Kontinente und Ozeane,* F. Vieweg, Braunschweig.

Chapter 12 Page 408: Drawn by A. N. Strahler; Page 408: Copyright © A. N. Strahler; Page 409 (upper): After data of NOAA. Copyright © A. N. Strahler; Page 409 (lower): Midoceanic ridge map copyright © A. N. Strahler; Page 410: Illustration by Frank Ippolito; Page 412: Drawn by Erwin Raisz. Copyright © A. N. Strahler; Page 413: Copyright © A. N. Strahler; Page 414: Copyright © A. N. Strahler; Page 415: Drawn by A. N. Strahler; Page 419 (lower): After E. Raisz; Page 420 (upper and lower left): Drawn by A. N. Strahler; Page 420 (lower right): Drawn by Erwin Raisz. Copyright © A. N. Strahler; Page 421 (middle, lower): A. N. Strahler; Page 423: Drawn by A. N. Strahler. Copyright © A. N. Strahler; Page 426 (upper): Compiled by A. N. Strahler from data of U.S. government. Copyright © A. N. Strahler; Page 426 (lower): Midoceanic ridge map copyright © A. N. Strahler; Page 430: Drawn by A. N. Strahler; Page 431: Drawn by A. N. Strahler; Page 431: Drawn by A. N. Strahler; Page 432: Drawn by A. N. Strahler; Page 433: Drawn by A. N. Strahler; Page 434: Drawn by A. N. Strahler.

Chapter 13 Page 443: Drawn by A. N. Strahler; Page 449: Drawn by A. N. Strahler; Page 449: After C. F. S. Sharpe; Page 450: After A. N. Strahler; Page 451: Drawn by A. N. Strahler; Page 453: Data from Canadian Geological Survey, Department of Mines. Drawn by A. N. Strahler. Copyright © A. N. Strahler; Page 456: Adapted from Troy L. Péwé, *Geotimes,* vol. 29, no. 2, p. 11, Copyright © 1984 by the American Geological Institute; Page 457: Adapted by permission from A. H. Lachenbruch in Rhodes W. Fairbridge, Ed., *The Encyclopedia of Geomorphology*, New York, Reinhold Publishing Corp; Page 459: After A. L. Washburn; Page 461: Adapted from C. F. S. Sharpe, *Landslides and Related Phenomena*, p. 37, Fig. 5, New York, Columbia University Press. Used by permission of the publisher.

Chapter 14 Page 471: Drawn by A. N. Strahler; Page 474: Drawn by Erwin Raisz. Copyright © A. N. Strahler; Page 474: Copyright © A. N. Strahler; Page 475: Drawn by Erwin Raisz. Copyright © A. N. Strahler; Page 477: A. H. Strahler; Page 479: Copyright © A. N. Strahler; Page 480 (lower left): Copyright © A. N. Strahler; Page 481: After U.S. Geological Survey; Page 481: Data of U.S. Geological Survey and Mark A. Melton; Page 482: After Hoyt and Langbein, *Floods,* Copyright © Princeton University Press. Used by permission; Page 483: Data of U.S. Geological Survey; Page 487: Redrawn from *A Geologist's View of Cape Cod*, Copyright © A. N. Strahler, 1966; Page 487 (upper): © A. N. Strahler; Page 487 (lower): Modified from A. N. Strahler, *The Earth Sciences.* Used by permission.

Chapter 15 Page 497: A. N. Strahler; Page 499: Data of S. J. Ursic U.S.D.A; Page 504: Copyright © A. N. Strahler; Page 505: Drawn by Erwin Raisz. Copyright © A .N. Strahler; Page 511: Drawn by A. N. Strahler; Page 512: Drawn by A. N. Strahler; Page 513: Drawn by Erwin Raisz. Copyright © A. N. Strahler; Page 514: Copyright © A. N. Strahler; Page 515: Copyright © A. N. Strahler; Page 516: Drawn by A. N. Strahler; Page 518: Drawn by A. N. Strahler.

Chapter 16 Page 527: Copyright © A. N. Strahler; Page 527: Copyright © A. N. Strahler; Page 528: After W. M. Davis; Page 530: Drawn by E. Raisz; Page 533: Copyright © A. N. Strahler; Page 535: Drawn by A. N. Strahler; Page 536: Drawn by A. N. Strahler; Page 537: Inset drawn by A. N. Strahler; Page 537: Inset drawn by A. N. Strahler; Page 538: Inset drawn by A. N. Strahler; Page 539: Inset drawn by A. N. Strahler; Page 540: Inset drawn by A. N. Strahler; Page 540: Inset drawn by A. N. Strahler; Page 541: Drawn by A. N. Strahler; Page 542: Chris Orr/ National Geographic; Page 545: Drawn by A. N. Strahler; Page 547: Drawn by A. N. Strahler; Page 548: Drawn by A. N. Strahler; Page 549: Data from *Map of Pleistocene Eolian Deposits of the United States,* Geological Society of America.

