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VISUALIZING PHYSICAL GEOGRAPHY

ALAN STRAHLER WITH ZEEYA MERALI

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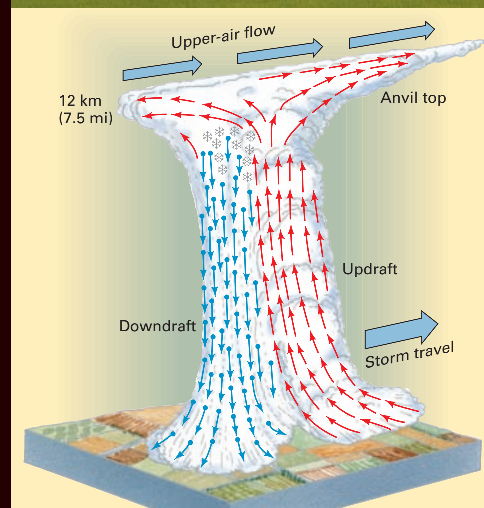
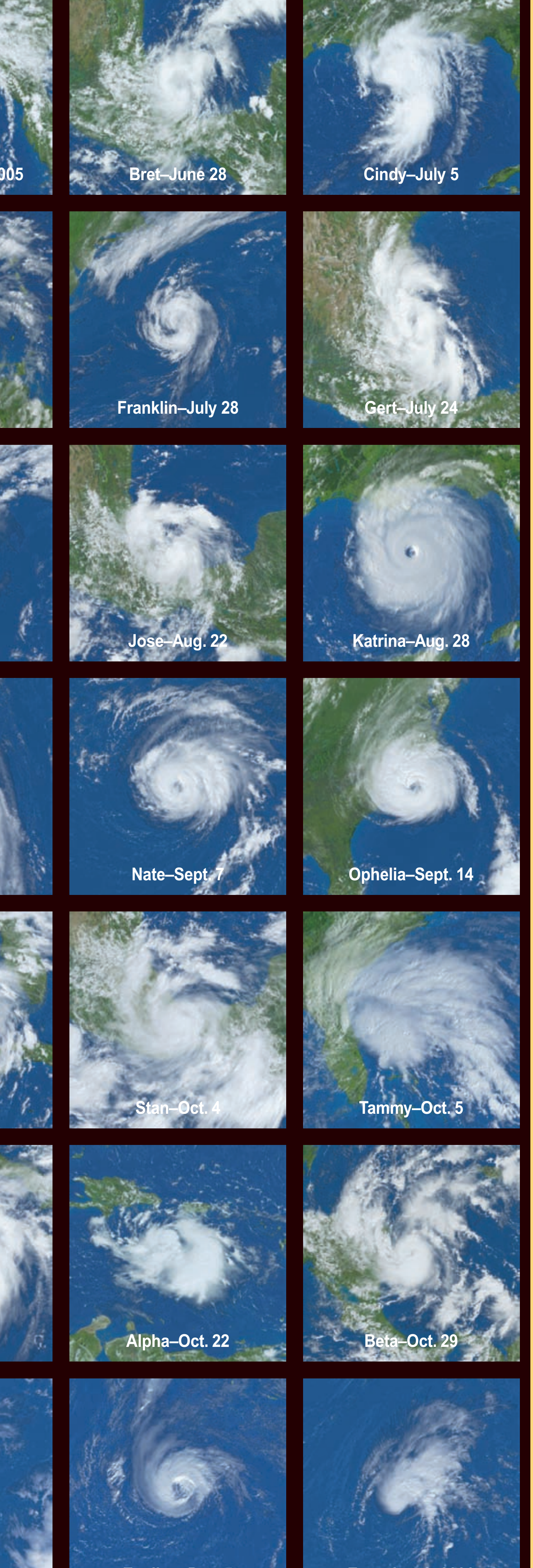
VISUALIZING PHYSICAL GEOGRAPHY

Alan Strahler, PhD
Boston University

with Zeeya Merali, PhD

In collaboration with
THE NATIONAL GEOGRAPHIC SOCIETY





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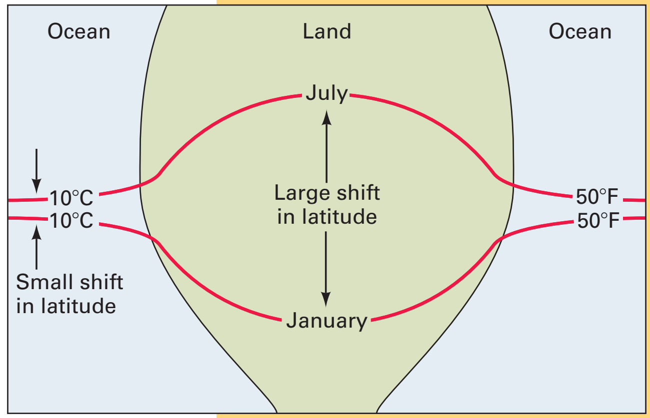
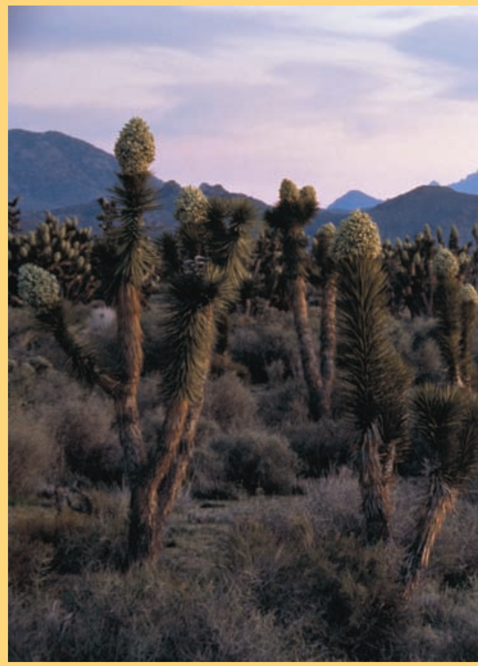
FOREWORD *From the Publisher*

Visualizing Physical Geography is designed to help your students learn effectively. Created in collaboration with the National Geographic Society and our Wiley Visualizing Consulting Editor, Professor Jan Plass of New York University, *Visualizing Physical Geography* integrates rich visuals and media with text to direct students' attention to important information. This approach represents complex processes, organizes related pieces of information, and integrates information into clear representations. Beautifully illustrated, *Visualizing Physical Geography* shows your students what the discipline is all about—its main concepts and applications—while also instilling an appreciation and excitement about the richness of the subject.



Visuals, as used throughout this text, are instructional components that display facts, concepts, processes, or principles. They create the foundation for the text and do more than simply support the written or spoken word. The visuals include diagrams, graphs, maps, photographs, illustrations, schematics, animations, and videos and are designed to direct attention, display processes, and organize and integrate information.

Why should a textbook based on visuals be effective? Research shows that we learn better from integrated text and visuals than from either medium separately. Beginners in a subject benefit most from reading about the topic, attending class, and studying well-designed and integrated visuals. A visual, with good accompanying discussion, really can be worth a thousand words!



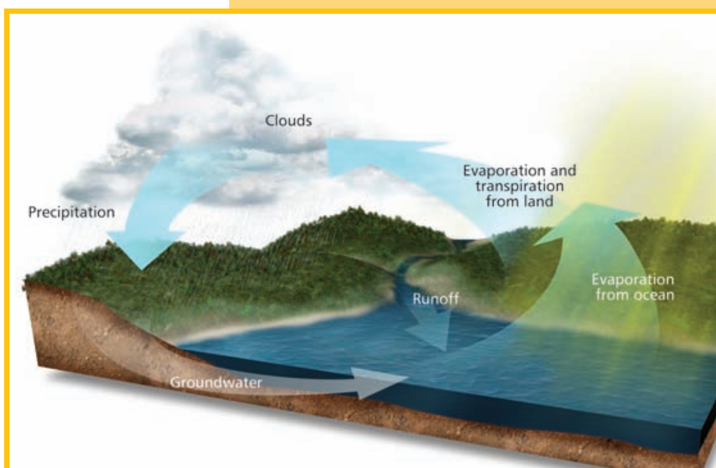
Well-designed visuals can also improve the efficiency with which a learner processes information. The more effectively we process information, the more likely it is that we will learn. This processing of information takes place in our working memory. As we learn, we integrate new information in our working memory with existing knowledge in our long-term memory.

Have you ever read a paragraph or a page in a book, stopped, and said to yourself: "I don't remember one thing I just read?" This may happen when your working memory has been overloaded, and the text you read was not successfully integrated into long-term memory. Visuals don't automatically solve the problem of overload, but well-designed visuals can reduce the number of elements that working memory must process, thus aiding learning.

You, as the instructor, facilitate your students' learning. Well-designed visuals, used in class, can help you in that effort. Here are six methods for using the visuals in the *Visualizing Physical Geography* in classroom instruction.

1. **Assign students visuals to study in addition to reading the text.**
   Instead of assigning only one medium of presentation, it is important to make sure your students know that the visuals are just as essential as the text.

2. **Use visuals during class discussions or presentations.**
   By pointing out important information as the students look at the visuals during class discussions, you can help focus students' attention on key elements of the visuals and help them begin to organize the information and develop an integrated model of understanding. The verbal explanation of important information combined with the visual representation can be highly effective.





3. **Use visuals to review content knowledge.**
   Students can review key concepts, principles, processes, vocabulary, and relationships displayed visually. Better understanding results when new information in working memory is linked to prior knowledge.

4. **Use visuals for assignments or when assessing learning.**
   Visuals can be used for comprehension activities or assessments. For example, you could ask students to identify examples of concepts portrayed in visuals. Higher-level thinking activities that require critical thinking, deductive and inductive reasoning, and prediction can also be based on visuals. Visuals can be very useful for drawing inferences, for predicting, and for problem solving.

5. **Use visuals to situate learning in authentic contexts.**
   Learning is made more meaningful when a learner can apply facts, concepts, and principles to realistic situations or examples. Visuals can provide that realistic context.

6. **Use visuals to encourage collaboration.**
   Collaborative groups often are required to practice interactive processes such as giving explanations, asking questions, clarifying ideas, and arguing a case. These interactive, face-to-face processes provide the information needed to build a verbal mental model. Learners also benefit from collaboration in many instances such as decision making or problem solving.

Visualizing Physical Geography not only aids student learning with extraordinary use of visuals, but it also offers an array of remarkable photos, media, and film from the National Geographic Society collections. Students using *Visualizing Physical Geography* also benefit from the long history and rich, fascinating resources of the National Geographic Society.

The National Geographic Society has also performed an invaluable service in fact-checking *Visualizing Physical Geography:* they have verified every fact in the book with two outside sources, ensuring the accuracy and currency of the text.

Given all of its strengths and resources, *Visualizing Physical Geography* will immerse your students in the discipline, and its main concepts and applications, while also instilling an appreciation and excitement about the richness of the subject area.

Additional information on learning and instructional design is provided in a special guide to using this book, *Learning from Visuals: How and Why Visuals Can Help Students Learn*, prepared by Matthew Leavitt, of Arizona State University. This article is available at the Wiley Web site: www.wiley.com/college/visualizing. The online *Instructor's Manual* also provides guidelines and suggestions on using the text and visuals most effectively.

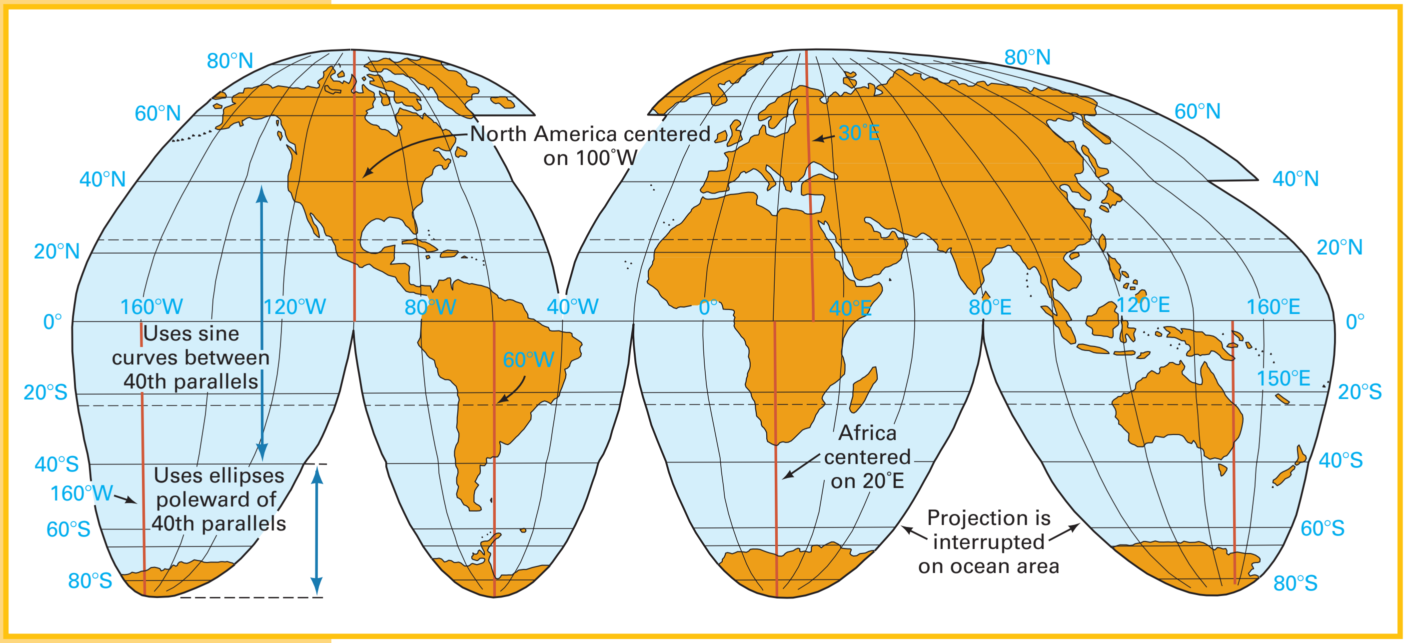
Visualizing Physical Geography also offers a rich selection of visuals in the supplementary materials that accompany the book. To complete this robust package, the following materials are available: Test Bank (with visual materials used for assessment), PowerPoint slides, Image Gallery (a digital version of all the visuals used in the text), Web-based learning materials for homework and assessment including images, video, and media resources from National Geographic.