Chapter 17 Page 556: Adapted with permission from C.R. Bentley, *Science* Vol. 275, p. 1077. Copyright © American Association for the Advancement of Science; Page 560: After A. N. Strahler; Page 566: Based on data of R. F. Flint, *Glacial and Pleistocene Geology,* John Wiley & Sons, New York; Page 566: Based on data of American Geophysical Union; Page 569: Copyright © A. N. Strahler; Page 570: Drawn by A. N. Strahler; Page 572: Based on data of R. F. Flint, *Glacial and Pleistocene Geology,* John Wiley & Sons, New York; Page 573: Courtesy of Prof. Thomas Crowley, Duke University; Page 576: Based on calculations by A.D. Vernekar, 1968. Copyright © A. N. Strahler.

Photo Credits

Introduction Page 2 & 3: Yann Arthus-Bertrand/Altitude; Page 6: Floris Leeuwenberg/Corbis; Page 8 (top): David Olsen/Weatherstock; Page 8 (bottom left): Digital Vision/Getty Images, Inc.; Page 8 (bottom right): James Randklev/Getty Images, Inc.; Page 9 (right): Fletcher & Baylis/Photo Researchers, Inc.; Page 9 (top): Danita Delimont/Alamy; Page 9 (right): Digital Vision/Getty Images; Page 10 (top): iStock; Page 10 (center): Andy Rouse/The Image Bank/Getty Images, Inc.; Page 10 (bottom left): Don Klumpp/Photographers Choice/Getty Images, Inc.; Page 10 (bottom right): Art Wolfe/Photo Researchers, Inc.; Page 12 (left): Courtesy EUMETSAT, Germany; Page 12 (right): (c) Fugro NPA Limited; Page 13 (left): Earth Satellite Corporation/Photo Researchers, Inc.; Page 13 (right): Jacques Descloitres, MODIS Land Rapid Response Team, Courtesy NASA, Visible Earth; Page 14 (center): imagebroker/Alamy; Page 14 (top left): Science Photo Library/Photo Researchers, Inc.; Page 14 (top right): Calvin Larsen/Photo Researchers, Inc.; Page 14 (bottom left): Mark Newman/Bruce Coleman, Inc.; Page 14 (bottom right): Dave Kaup/Corbis; Page 17 (left): Courtesy USGS; Page 17 (right): Selected graphic image supplied courtesy of Environmental Systems Research Institute, Inc. 2000, Environmental Systems Research Institute, Inc.; Page 17 (bottom): ORBIMAGE Orbital Imaging Corporation and SeaWiFS Project, NASA/Goddard Space Flight Center; Page 27: SAR image courtesy of Intera Technologies Corporation, Calgary, Alberta, Canada; Page 28 (top left): A. H. Strahler; Page 28 (top right): A. H. Strahler; Page 28 (bottom left): A. H. Strahler; Page 28 (bottom right): A. H. Strahler; Page 29 (left): A. H. Strahler; Page 29 (top right): Photo courtesy of Eastman Kodak Company; Page 30 (top): Image NASA, Image (c) 2007 TeraMetrics, http://www.truearth.com, Image (c) 2007 Europa Technologies, Image (c) 2007 DigitalGlobe; Page 30 (bottom): Image NASA, Image (c) 2007 TeraMetrics http://www.truearth.com, Image (c) 2007 Europa Technologies, Image (c) 2007 DigitalGlobe; Page 31 (bottom): Image NASA, Image (c) 2007 TeraMetrics http://www.truearth.com, Image (c) 2007 Europa Technologies, Image (c) 2007 DigitalGlobe.

Chapter 1 Page 36 & 37: Yann Arthus-Bertrand/Altitude; Page 39 (left): Courtesy NASA; Page 39 (right): Richard L. Carlton/Photo Researchers, Inc.; Page 42: National Maritime Museum, Greenwich, London; Page 43: Bridgeman Art Library/Getty Images; Page 51: Fred Hirschmann.

Chapter 2 Page 56 & 57: Yann Arthus-Bertrand/Altitude; Page 60: Courtesy Daedalus Enterprises, Inc. & National Geographic Magazine; Page 68 (center): Richard Nowitz/NG Image Collection; Page 68 (right): Tim Laman/NG Image Collection; Page 68 (top): Kike Calvo/V&W/The Image Works; Page 68 (bottom): George Steinmetz; Page 72 (left): Altrendo/Getty Images, Inc.; Page 72 (right): Jeremy Woodhoue/Masterfile; Page 72 (top): John Dunn/Arctic Light/NG Image Collection; Page 76 (bottom): Galaxy Contact/Explorer/Photo Researchers, Inc.; Page 76 (top left): Simon Fraser/Science Photo Library/Photo Researchers; Page 76 (top right): Joe Vogan/SuperStock Photo; Page 76 (bottom right): iStockphoto; Page 77: Courtesy NASA.

Chapter 3 Page 82 & 83: Yann Arthus-Bertrand/Altitude; Page 85: Michael Melford/NG Image Collection; Page 86: John Lawrence/Getty Images; Page 87: GIPhotoStock/Photo Researchers, Inc.; Page 89 (left): Ron Niebrugge/Alamy; Page 89 (right): Francois Goheir/Photo Researchers, Inc.; Page 90: Courtesy NASA/EPA. Provided by Dr. Dale Quattrochi, Marshall Space Flight Center; Page 91: Raymond Gehman/NG Image Collection; Page 97 (top): Ira Block/NG Image Collection; Page 97 (bottom): NG Image Collection; Page 106 (left): Peter Essick/Aurora Photos Inc.; Page 106 (top right): Taylor S. Kennedy/NG Image Collection; Page 106 (bottom right): Courtesy Rob Dunbar, Stanford University.

Chapter 4 Page 110 & 111: Yann Arthus-Bertrand/Altitude; Page 113 (left): Gerd Ludwig; Page 113 (right): Al Petteway/NG Image Collection; Page 115 (top left): Dr. Maurice G. Hornocker/NG Image Collection; Page 115 (top right): Bill Curtsinger/NG Image Collection; Page 115 (bottom left): Jodi Cobb/NG Image Collection; Page 115 (bottom right): Norbert Rosing/NG Image Collection; Page 119: Arthur N.Strahler; Page 122: Adalberto Rias Szalay/Sexto Sol/Photodisc/Getty Images; Page 123 (top left): John Eastcott and Yva Momatiuk/NG Image Collection; Page 123 (top right): Carsten Peter/NG Image Collection; Page 123 (bottom left): John Eastcott and Yva Momatiuk/NG Image Collection; Page 123 (bottom right): Todd Gipstein/NG Image Collection; Page 124 (top): Courtesy NASA. Image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters, and T. Neilsen; Page 124 (bottom): University of Wisconsin Space Science and Engineering Center; Page 125: (c)Ron Sanford/Stone/Getty Images; Page 131: Annie Griffiths Belt/NG Image Collection; Page 132: Dick Blume/Syracuse Newspapers//AP/Wide World Photos; Page 133 (top): (c)Nuridsany et Perennou/Photo Researchers; Page 133 (bottom): (c)John H. Hoffman/Bruce Coleman, Inc.; Page 134 (top left): Arthur N.Strahler; Page 134 (top right): Courtesy USGS, Branch of Quality Systems; Page 134 (bottom): NOAA; Page 137: Courtesy NOAA; Page 138: Richard Olsenius/NG Image Collection; Page 139 (top right): Priit Vesilind/NG Image Collection; Page 140 (top left): AFP PHOTO/YASSER AL-ZAYYAT/Getty Images; Page 140 (top right): Peter Carsten/NG Image Collection; Page 140 (center left): John McCombe/Getty Images; Page 140 (center right): Priit Vesilind/NG Image Collection; Page 140 (bottom left): Win Henderson/FEMA; Page 140 (bottom right): Greg Henshal/FEMA; Page 142: AP/Wide World Photos; Page 143: (c) John S. Shelton.

Chapter 5 Page 148 & 149: Yann Arthus-Bertrand/Altitude; Page 151 (top left): Courtesy Otis B. Brown, University of Miami, and Gene Carl Feldman, NASA/Goddard Space Flight Center; Page 151 (top right): Courtesy Otis B. Brown, University of Miami, and Gene Carl Feldman, NASA/Goddard Space Flight Center; Page 152:

Nick Caloyianis/NG Image Collection; Page 153: Bobby Model/NG Image Collection; Page 154: Courtesy Taylor Instrument Company and Wards Natural Science Establishment, Rochester, New York; Page 156: AP/Wide World Photos; Page 157 (top right): James Stevenson/Science Photo Library/ Photo Researchers; Page 157 (top left): Arthur N.Strahler; Page 162: Steve Raymer/NG Image Collection; Page 169: Courtesy NASA; Page 174: Courtesy Otis B. Brown, Robert Evans, and M. Carle, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Florida, and NOAA/Satellite Data Services Division; Page 175: Washington University; land layer by the SeaWiFS Project, fire maps from ESA, sea surface temperature layer from JPL and cloud layer by SSEC, U. Wisconsin.