ORGANIZATION

Physical geography is concerned with processes resulting from two vast energy flows—a stream of solar electromagnetic radiation that drives surface temperatures and flows of surface and atmospheric gases and fluids, and a stream of heat from the Earth's interior that manifests itself in the slow motion of earth materials in the upper layers of the Earth's crust. These flows interact at the Earth's surface, which is the province of the physical geographer. At this interface, the biological realm exploits these flows, adding a third element to the landscape. Following this schema, we present physical geography beginning with weather and climate, then turn to earth materials, geomorphology, and finally ecology and biogeography.

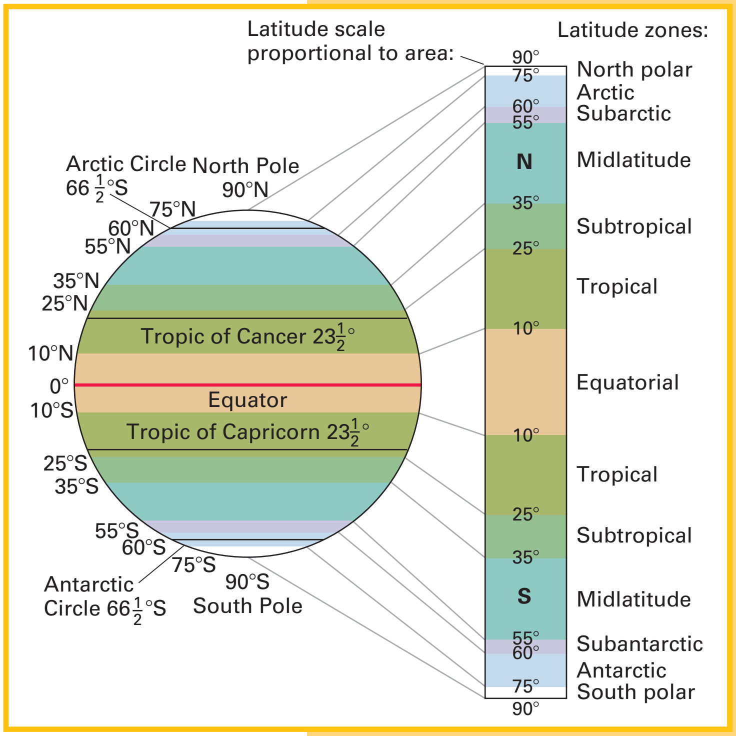
The book's opening three chapters cover core physical principles and lay the groundwork for understanding climate, surface features, and global biodiversity discussed in later chapters. In the first chapter, the student examines the effects of the Earth's rotation and revolution about the Sun on changing patterns of insolation around the globe. Insolation and electromagnetic radiation are covered in more detail in Chapter 2, while Chapter 3 builds on this foundation to explain daily and annual air temperature patterns at different locations. These chapters also introduce the greenhouse effect and global warming—describing both their physical origin and the most recent evidence for them, and expounding upon their possible impact in the future. The issues of climate change are revisited throughout the text.

Chapters 4, 5, and 6 of *Visualizing Physical Geography* investigate weather systems, including the development of precipitation and global wind patterns. The concepts are presented with references to examples covering the globe, including a discussion of



PREFACE

Visualizing Physical Geography encompasses the science of human environments from local to global scales. Using a uniquely visual approach, we take students on a journey from the top layers of the Earth's atmosphere to the rocks underlying the ocean basins to the forests of the farthest continents. Our primary goal is to help students understand and explain the many common natural phenomena that they experience every day, from the formation of a thunderstorm to the building of a sand dune on a beach. We also aim to excite them about the diversity of the Earth's environments, with the hope that they will be motivated to experience at first hand as much of the Earth's physical geography as they can. Our treatment builds on basic science principles from meteorology, climatology, geology, geomorphology, soil science, ecology, and biogeography, weaving them together to describe the physical processes that shape the varied landscapes of our planet. Throughout, we build understanding using the principles of visual learning, relying not only on the heritage of classic visuals that are part of the Strahler tradition, but also on the vast resources of the National Geographic Society, ranging from their superb collection of maps and graphics to their archive of famous photographs.



We begin *Visualizing Physical Geography* by stepping back and introducing the student to the Earth as a planet. We investigate our planet's relationship with the Sun, explaining how temperature differences around our world originate. Later chapters then focus in on the globe, showing how different weather patterns arise, culminating in the world's climate regions. We then zoom in to investigate the Earth's surface features in detail, beginning with a discussion of plate tectonics and examining a variety of processes that create our planet's landforms.

However, *Visualizing Physical Geography* does not simply describe the physical processes at play on the Earth's surface and in the atmosphere as abstract phenomena unrelated to human activity. Physical geography investigates the physical setting for human, animal, and plant life and examines the interconnections between human activities and natural processes. In the final chapters of the book, we examine how, why, and where biodiversity occurs. Throughout the book, the student is invited to consider climate change processes—how these processes occur and what their future implications may be for the fate of our planet.

This book is an introductory text aimed primarily at undergraduate nonscience majors, and we assume little prior knowledge of physical geography. The accessible format of *Visualizing Physical Geography* allows students to move easily from jumping-off points in the early chapters to more complex concepts covered later. Chapters are designed to be as self-contained as possible, so that instructors can choose chapter orderings and emphases that suit their needs. Our book is appropriate for use in one-semester physical geography courses offered by a variety of departments, including geography, earth sciences, environmental studies, biology, and agriculture.

the causes and consequences of some of the most dramatic recent weather events seen within the United States and around the world. In Chapter 7 we combine the foundational concepts from the core chapters on insolation and air temperature with the information on weather patterns from Chapters 4, 5, and 6 in a detailed discussion of climate regions. The student is invited to revisit the topic of climate change with this new understanding.

Chapters 8 to 15 deal with the formation of landforms and features on the Earth's surface. We begin with a simple yet thorough introduction to rock types, plate tectonics, and weathering processes. We then discuss volcanic and tectonic landforms, as well as features created by running water, waves and wind, and glaciers and ice, and provide a detailed discussion of soil formation and soil types around the globe.

The final two chapters of *Visualizing Physical Geography* turn to ecological, historical, and global biogeography, and the student is invited to see how the climates, surface features, and environments discussed earlier can affect living organisms now and in the future.

ILLUSTRATED BOOK TOUR

The topics covered in *Visualizing Physical Geography* are ideally suited to a visual-based teaching approach. Physical geography encompasses a range of highly varied and often technical concepts, which can be greatly simplified with graphics and diagrams, and placed within a real-world context with the aid of maps and photographs. We have developed a number of pedagogical features using visuals, specifically for *Visualizing Physical Geography*. The **Illustrated Book Tour** on the following pages provides a guide to the diverse features contributing to *Visualizing Physical Geography's* pedagogical plan.

ILLUSTRATED

CHAPTER INTRODUCTIONS focus on key geographical concepts that will be visited in the chapter, using concise but intriguing stories to give the student a sense of the scope, implications, and ramifications of the topics they are about to encounter. These narratives are featured alongside striking accompanying photographs. The chapter openers also include illustrated **Chapter Outlines** that use thumbnails of illustrations from the chapter to refer visually to the content.


The Earth as a Rotating Planet 1

STONEHENGE

The hushed crowd stands among the ruins, waiting for sunrise. It is the summer solstice—the longest day of the year.

A ruby gleam brightens the sky as the first light rays become visible. Slowly, the red solar disk emerges. The sky is bathed in reds and pinks, fading to deep blue. Small, puffy clouds above glow a spectacular rosy pink. And then it appears. The red solar ball hangs just to the left of the Slaughter Stone, the immense slab that marks the entrance to Stonehenge.

The old stone monument was built three to four thousand years ago. Legend tells us that Merlin the wizard magically transported this vast structure to Salisbury, England. Although we now know this is a myth, the structure's precision remains wondrous. The ancient peoples hauled huge sandstone slabs hundreds of miles to this site. They carefully arranged five pairs of immense vertical slabs—each pair crowned by a horizontal stone—into a giant horseshoe. Three pairs are still erect today, while single stones remain in the place of the other two.

The Slaughter Stone is missing its twin slab. Had it been present, the Sun would have appeared perfectly centered between the two vertical monoliths on this midsummer's morning. And the long shadows of the twins would have drawn a broad sunlit path stretching to the horseshoe center.

Although human society has changed over four thousand years, we share a fascination with the motion of the Sun across the sky, and its profound consequences for our planet and for us.

NATIONAL GEOGRAPHIC

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CHAPTER OUTLINE

- The Shape of the Earth p. 4
- The Earth's Rotation p. 6
- The Geographic Grid p. 8
- Map Projections p. 13
- Global Time p. 18
- The Earth's Revolution Around the Sun p. 24


Visualizing
Global Precipitation

GLOBAL CIRCULATION

Water vapor is carried far from its source by atmospheric circulation patterns. Where air currents converge together or rise over mountains, clouds and precipitation form.

◀ **Precipitation and global circulation** The circulation of the atmosphere mixes warm, moist air with cool, dry air in storm systems called cyclones. Where storms are abundant, so is precipitation.

▼ **Deserts** Most deserts are far from moisture sources or lie within the rain shadows of mountain ranges. A herd of camels crosses Australia's Simpson Desert.

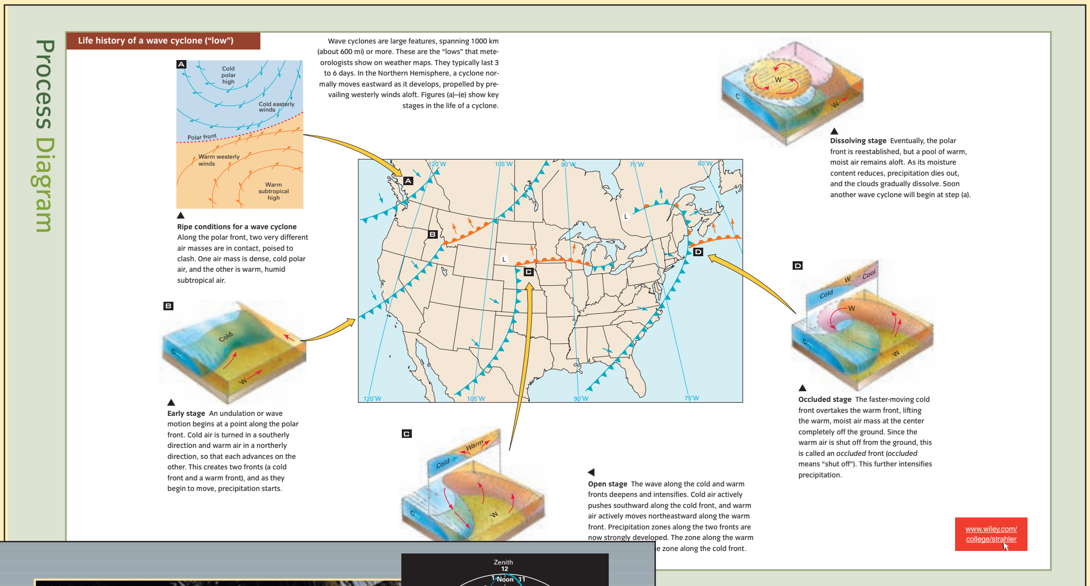
◀ **Monsoon rainfall** In tropical and equatorial regions, rainfall can be abundant and in some regions has a strong seasonal cycle. Here rice farmers plant a new crop while sheltered by woven rain shields called *patlas*.