Chapter 6 Page 182 & 183: Yann Arthus-Bertrand/Altitude; Page 185 (top): Courtesy EUMETSAT, Germany; Page 185 (center left): Raul Touzon/NG Image Collection; Page 185 (bottom right): John Eastcott and Yva Momatiuk/NG Image Collection; Page 186 (top right): David Doubilet/ NG Image Collection; Page 186 (bottom left): NG Image Collection; Page 186 (bottom right): John Dunn/NG Image Collection; Page 191: The Image Bank/ Getty Images; Page 192 (top): Courtesy NOAA; Page 192 (bottom): Courtesy NOAA; Page 193 (top): Courtesy NOAA; Page 193 (bottom): Courtesy NOAA; Page 197 (top): Courtesy David Dempsey, San Francisco State University; Page 200: Courtesy NASA; Page 202: Courtesy NOAA; Page 202 (inset): NG Maps; Page 206: NG Image Collection; Page 207 (center): FEMA News Photo; Page 207 (top): Ty Harrington/FEMA News; Page 207 (bottom): FEMA News Photo; Page 207 (just below center): Mark Wolfe/ FEMA; Page 207 (just below top): Andrea Booher/FEMA; Page 209: NASA/Goddard Space Flight Center; Page 210: AP/Wide World Photos; Page 211 (bottom left): Courtesy NASA.

Chapter 7 Page 216 & 217: Yann Arthus-Bertrand/Altitude; Page 219: Alain Nogues/ Corbis Sygma; Page 220 (right): John Dunn/ NG Image Collection; Page 220 (top left): George F. Mobley/NG Image Collection; Page 220 (bottom left): Rich Reid/NG Image Collection; Page 220 (bottom right): Tim Laman/NG Image Collection; Page 221 (top left): Jim Richardson/NG Image Collection; Page 221 (top right): John Dunn/ NG Image Collection; Page 221 (bottom left): Peter Carsten/NG Image Collection; Page 221 (bottom right): James P. Blair/ NG Image Collection; Page 233 (left): Justin Guariglia/NG Image Collection; Page 233 (right): Maciej Wojtkowiak/Alamy Images; Page 236 (top): William Albert Allard/ NG Image Collection; Page 236 (bottom): Raymond Gehman/NG Image Collection; Page 238: (c)Will & Deni McIntyre/Photo Researchers, Inc.; Page 240 (top): AP/ Wide World Photos; Page 240 (bottom left): Kari Niemelainen/Alamy Images; Page 240 (bottom right): bildagentur-online.com/th-foto/Alamy Images; Page 242 (top): Andrew McConnell/ Alamy; Page 242 (bottom): James P. Blair/ NG Image Collection; Page 243: Karsten Wrobel/Alamy Images; Page 244 (top): Richard Cummins/SUPERSTOCK; Page 244 (bottom): Jeff/Foott/Discovery Channel Images/Getty Images, Inc.; Page 246 (top): Raymond Gehman/NG Image Collection; Page 246 (bottom): Stephen Alvarez/NG Image Collection; Page 248: Sisse Brimberg/NG Image Collection; Page 249: David Alan Harvey/Magnum Photos, Inc.; Page 250 (top): Andre Jenny/ The Image Works; Page 250 (bottom): Jim Richardson/NG Image Collection; Page 252: Brand X/SUPERSTOCK; Page 253 (top): Gerd Ludwig; Page 253 (bottom): Doug Cheeseman/Alamy Images; Page 255: Hinrich Baesemann/Landov LLC; Page 256: Maria Stenzel/NG Image Collection.

Chapter 8 Page 264 & 265: Yann Arthus-Bertrand/Altitude; Page 267 (right): Bob Gibbons/Photo Researchers, Inc.; Page 267 (top): James P. Blair/NG Image Collection; Page 267 (bottom): Mark Moffett/Minden Pictures/NG Image Collection; Page 269 (top): Michio Hoshino/Minden Pictures, Inc.; Page 269 (bottom left): Raymond Gehman/NG Image Collection; Page 269 (bottom right): Joel Sartore/NG Image Collection; Page 270 (left): Berkeley/ Visuals Unlimited; Page 270 (center): Paul Whitten/Photo Researchers, Inc.; Page 270 (right): Corbis; Page 270 (bottom): David Lyons/Alamy; Page 270 (center left): Florida Images/Alamy; Page 270 (center right): Mike Baylan/U.S. Fish &Wildlife Service; Page 277: Raymond Gehman/ NG Image Collection; Page 278 (left): Annie Griffiths Belt/NG Image Collection; Page 278 (top): (c)Josef Muench; Page 278 (bottom): Michael and Patricia Fogden/ Corbis; Page 279 (left): Jeff Lepore/ Photo Researchers, Inc.; Page 279 (top): Roy Toft/NG Image Collection; Page 279 (bottom): Nick Caloyianis/NG Image Collection; Page 280 (left): Marc Moritsch/ NG Image Collection; Page 280 (right): Phil Shermeister/NG Image Collection; Page 281: Gregory G. Dimijian/Photo Researchers; Page 282: Kent Dannen/ Photo Researchers, Inc.; Page 283 (left): Paul Collis/Alamy; Page 283 (right): Francois Goheir/Photo Researchers, Inc.; Page 283 (bottom): Berverly Joubert/ NG Image Collection; Page 284: Mira/ Alamy; Page 285 (left): Phil Schermeister/ National Geographic/Getty Images, Inc.; Page 285 (right): Raymond Gehman/ NG Image Collection; Page 286 (top): Jeff Schmaltz MODIS Land Rapid Response Team, NASA GSFC; Page 286 (bottom): Los Angeles Times Syndicate; Page 287: NASA; Page 289 (top left): Bill Curtsinger/ NG Image Collection; Page 289 (top right): Jason Edwards/NG Image Collection; Page 289 (bottom left): Roy Toft/NG Image Collection; Page 289 (bottom right): Darlyne A. Murawski/NG Image Collection; Page 290 (left): Richard Parker/Photo Researchers; Page 290 (right): Wendy Neefus/Animals Animals/Earth Scenes; Page 292 (left): Eric Rorer/Aurora Photos; Page 292 (right): TUI DE ROY/MINDEN PICTURES/NG Image Collection; Page 293 (top): Joel Sartore/NG Image Collection; Page 293 (bottom): Wes C. Skiles/NG Image Collection; Page 294 (left): Chris Schenk/Minden Pictures/ NG Image Collection, NJ; Page 294 (right): Kenneth W. Fink/Photo Researchers; Page 295 (left): James P. Blair/NG Image Collection; Page 295 (right): S.W. Carter/ Photo Researchers; Page 296 (left): Tim Laman/NG Image Collection; Page 296 (center): Bates Littlehales/NG Image Collection; Page 296 (right): Joel Sartore/ NG Image Collection; Page 298 (left): Douglas Faulkner/Photo Researchers, Inc.; Page 298 (right): Corbis.

Chapter 9 Page 304 & 305: Yann Arthus-Bertrand/Altitude; Page 306: (c) Jacques Jangoux/Peter Arnold, Inc.; Page 307 (left): Jonathan Blair/Corbis Images; Page 307 (right): M.P. Kahl/ Photo Researchers; Page 308 (top): Digital Vision/Getty Images; Page 308 (bottom): Panos Pictures; Page 309 (top): Michael Nichols/NG Image Collection; Page 309 (bottom): Photoshot Holdings LTD/Alamy; Page 310: Raymond Gehman/NG Image Collection; Page 314 (bottom): Tim Laman/ NG Image Collection; Page 314 (top left): Tom & Susan Bean, Inc.; Page 314 (top right): Tim Laman/NG Image Collection; Page 318: John Shelton/NG Image Collection; Page 319 (left): George Gall/ NG Image Collection; Page 319 (right): Raymond Gehman/NG Image Collection; Page 320 (top left): Raymond Gehman/ NG Image Collection; Page 320 (top right): Raymond Gehman/NG Image Collection; Page 320 (bottom left): Joel Sartore/NG Image Collection; Page 320 (bottom right): Melissa Farlow/NG Image Collection; Page 321: (c)Michael Townsend/Stone/ Getty Images; Page 322: Raymond Gehman/ NG Image Collection; Page 324 (top): Rich Reid/Animals Animals/Earth Scenes; Page 324 (left): Peter Johnson/Corbis; Page 324 (right): Annie Griffiths Belt/ NG Image Collection; Page 326 (right): Norbert Rosing/NG Image Collection; Page 326 (top): Michael Nichols/NG Image Collection; Page 326 (bottom): Minden Pictures, Inc.; Page 327 (left): Joel Sartore/

NG Image Collection; Page 327 (right): Tom Bean/Corbis; Page 329 (left): Raymond Gehman/NG Image Collection; Page 329 (center): Joel Sartore/NG Image Collection; Page 329 (right): Bates Littlehales/NG Image Collection; Page 331: Rich Reid/NG Image Collection; Page 331 inset: Marcello Calandrini/Corbis; Page 332 (left): Bartlett, Des and Jen/NG Image Collection; Page 332 (right): Mattias Klum/NG Image Collection; Page 332 (top): Arthur N. Strahler; Page 333: Jorma Jaemsen/zefa/Corbis; Page 334 (left): Michael S. Quinton/NG Image Collection; Page 334 (right): Joel Sartore/NG Image Collection; Page 334 (bottom): Joel Sartore/NG Image Collection; Page 338 (left): Carr Clifton/Minden Pictures, Inc.; Page 338 (right): Jim Zipp/Photo Researchers, Inc.; Page 338 (bottom): U.S. Forest Service.