NATIONAL GEOGRAPHIC

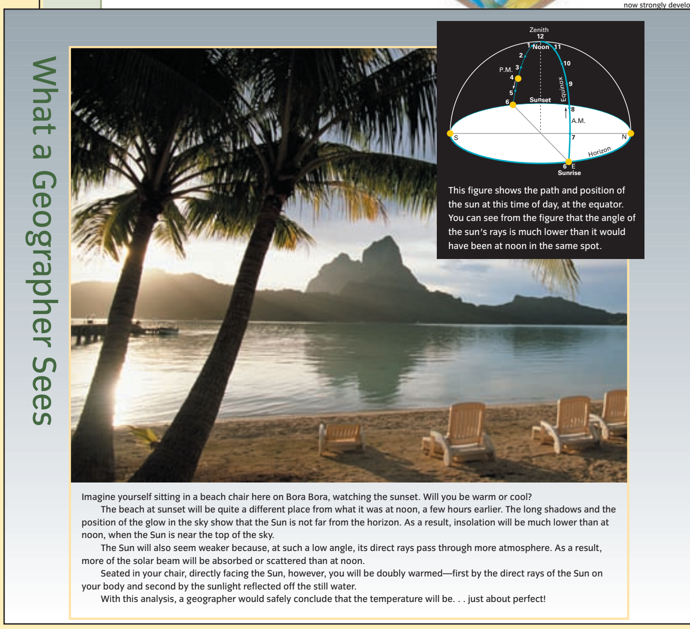
Water and the Hydrosphere 99

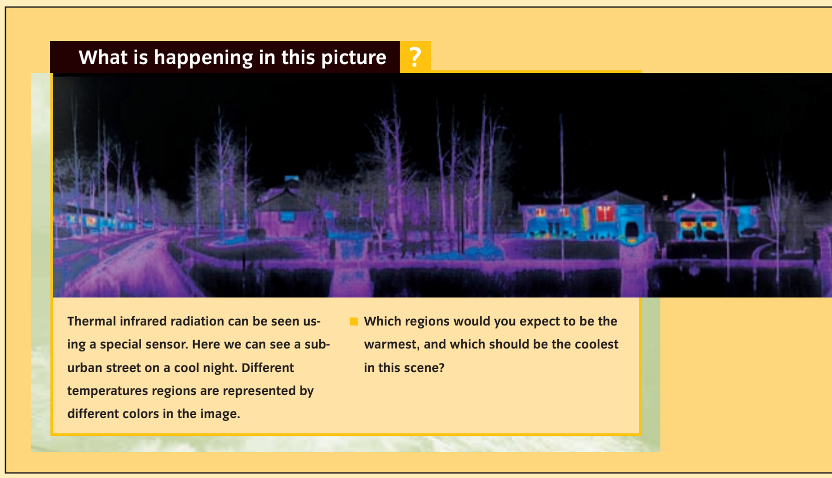
NATIONAL GEOGRAPHIC VISUALIZING PLATES are specially designed multipart visual spreads that appear in a special section within each chapter. They bring together key concepts from the chapter and use National Geographic maps and photographs, as well as figures, to highlight the most important ideas in the chapter, exploring them in detail or in broader context.

BOOK TOUR



PROCESS DIAGRAMS break down complex processes into a series of simple figures, helping students to observe, follow, and understand the process.

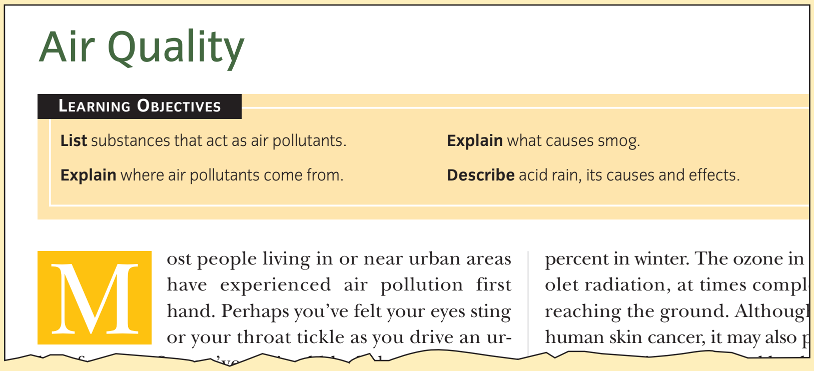




WHAT A GEOGRAPHER SEES features demonstrate how a professional in the field interprets real-world situations. Photographs or satellite images depict intriguing and puzzling geographical phenomena, and accompanying figures and graphs are used to explain integral concepts. The features help students to develop observational skills and to analyze images given the ideas met within the chapter.

WHAT IS HAPPENING IN THIS PICTURE? is an end-of-chapter feature that presents students with a photograph relevant to chapter topics but that illustrates a situation students are not likely to have encountered previously. The photograph is paired with questions and a discussion of the image designed to stimulate creative thinking.

OTHER PEDAGOGICAL FEATURES



Air Quality

Learning Objectives

List substances that act as air pollutants.

Explain where air pollutants come from.

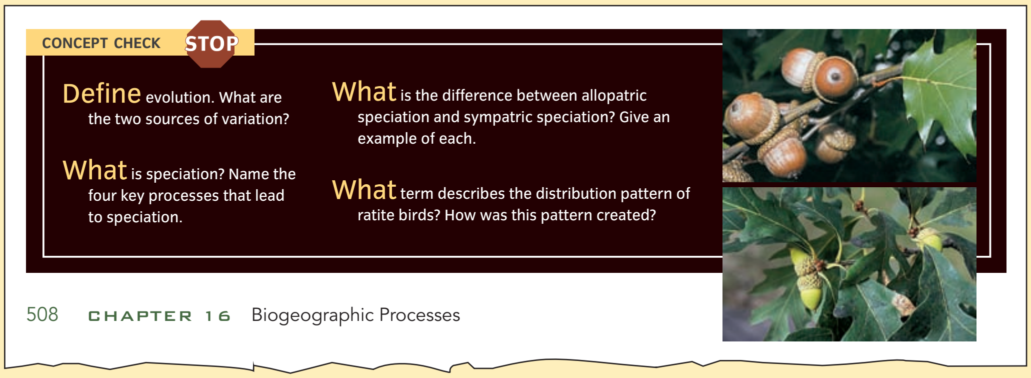
Explain what causes smog.

Describe acid rain, its causes and effects.

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 ur-

percent in winter. The ozone in … olet radiation, at times compl… reaching the ground. Althoug… human skin cancer, it may also …

LEARNING OBJECTIVES at the beginning of each section head identify the key points in the section that follows, providing active goals to guide students' learning as they read the text and indicating what they must be able to do to demonstrate mastery of the material in the chapter.



CONCEPT CHECK STOP

Define evolution. What are the two sources of variation?

What is speciation? Name the four key processes that lead to speciation.

What is the difference between allopatric speciation and sympatric speciation? Give an example of each.

What term describes the distribution pattern of ratite birds? How was this pattern created?

508 CHAPTER 16 Biogeographic Processes

CONCEPT CHECK questions at the end of each section give students the opportunity to test their comprehension of the learning objectives, before moving on to the next subject.

Ecological 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, clear cutting, or other agents.

MARGINAL GLOSSARY TERMS (in green boldface) introduce each chapter's most important terms, often reinforced with a thumbnail photograph. The second most important terms appear in italics and are defined within the chapter text and included in a full glossary at the end of the text.

Global Locator

Qosqo by night FIGURE 3.7

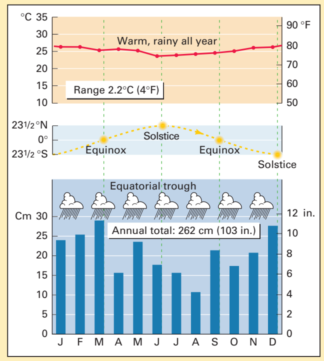
Urban power consumption in Qosqo (formerly Cuzco) keeps nighttime temperatures higher than in the surrounding areas.

GLOBAL LOCATOR MAPS, prepared specifically for this book by National Geographic, accompany figures addressing issues encountered in a particular geographic region to help students visualize where the area discussed is situated around the globe.

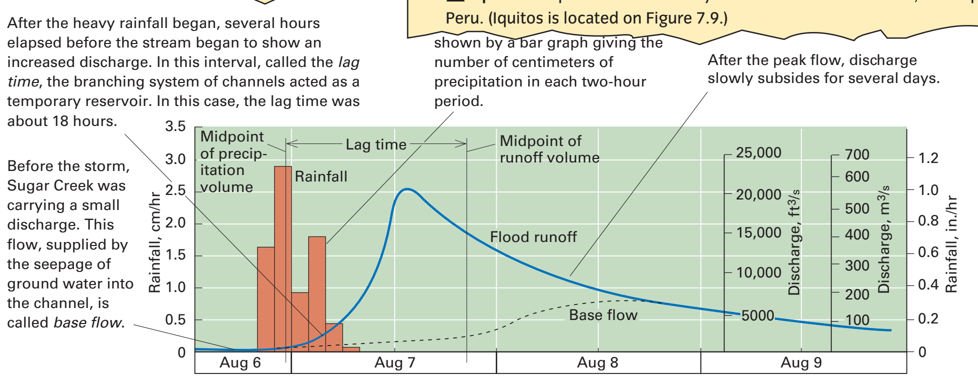
ILLUSTRATIONS AND PHOTOS support and elaborate on concepts covered in the text, allowing students to visualize theoretical concepts within a real-world setting and contextualize their learning. Many of the photos are from the National Geographic Society's rich resources.

Wet equatorial climate ① FIGURE 7.10

▲ **Iquitos** Frequent rainfall is a way of life on the Amazon River, near Iquitos, Peru. (Iquitos is located on Figure 7.9.)



▲ **Iquitos climograph** Iquitos, in Peru (lat. 3° S), is located in the upper Amazon



Sugar Creek hydrograph FIGURE 11.18

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 15 cm (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.

TABLES AND GRAPHS, with data sources cited at the end of the text, summarize and organize important information.

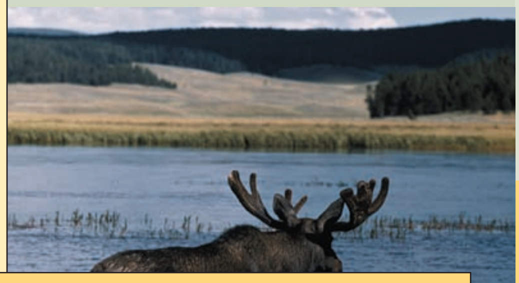
END-OF-CHAPTER FEATURES

The **VISUAL SUMMARY** revisits each learning objective, with relevant accompanying images taken from the chapter that act as visual cues, reinforcing important elements from the chapter. Each marginal glossary term is redefined and included in a list of **Key Terms**, so that students can review vocabulary words in the context of related concepts.

VISUAL SUMMARY

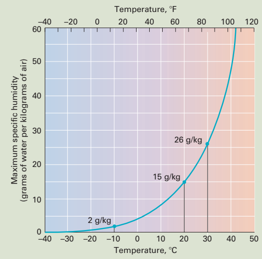
1 Water and the Hydrosphere

1. Water can change state by evaporating, condensing, melting, freezing, and through sublimation and deposition.
2. The hydrosphere is the realm of water in all its forms. The fresh water in the atmosphere and on land in lakes, streams, rivers, and ground water is only a very small portion of the total water in the hydrosphere.
3. Precipitation is the fall of liquid or solid water from the atmosphere to reach the Earth's land or ocean surface.



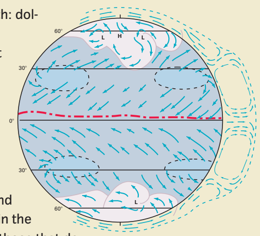
2 Humidity

1. Humidity describes the amount of water vapor present in air.
2. Warm air can hold much more water vapor than cold air.
3. Specific humidity measures the mass of water vapor in a mass of air, in grams of water vapor per kilogram of air. 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.
4. Condensation occurs at the dew-point temperature.



CRITICAL AND CREATIVE THINKING QUESTIONS

1. What is 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? How does atmospheric pressure change with altitude?
2. Describe a simple convective wind system. In your answer, explain how air motion arises.
3. How do land and sea breezes form? How do they illustrate the concepts of pressure gradient and convection loop?
4. Define cyclone and anticyclone. What type of weather is associated with each and why? Draw four spiral patterns showing outward and inward flow in clockwise and counterclockwise directions. Explain why different diagrams are needed for the northern and southern hemispheres.
5. What is the Asian monsoon? What are its features in summer and winter? How is the ITCZ involved? How is the monsoon circulation related to seasonal high- and low-pressure centers in Asia?
6. On th… ocea… 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.

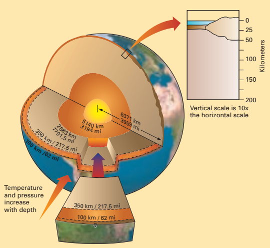


7. Compare the winter and summer patterns of high and low pressure that develop in the northern hemisphere with those that develop in the southern hemisphere.
8. An airline pilot is planning a nonstop flight from Los Angeles to Sydney, Australia. What general wind conditions can the pilot expect to find in the upper atmosphere as the airplane travels? What jet streams will be encountered? Will they slow or speed the aircraft on its way?

CRITICAL AND CREATIVE THINKING QUESTIONS bring together each chapter's important concepts. They range from simple to more advanced levels, encouraging the students to think critically and develop an analytical understanding of the ideas discussed in the chapter.

SELF-TEST

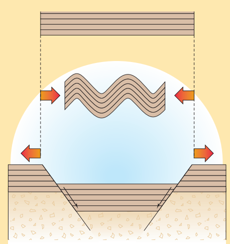
1. This cutaway diagram of the Earth's interior shows several layers. Label the mantle, outer core, inner core, asthenosphere, and lithosphere. Indicate whether the layer is solid, plastic, or liquid.



2. A ______________ is a naturally occurring, inorganic substance that usually possesses a definite chemical composition and characteristic atomic structure.
   a. crystal c. rock
   b. mineral d. metamorphic rock
3. Intrusive igneous rocks are noted for their:
   a. large mineral crystals
   b. interesting mineral composition
   c. hardness, compared to extrusive igneous rocks
   d. darker colors
4. The metamorphic equivalent of sandstone is ______________, which is formed by the addition of silica to fill completely the open spaces between the grains.
5. Shale, shown in the photograph, is formed from layered accumulations of mineral particles derived mostly by weathering and erosion of preexisting rocks. Which rock class does it belong to?
   a. Sedimentary rocks c. Metamorphic rocks
   b. Igneous rocks d. Volcanic rocks

6. The theory describing the motions and changes through time of the continents and ocean basins, and the processes that fracture and fuse them, is called ______________.
   a. continental drift c. plate tectonics
   b. Earth dynamics d. the Wilson cycle
7. The ______________ is a soft, plastic layer that underlies the lithosphere.
   a. mantle c. inner core
   b. outer core d. asthenosphere
8. All time older than 570 million years before the present is ______________ time.
   a. Cambrian c. Triassic
   b. Mesozoic d. Precambrian

10. The diagram shows two basic forms of tectonic activity. Identify and describe both processes. Which would we expect to see between separating oceanic plates? Which occurs between converging plate boundaries?