Chapter 10 Page 342 & 343: Yann Arthus-Bertrand/Altitude; Page 345 (top left): D. Russ Munn/AG Stock USA/Alamy; Page 345 (top right): TASS/Sovfoto/Eastfoto; Page 345 (bottom left): Leonard Lee Rue III/Bruce Coleman, Inc.; Page 345 (bottom right): Charlie Waite/Stone/Getty Images; Page 346: George F. Mobley/NG Image Collection; Page 348 (bottom): Marli Miller/Visuals Unlimited; Page 348 (top left): Tom Bean/Corbis; Page 348 (top right): Sam Abell/NG Image Collection; Page 350 (top): R. Schaetzl; Page 350 (bottom): James L. Amos/NG Image Collection; Page 353: Arthur N. Strahler; Page 357: Alan H. Strahler; Page 357: Estate of Henry D. Foth; Page 357: Estate of Henry D. Foth; Page 357: Estate of Henry D. Foth; Page 357: Estate of Henry D. Foth; Page 357: Estate of Henry D. Foth; Page 357: Estate of Henry D. Foth; Page 357: Courtesy Soil Conservation Service; Page 360 (right): Estate of Henry D. Foth; Page 360 (left): Alan H. Strahler; Page 361 (left): Estate of Henry D. Foth; Page 361 (right): James P. Blair/NG Image Collection; Page 362 (left): Estate of Henry D. Foth; Page 362 (right): William E. Ferguson; Page 363 (left): Estate of Henry D. Foth; Page 363 (right): Estate of Henry D. Foth; Page 364: Estate of Henry D. Foth; Page 365 (left): Estate of Henry D. Foth; Page 365 (right): Ric Ergenbright/Stone/Getty Images; Page 366: Steve Raymer/NG Image Collection; Page 367 (left): Estate of Henry D. Foth; Page 367 (center): Estate of Henry D. Foth; Page 367 (right): R. Schaetzl; Page 368 (left): Estate of Henry D. Foth; Page 368 (right): Courtesy Soil Conservation Service; Page 369: Ron Chapple Stock/Alamy.

Chapter 11 Page 372 & 373: Yann Arthus-Bertrand/Altitude; Page 375 (left): Carsten Peter/NG Image Collection; Page 375 (right): Michael Nichols/NG Image Collection; Page 377 (left): Ralph Lee Hopkins/NG Image Collection; Page 378: A. N. Strahler; Page 379 (top): Bill Hatcher/NG Image Collection; Page 379 (bottom center): Norbert Rosing/NG Image Collection; Page 379 (top center): Walter Meayers Edwards/NG Image Collection; Page 379 (bottom): Melissa Farlow/NG Image Collection; Page 380 (left): Gordon Wiltsie/NG Image Collection; Page 380 (top): (c)Carr Clifton//Minden Pictures, Inc.; Page 380 (bottom): Walter Meayers Edwards/NG Image Collection; Page 381 (top): Norbert Rosing/NG Image Collection; Page 381 (bottom): Melissa Farlow/NG Image Collection; Page 382 (left): Raymond Gehman/NG Image Collection; Page 382 (right): Michael P. Gadomski/Photo Researchers, Inc.; Page 385 (top left): John Sibbick/NG Image Collection; Page 385 (top right): Lloyd K. Townsend/NG Image Collection; Page 385 (bottom left): Marvin Mattelson/NG Image Collection; Page 385 (bottom right): NG Image Collection; Page 387: All Canada Photos/Alamy; Page 388: Jonathan Kingston/Aurora Photos Inc.; Page 390 (left): Copyright (c) 1995, David T. Sandwell. Used by permission; Page 390 (right): Copyright (c) 1995, David T. Sandwell. Used by permission; Page 395: Priit Vesilind/NG Image Collection.

Chapter 12 Page 404 & 405: Yann Arthus-Bertrand/Altitude; Page 407: Digital Globe/HO/AFP/Getty Images; Page 407 (bottom left): Courtesy DigitalGlobe; Page 407 (bottom right): Courtesy DigitalGlobe; Page 410 (left): James Mason/Black Star; Page 410 (right): K. Hamdorf/Auscape International Pty. Ltd; Page 411: Kevin West/Liaison Agency, Inc./Getty Images; Page 412 (top): John Richardson/NG Image Collection; Page 412 (bottom): Paul Chesley/NG Image Collection; Page 413: Frans Lanting/Danita Delimont; Page 414: Emory Kristof/NG Image Collection; Page 415 (top): Nasa Jet Propulsion Laboratory; Page 415 (bottom): A. N. Strahler; Page 416 (left): Image courtesy NASA/GSFC/MITI/ERSDAC/JAROS and U.S./Japan ASTER Science Team; Page 416 (right): Image courtesy NASA/JPL/NIMA; Page 417 (top): Image courtesy Ron Beck, EROS Data Center; Page 417 (bottom): ORBIMAGE (c) Orbital Imaging Corporation and SeaWiFS Project, NASA/Goddard Space Flight Center; Page 418 (top): Steve Vidler/eStock Photo; Page 418 (bottom left): (c)Larry Ulrich; Page 418 (bottom right): Images & Stories/Alamy; Page 420 (top): Earth Satellite Corporation; Page 421: USGS; Page 422: Francois Goheir/Photo Researchers, Inc.; Page 424 (bottom): Georg Gerster/Photo Researchers; Page 427: Joe Klamar/AFP/Getty Images, Inc.; Page 428: G. Hall/Woodfin Camp & Associates; Page 429: (c) AP/Wide World Photos; Page 430 (right): (c) John S. Shelton; Page 430 (top): (c) Marli Miller/Visuals Unlimited; Page 430 (bottom): O. Louis Mazzatenta/NG Image Collection; Page 434 (left): Reni Burri/Magnum Photos, Inc.; Page 434 (right): Danita Delimont/Alamy.

Chapter 13 Page 438 & 439: Yann Arthus-Bertrand/Altitude; Page 441 (top): A. N. Strahler; Page 441 (bottom): USGS; Page 442: George F. Mobley/NG Image Collection; Page 444 (top): Cary Wolinsky/NG Image Collection; Page 444 (bottom): A. N. Strahler; Page 445 (left): Bruce Dale/NG Image Collection; Page 445 (right): George F. Mobley/NG Image Collection; Page 446 (left): (c)George Wuerthner; Page 446 (right): (c)David Muench Photography; Page 447 (bottom): (c) Douglas Peebles Photography; Page 447 (top left): Darlyne A. Murawski/NG Image Collection; Page 447 (top right): Todd Gipstein/NG Image Collection; Page 449: (c) John S. Shelton, La Jolla, California; Page 450 (bottom): Landslide Hazards at La Conchita, California by Randall W. Jibson, USGS Open-File Report 2005-1067, Fig. 10; Page 452 (top): Steve Raymer/NG Image Collection; Page 452 (bottom): Arno Balzarini/epa/Corbis Images; Page 453: (c)AP/Wide World Photos; Page 454: Courtesy Los Angeles County Department of Public Works; Page 455 (bottom): Norbert Rosing/NG Image Collection; Page 455 (top left): Emory Kristof/NG Image Collection; Page 455 (top right): Melissa Farlow/NG Image Collection; Page 457 (right): Courtesy Troy L. Pewe; Page 458: Steven Kazlowski/Science Faction/Corbis Images; Page 459: Steve McCutcheon / Alaska Pictorial; Page 460: Christopher R. Burn; Page 461: Bernard Hallet, Periglacial Laboratory, Quaternary Research Center; Page 462 (top): (c)Steve McCutcheon/Steve McCutcheon /Alaska Pictorial; Page 462 (bottom): Maria Stenzel/NG Image Collection.

Chapter 14 Page 466 &467: Yann Arthus-Bertrand/Altitude; Page 469 (bottom): Dieter Telemans/Panos Pictures; Page 469 (center left): Panos Pictures; Page 469 (center right): Shepard Sherbell/SABA; Page 469 (top left): Courtesy of Worldsat International; Page 469 (top right): Jacques Descloitres, MODIS Land Rapid Response Team; Page 470: Medford Taylor/NG Image Collection; Page 473 (left): Gordon Wiltsie/NG Image Collection; Page 473 (right): Phil Schermeister/NG Image Collection; Page 475: (c) John S. Shelton; Page 476: (c)Bruno Barbey/Magnum Photos, Inc.; Page 477: George F. Mobley/NG Image Collection; Page 478: (c)M. Smith/Sipa Press; Page 479 (top): Medford Taylor/NG Image Collection; Page 479 (bottom):

Tom Bean/Tom & Susan Bean, Inc.; Page 483: Jodi Cobb/NG Image Collection; Page 484 (bottom): Chris Johns/NG Image Collection; Page 484 (top left): Skip Brown/NG Image Collection; Page 484 (top right): Cameron Davidson/NG Image Collection; Page 485 (left): Raymond Gehman/NG Image Collection; Page 485 (right): James P. Blair/NG Image Collection; Page 486: Volkmar K. Wentzel/NG Image Collection; Page 488: (c)Tom Till Photography; Page 489 (top): Priit Vesilind/NG Image Collection; Page 489 (bottom): Walter Meayers Edwards/NG Image Collection; Page 490 (top): Jim Holmes/Panos Pictures; Page 490 (bottom): George F. Mobley/NG Image Collection; Page 491: Stephen Sharnoff/NG Image Collection.