11. Ocean basins are characterized by a central ______________ consisting of submarine hills that rise gradually to a rugged central zone delineated by a narrow, trench-like feature called a(n) ______________.
    a. cordillera, rift
    b. midocean ridge, rift
    c. midocean ridge, axial rift
    d. ridge, axial rift
12. Some continental margins are ______________ and accumulate thick deposits of continental sediments while other continental margins are ______________ and have trenches marking the location at which ocean crust is sliding beneath continental crust.
13. The process in which one plate is carried beneath another is called ______________.
    a. advection c. liposuction
    b. convection d. subduction
14. ______________ plate boundaries with ______________ in progress are zones of intense tectonic and volcanic activity.
    a. Transform, subduction
    b. Subduction, orogeny
    c. Converging, subduction
    d. Spreading, axial motion
15. Alfred Wegener, a German meteorologist and geophysicist, suggested in 1915 that the continents had once been adjoined as a supercontinent, which he named ______________.
    a. Wegener Land c. Pangea
    b. Gondwanaland d. Laurasia

SELF TESTS combine multiple-choice and short answer questions to allow students to assess their own progress upon completing the chapter. The tests include questions based on graphs, diagrams, and images taken from the text, encouraging the students to actively and visually engage with the material.

MEDIA AND SUPPLEMENTS

Visualizing *Physical Geography* is accompanied by a rich array of media and supplements that incorporate the visuals from the textbook extensively to form a pedagogically cohesive package. For example, a process diagram from the book appears in the Instructor's Manual with suggestions on using it as a PowerPoint in the classroom; it may be the subject of a short video or an online animation; and it may also appear with questions in the Test Bank, as part of the chapter review, homework assignment, assessment questions, and other online features.

MEDIA ADVISORY BOARD

Special thanks to the following people who contributed to creation and organization of the media for *Visualizing Physical Geography*: Miriam Helen Hill and Jon Van de Grift.

INSTRUCTOR SUPPLEMENTS

VIDEOS

A collection of videos, many of them from the award-winning National Geographic Film Collection, have been selected to accompany and enrich the text. Each chapter includes video clips, available online as digitized streaming video, that illustrate and expand on a concept or topic to aid student understanding.

NATIONAL GEOGRAPHIC indicates video drawn from the award-winning archives of the National Geographic Society.

Accompanying each of the videos is contextualized commentary and questions that can further develop student understanding.

The videos are available on the main Web site: www.wiley.com/college/strahler

POWERPOINT PRESENTATIONS AND IMAGE GALLERY

A complete set of highly visual PowerPoint presentations by Jake Armour of the University of North Carolina at Charlotte is available online to enhance classroom presentations. Tailored to the text's topical coverage and learning objectives, these presentations are designed to convey key text concepts, illustrated by embedded text art.

All photographs, figures, maps, and other visuals from the text are online in electronic files that allow you to easily incorporate them into your PowerPoint presentations as you choose, or to create your own overhead transparencies and handouts.

TEST BANK (AVAILABLE IN WILEYPLUS AND ELECTRONIC FORMAT)

The visuals from the textbook are also included in the Test Bank by Jake Armour of the University of North Carolina at Charlotte, Miriam Helen Hill of Jacksonville State University, and Steven Namikas of Louisiana State University. The test items include multiple-choice and essay questions testing a variety of comprehension levels. The test bank is available in two formats: online in MS Word files and a Computerized Test Bank, a multiplatform CR-ROM. The easy-to-use text-generation program fully supports graphics and prints tests, student answer sheets, and answer keys. The software's advanced features allow you to create an exam to your exact specifications.

INSTRUCTOR'S MANUAL (AVAILABLE IN ELECTRONIC FORMAT)

The Manual begins with a special introduction on *Using Visuals in the Classroom*, prepared by Matthew Leavitt of the Arizona State University, in which he provides guidelines and suggestions on how to use the visuals in teaching the course. For each chapter, materials by James Duvall of Contra Costa College include suggestions and directions for using Web-based learning modules in the classroom and for homework assignments.

WEB-BASED LEARNING MODULES

A robust suite of multimedia learning resources have been designed for *Visualizing Physical Geography*, again focusing on and using the visuals from the book. Delivered via the Web, the content is organized in the following categories:

www.wiley.com/college/strahler

Tutorial Animations: Animations visually support the learning of a difficult concept, process, or theory, many of them built around a specific feature such as a Process Diagram, Visualizing piece, or key visual in the chapter. The animations go beyond the content and visuals presented in the book, providing additional visual examples and descriptive narration.

BOOK COMPANION SITE (WWW.WILEY.COM/COLLEGE/STRAHLER)

Instructor Resources on the book companion site include the Test Bank, Instructor's Manual, all illustrations and photos in the textbook in jpeg format, and select flash animations for use in classroom presentations.

WILEYPLUS

Visualizing Physical Geography is available with **WileyPlus**, a powerful online tool that provides instructors and students with an integrated suite of teaching and learning resources in one easy-to-use Web site.

ACKNOWLEDGMENTS

STUDENT FEEDBACK/CLASS TESTING

In order to make certain that *Visualizing Physical Geography* met the needs of current students, we asked several instructors to class test a chapter. The feedback that we received from students and instructors confirmed our belief that the visualizing approach taken in this book is highly effective in helping students to learn.

We wish to thank the following instructor and her students who provided us with helpful feedback and suggestions: Dorothy Sack of Ohio State University.

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Alan Strahler
Boston Massachusetts

Zeeya Merali

And lastly, I add my own thanks to Zeeya Merali for showing me the way to say more with less.

Alan Strahler

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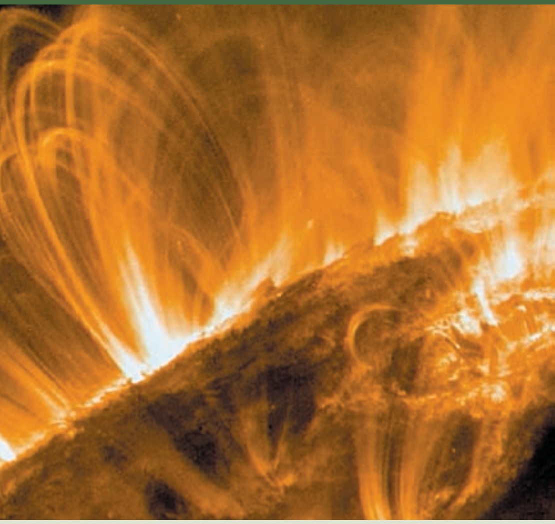

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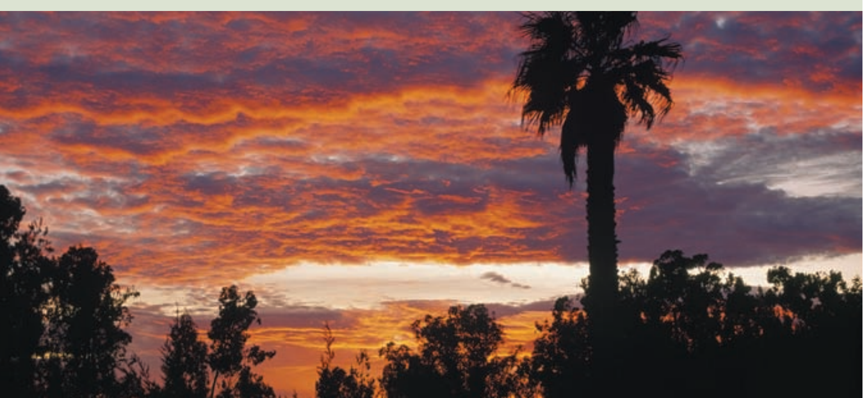

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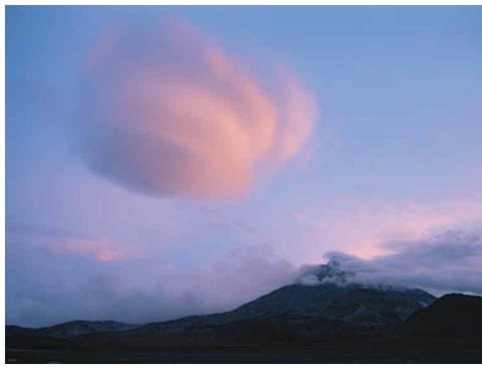

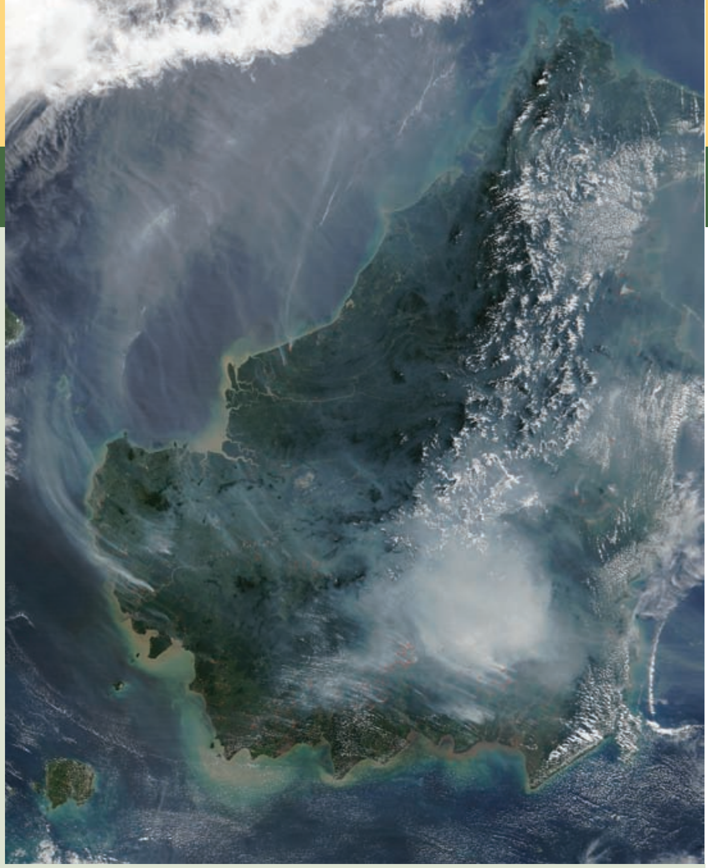

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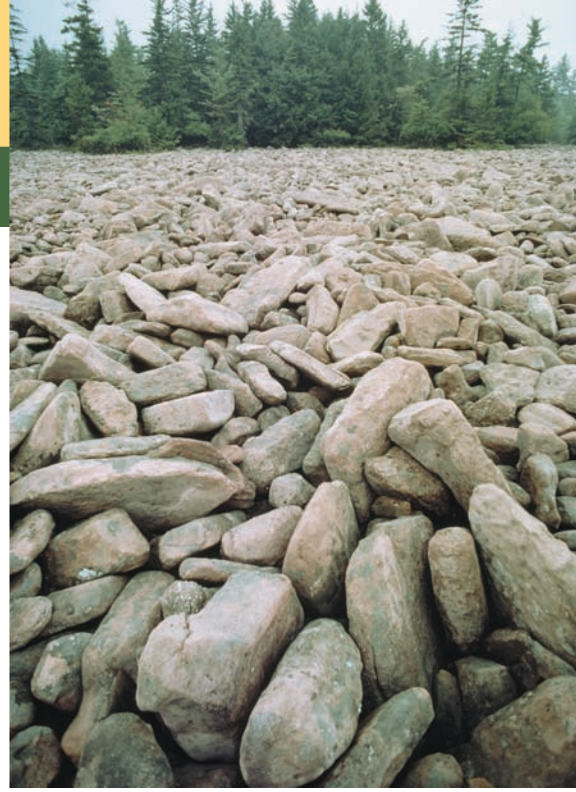

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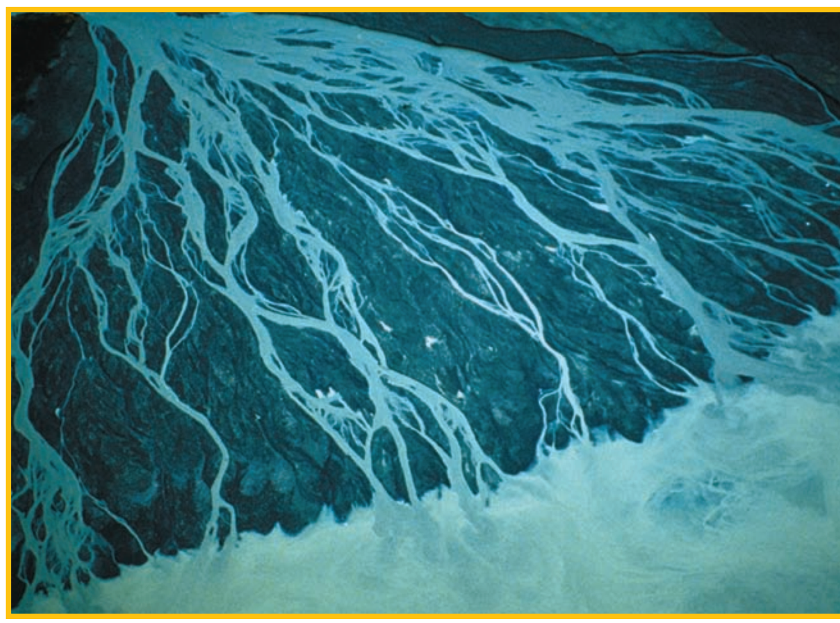

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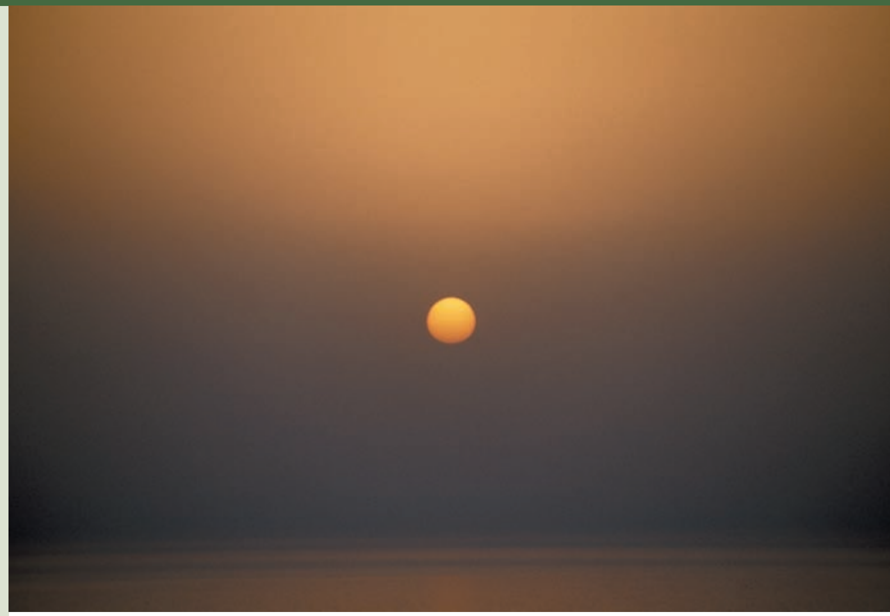

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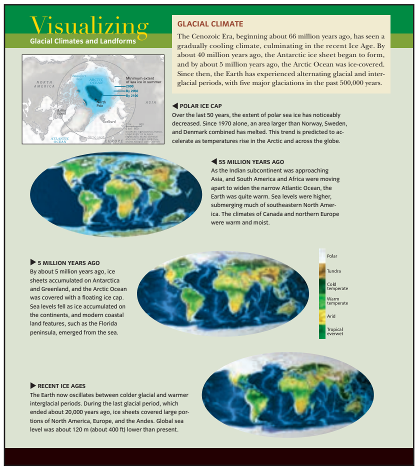
PROCESS DIAGRAMS



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The Earth as a Rotating Planet

1

STONEHENGE

The hushed crowd stands among the ruins, waiting for sunrise. It is the summer solstice—the longest day of the year.

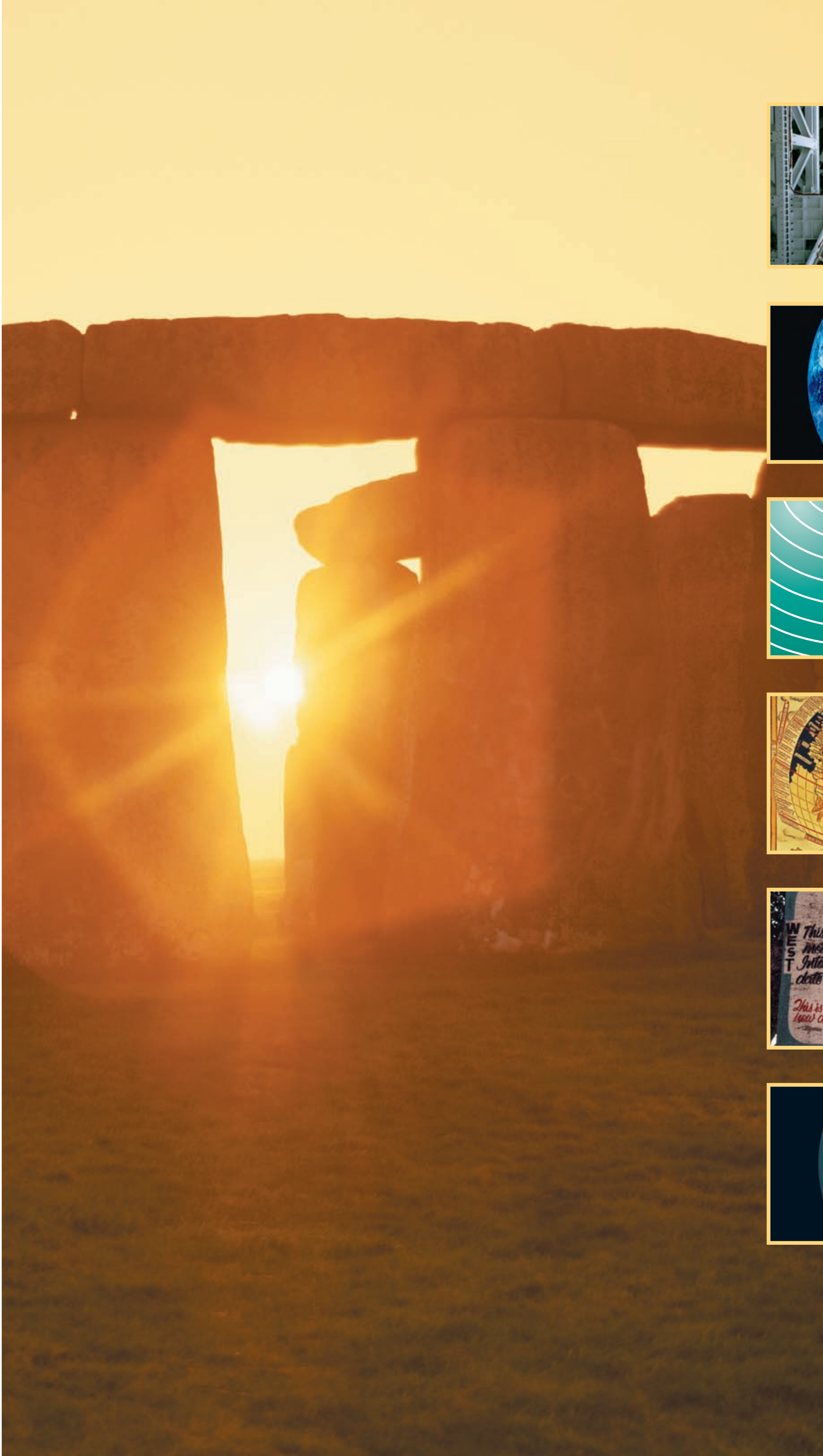
A ruby gleam brightens the sky as the first light rays become visible. Slowly, the red solar disk emerges. The sky is bathed in reds and pinks, fading to deep blue. Small, puffy clouds above glow a spectacular rosy pink. And then it appears. The red solar ball hangs just to the left of the Slaughter Stone, the immense slab that marks the entrance to Stonehenge.

The old stone monument was built three to four thousand years ago. Legend tells us that Merlin the wizard magically transported this vast structure to Salisbury, England. Although we now know this is a myth, the structure's precision remains wondrous. The ancient peoples hauled huge sandstone slabs hundreds of miles to this site. They carefully arranged five pairs of immense vertical slabs—each pair crowned by a horizontal stone—into a giant horseshoe. Three pairs are still erect today, while single stones remain in the place of the other two.

The Slaughter Stone is missing its twin slab. Had it been present, the Sun would have appeared perfectly centered between the two vertical monoliths on this midsummer's morning. And the long shadows of the twins would have drawn a broad sunlit path stretching to the horseshoe center.

Although human society has changed over four thousand years, we share a fascination with the motion of the Sun across the sky, and its profound consequences for our planet and for us.

Stonehenge at dawn.

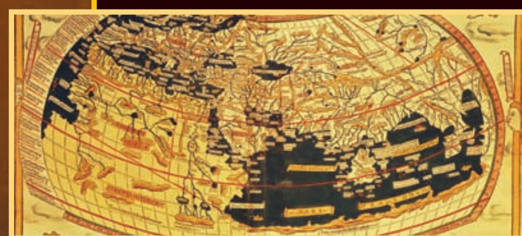


CHAPTER OUTLINE

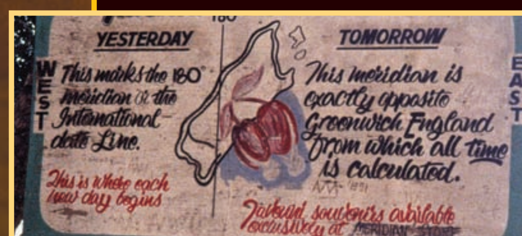
- The Shape of the Earth p. 4

- The Earth's Rotation p. 6

- The Geographic Grid p. 8



- Map Projections p. 13



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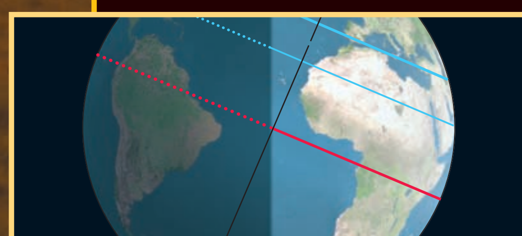

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The Shape of the Earth

LEARNING OBJECTIVES

Explain how we know the Earth's approximate shape.

Describe the actual shape of the Earth.

We are so familiar with the image of our spherical planet, that we rarely question whether or not it is perfectly round. But what do we actually know about the Earth's shape?

We all grew up with globes in our homes and classrooms. Meanwhile, pictures from space, taken by astronauts or sent to us by orbiting satellites, display our round planet in its full glory (FIGURE 1.1). 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 true 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 (FIGURE 1.2).

We also see information about the shape of the Earth when we watch the sunset with clouds in the sky (FIGURE 1.3). A rotating, spherical Earth explains the movement of solar illumination across the clouds.

The familiar images of our round planet that we take for granted are a little misleading. 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

Earth curvature FIGURE 1.1

This astronaut photo shows the Earth's curved horizon from low-Earth orbit.

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Distant ship FIGURE 1.2

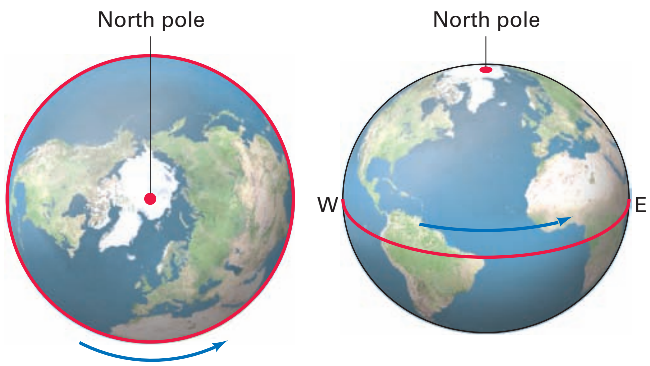
If the telescope had been invented then, ancient sailors might have peered through the lens at a distant ship sailing along the horizon. The ship's decks are mysteriously immersed below the water line—a clear demonstration of the Earth's curvature.

Cloud illumination FIGURE 1.3

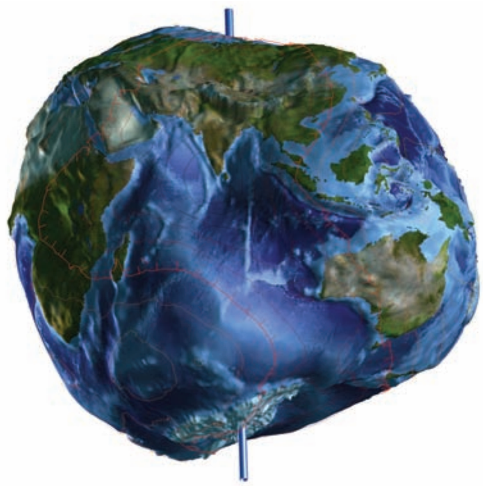
As you watch the sunset from the ground, the Sun lies below the horizon, no longer illuminating the land around you. But at the height of the clouds, the Sun has not yet dipped below the horizon, so it still bathes the clouds in red and pinkish rays. As the Sun descends, the red band of light slowly moves farther toward your 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 to bulge slightly at the equator and flatten at the poles (FIGURE 1.4). 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. It is defined by a set of mathematical equations and has many applications in mapmaking.



The direction of rotation of the Earth can be thought of as **A** counterclockwise at the North Pole, or **B** from left to right (eastward) at the equator.



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

Earth rotation FIGURE 1.4

The Earth's rotation causes it to bulge slightly at the equator.

CONCEPT CHECK STOP

How do we know the approximate shape of the Earth?

What simple shape closely approximates the true shape of the Earth?

The Earth's Rotation

Learning Objectives

Define the axis and poles.

Describe the environmental effects of the Earth's rotation.

The Earth spins slowly on its **axis**—an imaginary straight line through its center and poles—through day and night. It makes one full turn with respect to the Sun every day. We define a solar day by one *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. If we want to work out the direction of the Earth's rotation, we can use the poles to guide us.

Axis An imaginary straight line through the center of the Earth around which the Earth rotates.

Poles The two points on the Earth's surface where the axis of rotation emerges.

ENVIRONMENTAL EFFECTS OF THE EARTH'S ROTATION

The most obvious effect of the Earth's rotation is that it gives us our measure of time. All walks of life on the planet's surface are governed by the daily rhythms of the Sun and its regular beats as it changes from day to night. Green plants store solar energy during daylight, consuming it at night. Some animals are active during the day, while others move around at night.

The daily influx of solar energy and the cycle of fluctuating air temperature it produces will be analyzed later in this book.

The directions of large motions of the atmosphere and oceans are also affected, as the turning planet makes their paths curve. Our weather systems respond to this phenomenon, which is known as the *Coriolis effect*.