Chapter 15 Page 494 & 495: Yann Arthus-Bertrand/Altitude; Page 496: Raymond Gehman/NG Image Collection; Page 497 (left): Steve Winter/NG Image Collection; Page 497 (right): Frans Lanting Photography; Page 498: U.S. Navy Photographs; Page 499: Vic Cox/Peter Arnold, Inc.; Page 500: Alan H. Strahler; Page 501: Alan H. Strahler; Page 502 (left): Oxford Scientific/Photolibrary/Getty Images, Inc.; Page 503: Oxford Scientific/Photolibrary/Getty Images, Inc.; Page 506 (top): Courtesy NASA/GSFC/LARC/JPL, MISR Team; Page 506 (bottom): Courtesy NASA/GSFC/MITI/ERSDAC/JAROS and U. S. Japan ASTER Science Team; Page 507 (top): Courtesy NASA/GSFC/LARC/JPL, MISR Team; Page 507 (bottom): Courtesy NASA/GSFC/MITI/ERSDAC/JAROS and U. S. Japan ASTER Science Team; Page 508: Larry Dale Gordon/The Image Bank/Getty Images; Page 509: Richard Nowitz/NG Image Collection; Page 510: Tom & Susan Bean, Inc.; Page 511 (top): A. N. Strahler; Page 511 (bottom): James P. Blair/NG Image Collection; Page 513 (left): Owen Franken/Corbis; Page 513 (right): Breck Kent/Earth Scenes; Page 514: John Cancalosi/Peter Arnold, Inc.; Page 515 (left): Michael Collier, Flagstaff, Arizona; Page 517: Alan H. Strahler.

Chapter 16 Page 522 & 523: Yann Arthus-Bertrand/Altitude; Page 525 (top): Bob Jordan/AP/Wide World Photos; Page 525 (bottom): Stephen Crowley/New York Times Pictures; Page 526 (top): BIOS (P.Kobeh)/Peter Arnold, Inc.; Page 526 (bottom): Tui De Roy/Minden Pictures, Inc.; Page 527: Raymond Gehman/NG Image Collection; Page 529: Alex McLean/Landslides; Page 530 (right): Chad Ehlers/Alamy; Page 530 (left): Arthur N. Strahler; Page 531: Priit Vesilind/NG Image Collection; Page 533 (top): Steve Dunwell, Boston, MA; Page 533 (bottom): Doug Steley/Alamy; Page 534: Raymond Gehman/NG Image Collection; Page 536: age fotostock/SUPERSTOCK; Page 537 (top): Paul Chesley/NG Image Collection; Page 537 (bottom): David Alan Harvey/NG Image Collection; Page 538: USGS/Photo Researchers, Inc.; Page 539: Paul Chesley/NG Image Collection; Page 540 (top): Peter McBride/Getty Images, Inc.; Page 541: (c) John S. Shelton, L Jolla, California; Page 542: Andrew Kleinhesselink; Page 543: Tom & Susan Bean, Inc.; Page 544: AP/Wide World Photos; Page 545 (top): Gerry Ellis/Minden Pictures/NGS; Page 545 (bottom): Annie Griffiths Belt/NG Image Collection; Page 546: George Steinmetz; Page 547: Melissa Farlow/NG Image Collection; Page 548: Joe Scherschel/NG Image Collection; Page 549 (top): J. A. Kraulis/Masterfile; Page 549 (bottom): G. R. Roberts, Nelson, New Zealand; Page 550: Chris Johns/NG Image Collection.

Chapter 17 Page 554 & 555: Yann Arthus-Bertrand/Altitude; Page 557 (top left): NASA Earth Observatory; Page 557 (top right): NASA Earth Observatory; Page 557 (bottom left): NASA Earth Observatory; Page 557 (bottom right): NASA Earth Observatory; Page 558: Fred Hirschmann; Page 559: Carr Clifton; Page 562: David Wrench/Leslie Garland Pic. Lib./Alamy Images; Page 563 (left): ∏Marli Bryant Miller; Page 563 (right): Harvey Lloyd/Getty Images, Inc.; Page 564: Courtesy NASA; Page 565 (top): Image courtesy NASA/GSFC/MITI/ERSDAC/JAROS and U.S./Japan ASTER Science Team; Page 565 (bottom): Image courtesy Canadian Space Agency/NASA/Ohio State University/Jet Propulsion Laboratory, Alaska SAR Facility; Page 566: Courtesy NASA; Page 567 (top): Bill Curtsinger/NG Image Collection; Page 567 (bottom): Michael Sewell/Peter Arnold, Inc.; Page 568: Courtesy NASA; Page 570 (left): Tom & Susan Bean, Inc.; Page 570 (right): C. Wolinsky/Stock Boston; Page 571 (left): Arthur N. Strahler; Page 571 (right): Tom & Susan Bean, Inc.; Page 574 (left): Todd Gipstein/NG Image Collection; Page 574 (right): Klaus Nigge/NG Image Collection; Page 577: Scott Camazine/Alamy Images.

Index

Note: Page references followed by "f" indicate illustrations; while "t" indicates tables.