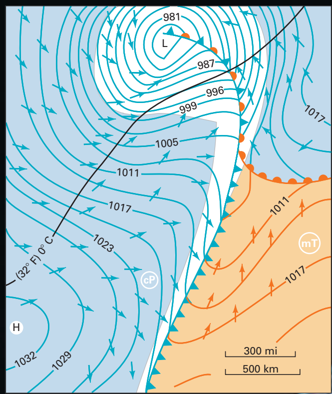
Finally, the Earth's rotation combined with the Moon's gravitational pull on the planet creates the rhythmic rise and fall of the ocean surface that we witness as the tides. The ebb and flow of tidal currents is a life-giving pulse for many plants and animals and provides a clock regulating many daily human activities in the coastal zone.

CONCEPT CHECK STOP

How are the Earth's axis and the poles defined?

What are the main effects of the Earth's rotation on its axis?

What a Geographer Sees



This simplified weather map shows the occluded stage of a midlatitude cyclone—the "comma-shaped cloud" in the photo. A cold front has overtaken a warm front, and a large pool of warm, moist air has been forced aloft.

In this photo from the Meteosat geostationary satellite, Earth appears as a round ball, obscured by swirls of cloud.

Countries with distinctive shapes, like Great Britain, Ireland, Greece, Turkey, Sweden and Denmark, are easily recognizable. We can also pick out the white lines of cloud and snow that run along the Pyrenees and the Alps.

But to a geographer, these white lines reveal more than just the position of mountains—they mark the edges of crustal Earth plates, which are slowly colliding and pushing up these mountain chains. A geographer would also recognize that the comma-shaped cloud patterns on the top left of the image are cyclones moving eastward. The inset shows how a weather map might depict such a midlatitude cyclone.

The Geographic Grid

Learning Objectives

Define parallels, meridians, latitude, and longitude.

Explain how we determine position on the globe.

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 a **geographic grid**. This is made up of a system of imaginary circles, called **parallels** and **meridians**, which are described in Figure 1.5.

Geographic grid Network of parallels and meridians used to fix location on the Earth.

Parallel East-west circle on the Earth's surface, lying in a plane parallel to the equator.

Meridian North-south line on the Earth's surface, connecting the poles.

PARALLELS AND MERIDIANS

Imagine cutting the globe just as you might slice an onion to make onion rings (Figure 1.5A). 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 right 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.

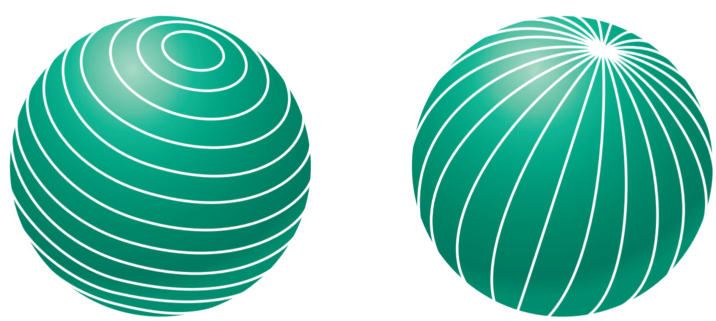
Now, imagine slicing the Earth through the axis of rotation instead of across it, just as you would cut up a lemon to produce wedges (Figure 1.5B). The outlines of the cuts form circles on the globe, each of which passes through both poles. A meridian of longitude, or simply meridian, is formed by half of this circular outline, which connects one pole to the equator.

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

Equator Parallel of latitude lying midway between the Earth's poles; it is designated latitude 0°.

Latitude Arc of a meridian between the equator and a given point on the globe.

Longitude Arc of a parallel between the prime meridian and a given point on the globe.



A Parallels of latitude divide the globe crosswise into rings.

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

Parallels and meridians Figure 1.5

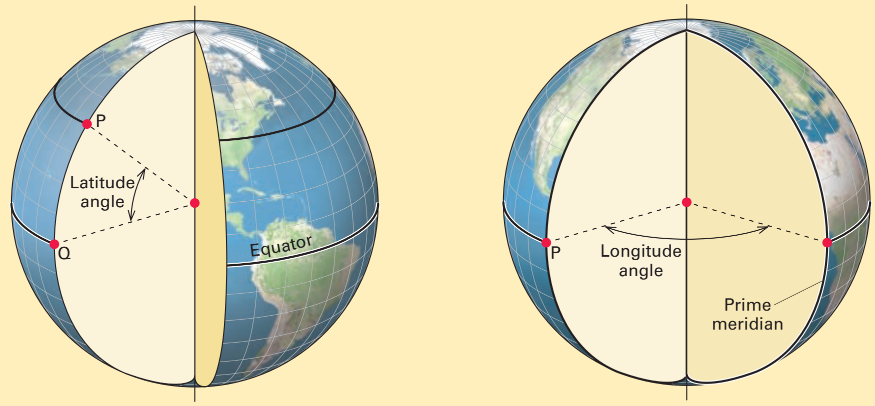
unique combination of one parallel and one meridian. The position of the point is defined by their intersection.

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, or hemispheres. All parallels in the northern hemisphere are described by a north latitude, and all points south of the equator are given as south latitude (N or S).

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 old Royal Observatory at Greenwich, near London, England (FIGURE 1.7). It has a value longitude 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. So longitude ranges from 0° to 180°, east or west (E or W).



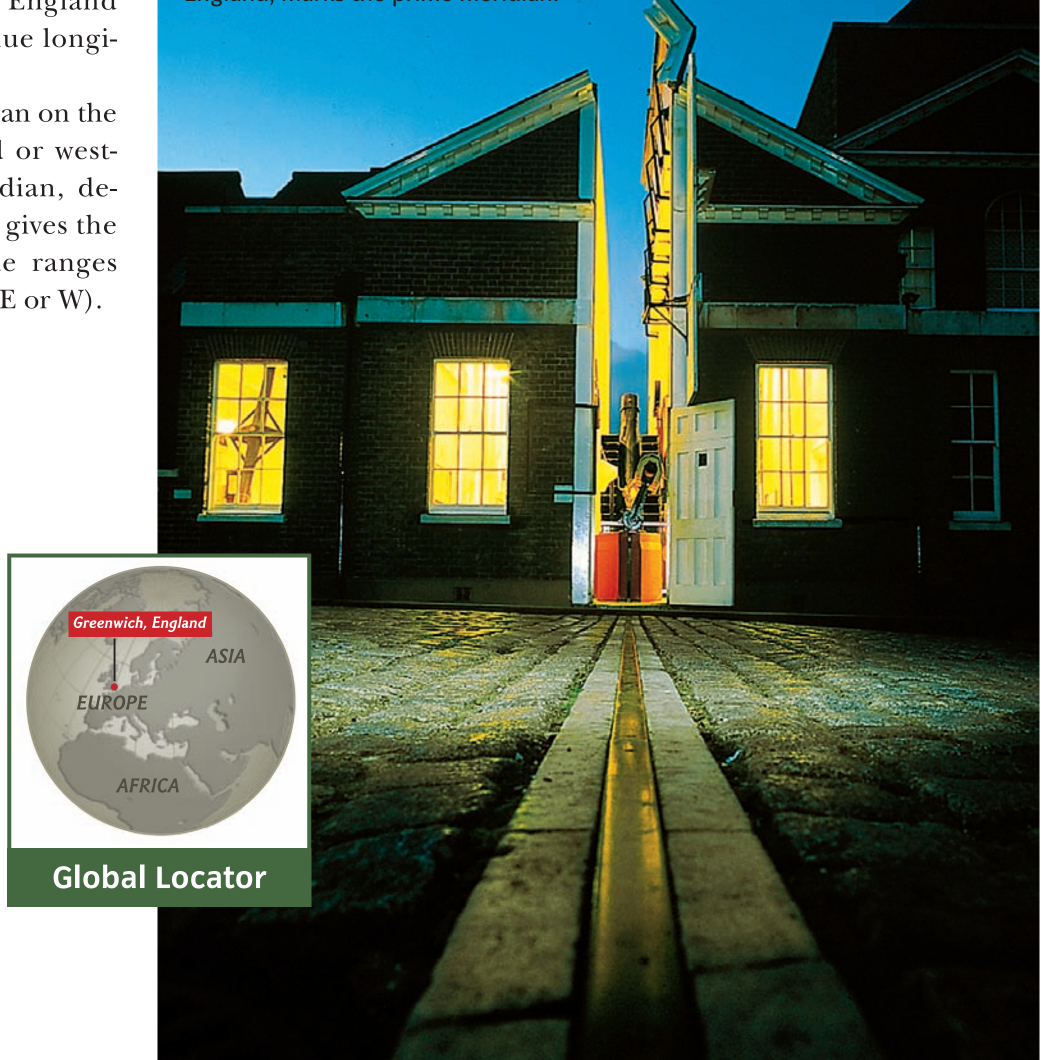
A The latitude of a parallel is the angle between a point on the parallel (P) and a point on the equator at the same meridian (Q) as measured from the Earth's center.

B Longitude is the angle between a plane passing through the meridian and a plane passing through the prime meridian.
The longitude of a meridian is the angle between a point on that meridian at the equator (Q) as measured at the Earth's center.

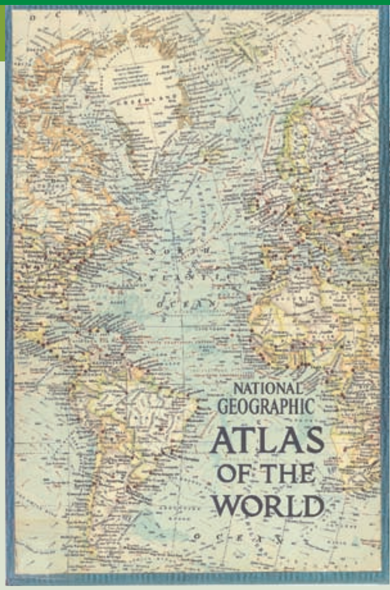
Latitude and longitude angles FIGURE 1.6

Prime meridian FIGURE 1.7

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



Global Locator



▲ A map centered on the Atlantic Ocean as it appeared on the cover of the first *National Geographic Atlas of the World*.

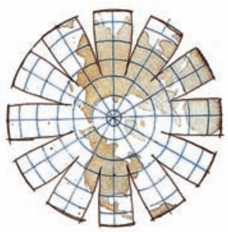
▲ A topographic map of Mount Everest combining topographic contours with shaded relief.

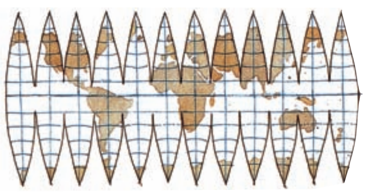
EXAMPLES OF MAPS

◀ A map of Arctic Regions from 1925, showing a large section of the Arctic as "unexplored."

Applying projections onto flat paper

▶ **Geometry at work**
The surface of a sphere cannot be made to lie flat, but planes, cones, and cylinders can. Using these "developable surfaces" and applying calculations, cartographers can project the Earth's features onto flat paper. Some distortion is unavoidable. Only at exactly the points where the developable surface touches the globe is the flat map completely accurate. The farther from these points of contact, the more stretched or squeezed features become. Thus, map-makers place the points of contact at the part of the globe they wish to map most faithfully (right).

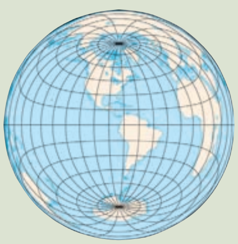




Oblique Mercator
This projection wraps a cylinder around the globe along any great circle other than a meridian or the equator. The result: high accuracy along the shortest route between two points.

◀ **Mercator**
Straight lines plotted on the Mercator show true compass direction, ideal for navigation. Areas are increasingly enlarged toward the poles. For example, Alaska looks as big as Brazil; it is less than a fifth the size. Greenland appears 17 times as large as it really is.

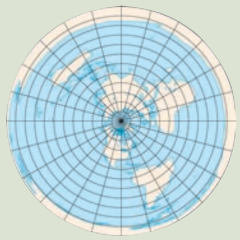
Cartographic projections of the Earth



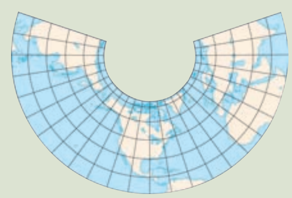
Orthographic
Designed to show the Earth as seen from a distant point in space, the orthographic is usually used to portray hemispheres. Distortion at the edges, however, compresses land masses.

Azimuthal Equidistant
Map-makers can choose any center point, from which directions and distances are true, but in outer areas shapes and sizes are distorted. On this projection, Antarctica, the Arctic Ocean, and several continents appear.

Lambert Azimuthal Equal-Area
Distortion away from the center makes this projection a poor choice for world maps but useful for fairly circular regions, such as the lunar hemispheres.



Stereographic
Like the orthographic, this projection was used in the second century B.C. by Hipparchus. It was one of the first to show the world as round. All points lie in true direction from the center, but outer areas are stretched.



Albers Conic Equal-Area
The Albers is a good format for mapping mid-latitude regions that are larger east to west than north to south.

NATIONAL GEOGRAPHIC

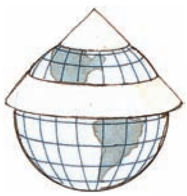
MAPPING AS A SCIENCE AND AN ART

A map projection changes the geographic (latitude-longitude) grid of the globe into a grid that can be displayed as a flat map. Making a map is both a science and an art.≤

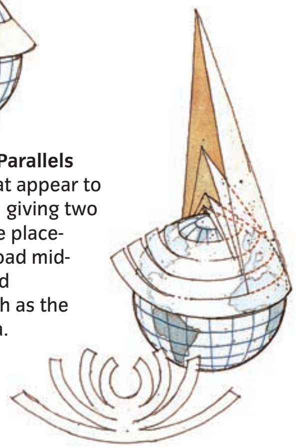
The National Geographic's chief cartographer and art director create layouts of map and satellite data for the eighth edition of the *National Geographic Atlas of the World*.

An artist applies color shading to a map of the ocean floor.

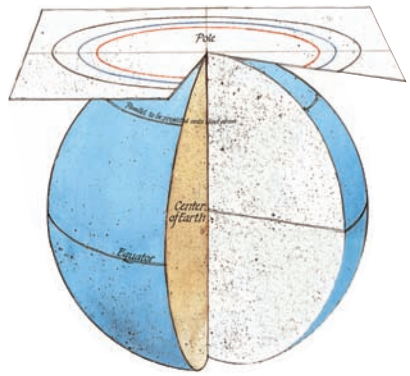
Conic
The ancient Greeks developed the conic projection to chart the known world. A cone sits atop the globe like a dunce cap, and accuracy is greatest along the circle it touches—the standard parallel.



Conic—Two Standard Parallels
Cones can be drawn that appear to slice through the globe, giving two standard parallels. Cone placement can follow any broad mid-latitude region of limited north-south extent, such as the United States and China.

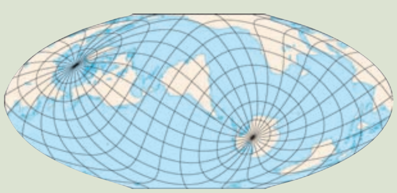


Polyconic
Good for mapping narrow regions extending north and south, the polyconic uses a series of cones that produce collar-shaped strips; the curving ends must be stretched in order to join. Thus, the farther from the central meridian, the greater the distortion.

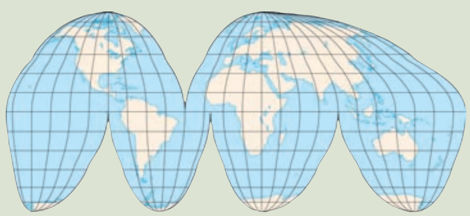


How maps differ
Some map projections are based on cones and cylinders; others derive from flat paper held against the globe. The orthographic projection represents the Earth as if from a point in space. The stereographic projection appears as if seen from a point on the opposite side of the globe; the gnomonic, as viewed from the center of the Earth. Such perspective projections plot what the eye would see from the vantage points at which the maps are projected and drawn. The diagram (left) illustrates how these methods change the position of a parallel.

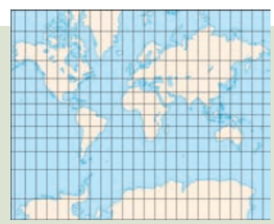
Mollweide
In 1805 Carl B. Mollweide, a German mathematician, devised this elliptical equal-area projection that represents relative sizes accurately but distorts shapes at the edges. Many thematic maps use the Mollweide.



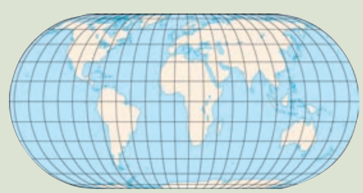
Oblique Flat Polar Quartic
This equal-area projection, first presented in 1949, produces axes oblique to each other. Unlike many conventional world projections that display the two poles as lines, poles appear here as points, with less distortion.



Interrupted Goode Homolosine
To minimize distortion of scale and shape, this projection interrupts the globe. Its equal-area quality makes it suitable for mapping distributions of various kinds of information.



Mercator
Named for Gerardus Mercator, the Flemish geographer who invented it in 1569, this most famous of all map projections was intended for navigation. Useful for showing constant bearings as straight lines, the Mercator greatly exaggerates areas at higher latitudes.



Eckert Equal-Area
Produced by German educator Max Eckert, line-poles for this projection are half the length of the equator. Polar regions are less compressed than on elliptical projections; low-latitude land masses are elongated.

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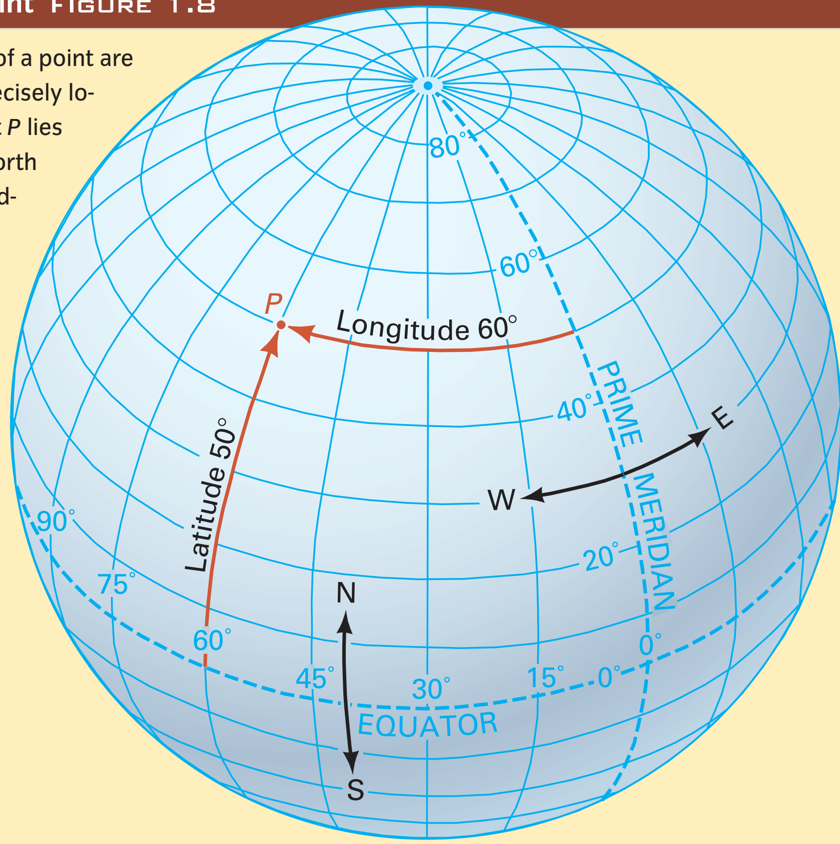
Latitude and longitude of a point FIGURE 1.8

When both the latitude and longitude of a point are known, it can be accurately and precisely located on the geographic grid. 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.



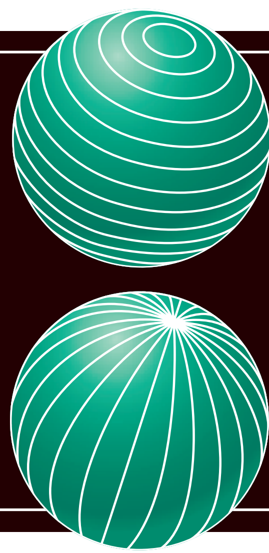
Together, latitude and longitude pinpoint locations on the geographic grid (FIGURE 1.8). Fractions of latitude or longitude angles are described using minutes and seconds. A minute is 1/60 of a degree, and a second is 1/60 of a minute, or 1/3600 of a degree. So, the latitude 41°, 27 minutes (′), and 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.

CONCEPT CHECK STOP

What is the difference between a parallel and a meridian?

What is the difference between latitude and longitude?

How do we label position on the Earth's surface?



Map Projections

Learning Objectives

Explain what a map projection is.

Discuss the differences between the Mercator, the Polar, and the Goode projection.

The problem of just how to display the Earth has puzzled cartographers, or map-makers, 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 6th century B.C. show the world as an island, with Greece at its center, while medieval maps from the 14th century placed Jerusalem at the focus.

But by the 15th century, ocean-faring explorers such as Columbus and Magellan were extending the reaches of the known world. These voyagers took map-makers with them to record the new lands that that they discovered, and navigation charts were highly valued. Map-makers, 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.

For any map to be useful, we must know how the shapes on the flat page relate to the three dimensional world around us. Every map has a scale fraction—a

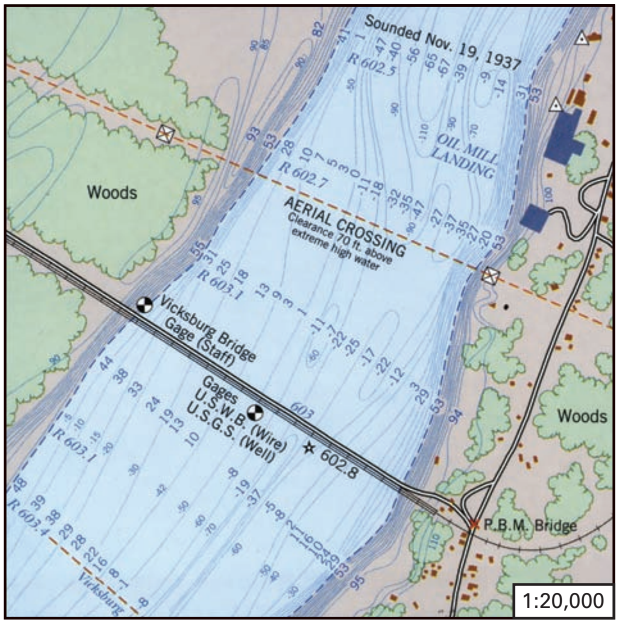
Ptolemy's map of the world Figure 1.9

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

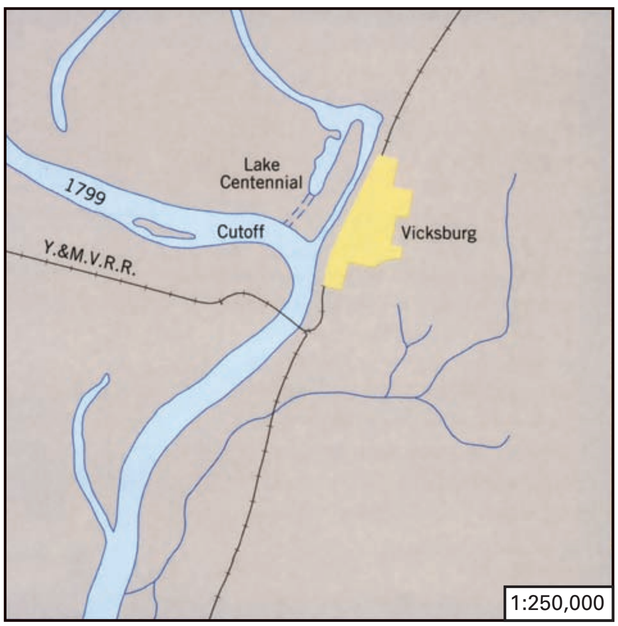
ratio that tells us how to convert between the distances drawn on our map and true Earth distances. A scale fraction of 1:50,000, for example, means that one unit of map distance equals 50,000 units of distance on the Earth (FIGURE 1.10).

But because we cannot project a curved surface onto a flat sheet without some distortion, the scale fraction of a map will only be true for one point or for one or two single lines on the map. Away from that point or line, the scale fraction will be different. This variation is only a problem for maps that show large regions, such as continents or hemispheres. One of the earliest attempts to tackle the curvature problem for large-scale maps was made by the Belgian cartographer, Gerardus Mercator, in the 16th century, and it is still used today. There are a number of other systems, or **map projections**, which have been developed to translate the geographic grid to a flat one. The feature called, "Visualizing: Map Projections" provides many examples of map projections. We will concentrate on the three most useful types, including Mercator's. Each has its own advantages and drawbacks.

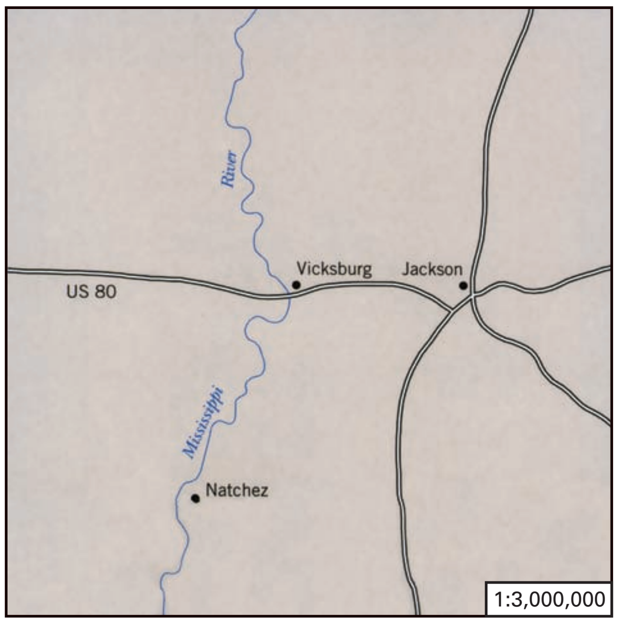
Map projection A system of parallels and meridians representing the Earth's curved surface drawn on a flat surface.



A 1:20,000. Channel contours give depth below mean water level.



B 1:250,000. Waterline only shown to depict channel.



C 1:3,000,000. Channel shown as a solid line symbol.

Scale fractions FIGURE 1.10

Maps of the Mississippi River on three scales. (Maps slightly enlarged for reproduction. Modified from U.S. Army Corps of Engineers.)

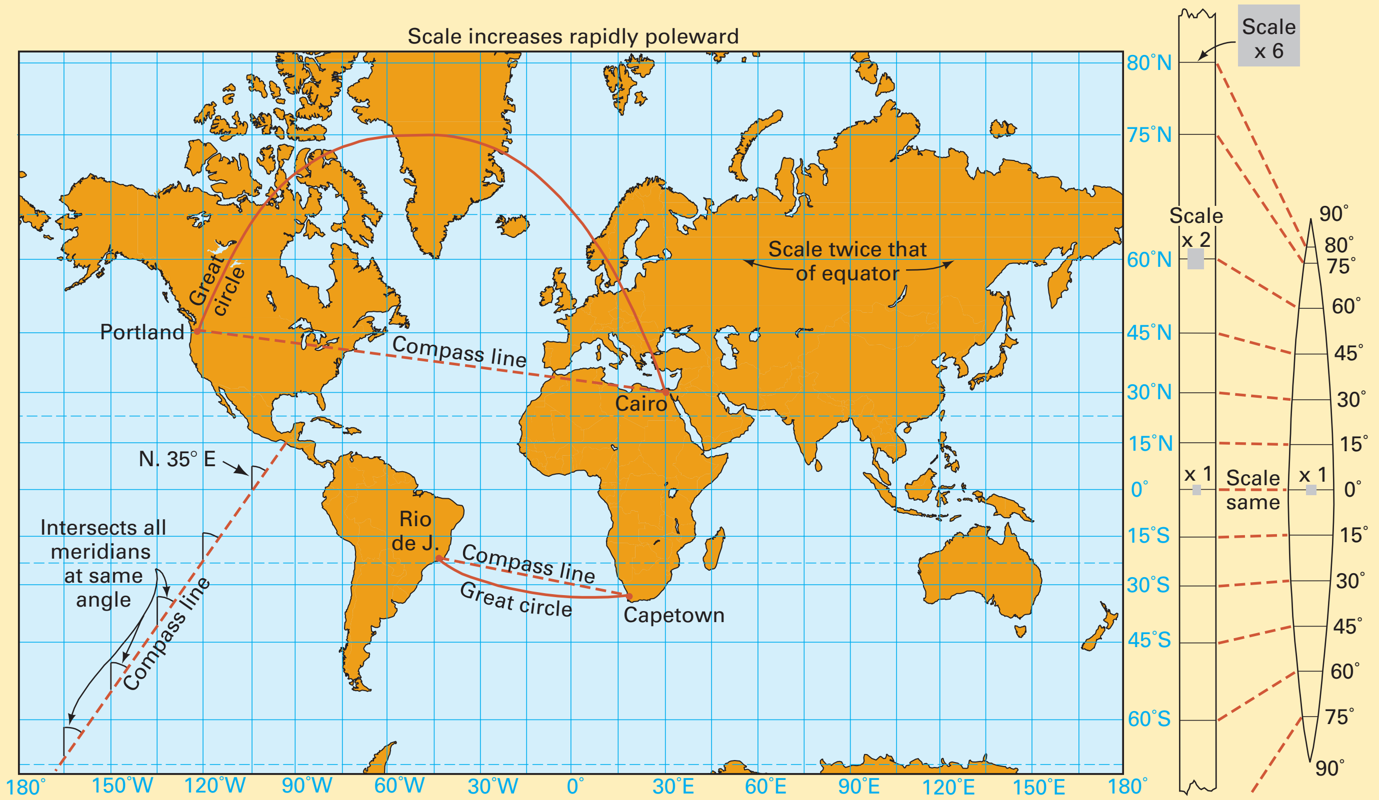
MERCATOR PROJECTION

Gerardus Mercator invented his navigator's map in 1569. It is a classic that has never gone out of style.

In the **Mercator projection**, the meridians form a rectangular grid of straight vertical lines, while the parallels form straight horizontal lines. 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.

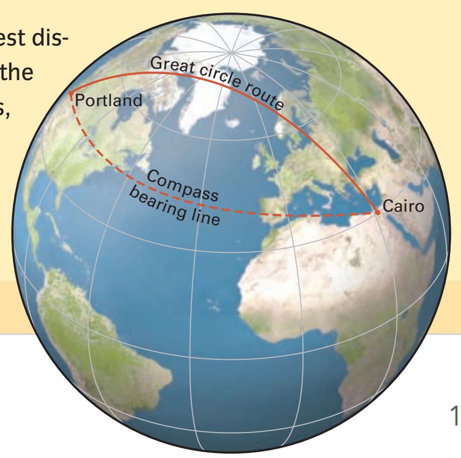
> **Mercator projection** Map projection with horizontal parallels and vertical meridians.

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 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).



A 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.

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



The Mercator projection FIGURE 1.11

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. These include wind and ocean current flow lines, 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.

THE GOODE PROJECTION

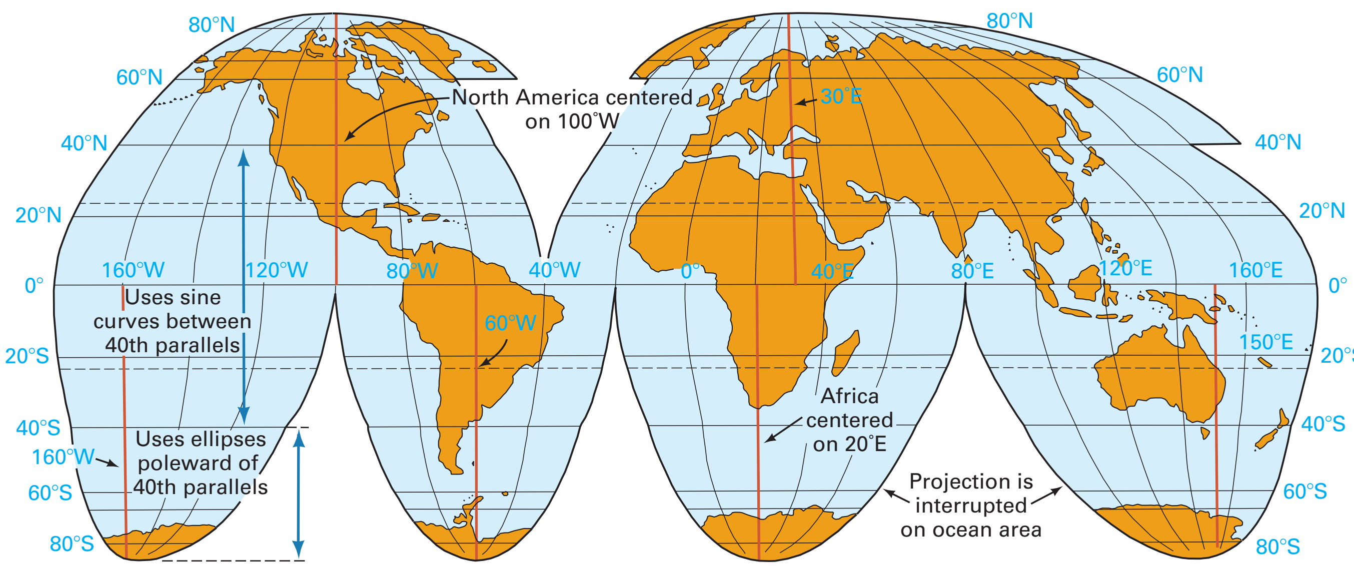
The **Goode projection** (FIGURE 1.12) is named after its designer, J. Paul Goode. It has one very important property—it indicates the true sizes of regions on the Earth's surface. So, if we drew a small circle on a sheet of clear plastic and moved it over all parts of the Goode world map, all the regions enclosed would share the same actual area in square kilometers or square miles. So we can easily scan over regions and get a feel for the relative sizes of places affected by different features. This makes the Goode map ideal for showing the world's climate, soils, and vegetation.

Although the Goode map preserves the relative surface areas of different regions, it has a serious defect. It distorts the shapes of places, particularly in high latitudes and at the far right and left edges.

Goode projection Equal-area map projection often used to display information such as climate or soil type.

The Goode projection FIGURE 1.12

The Goode projection does not use straight lines to represent its meridians. Instead, the meridians follow sine curves between lat. 40° N and lat. 40° S, and ellipses between lat. 40° and the poles. The entire globe can be shown because the ellipses converge to meet at the pole. The straight, horizontal parallels make it easy to scan across the map at any given level to compare regions most likely to be similar in climate.

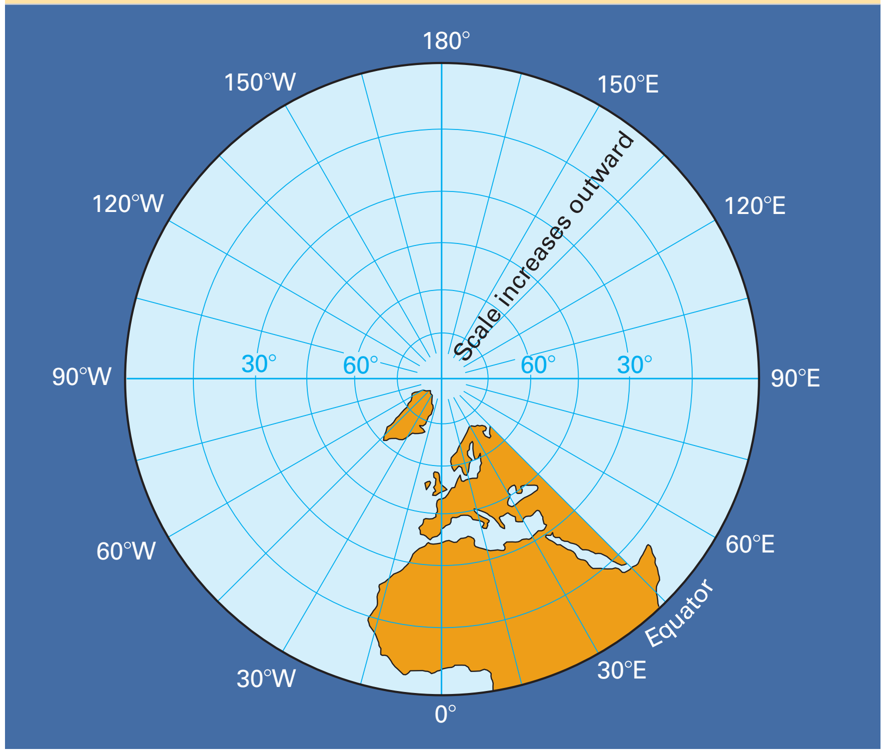


POLAR PROJECTION

The **polar projection** (FIGURE 1.13) is normally centered on either the North or the South Pole. It is essential for weather maps of the polar regions. The map is usually cut off to show only one hemisphere so that the equator forms the outer edge of the map.

Polar projection Map projection centered on Earth's North or South Pole.

A polar projection FIGURE 1.13



The map is centered on the North Pole. All meridians are straight lines radiating from the center, and all parallels are concentric circles. The scale fraction increases in an outward direction, making shapes toward the edges of the map appear larger. Because the intersections of the parallels with the meridians always form true right angles, this projection shows the true shapes of all small areas. The shape of a small island will always be shown correctly, no matter where it appears on the map.

CONCEPT CHECK STOP

Identify three types of map projections used in this book.

Which projection should you use if you want to easily compare the sizes of regions on the map?

Which projection is most useful for plotting directions?

Identify an important application of the polar projection.

Global Time

LEARNING OBJECTIVES

Describe how the Sun's position regulates global time.

Discuss the need for world time zones.

Explain why we use Daylight Saving Time.

There's an old Canadian joke that goes, "The world will end at midnight, or 12:30 a.m. in Newfoundland." 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 (FIGURE 1.14).

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. But different regions around the world 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

A London's Big Ben, a mechanical clock, atop the Parliament Building.

B This version of a sundial at the University of Arizona is a solar timekeeper. The user selects a standing position based on the day of the year and reads the time from his or her shadow.

Timekeepers FIGURE 1.14

does it work? The Earth's geographic grid and the rotation of the Earth help define global time.

While we are waking up, people on the other side of the planet are going to sleep. 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.

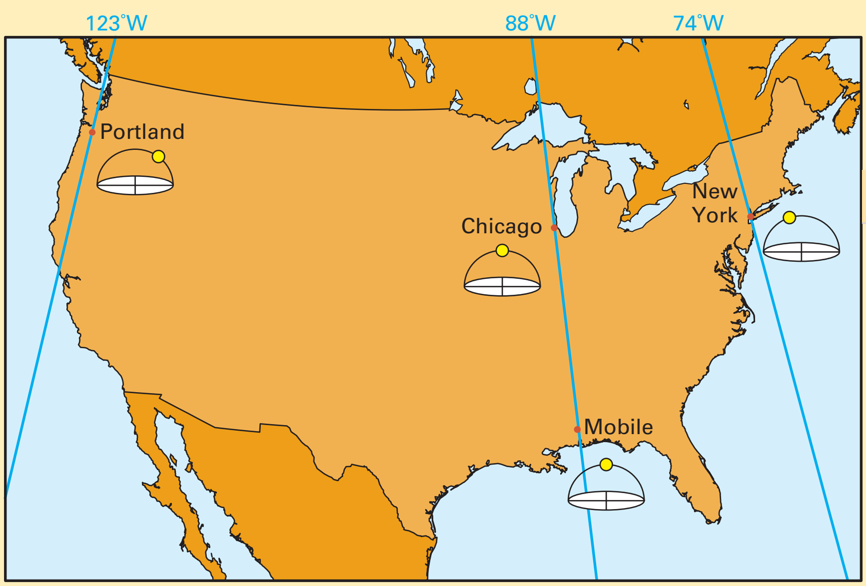
Imagine for a moment that you are in Chicago (FIGURE 1.15). The time is noon, and the Sun is at or near its highest point in the sky. You call a friend in New York and ask about the position of the Sun. Your friend will say that the Sun has already passed solar noon, its highest point, and is beginning its downward descent. 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.

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. In these days of instantaneous global communication, chaos would soon result.

Some of that chaos was seen in the 19th century, before World Standard Time was introduced. As new railroads were developed in the United States, people were able to cross large distances with new ease. But each railroad used its own standard time, based on the



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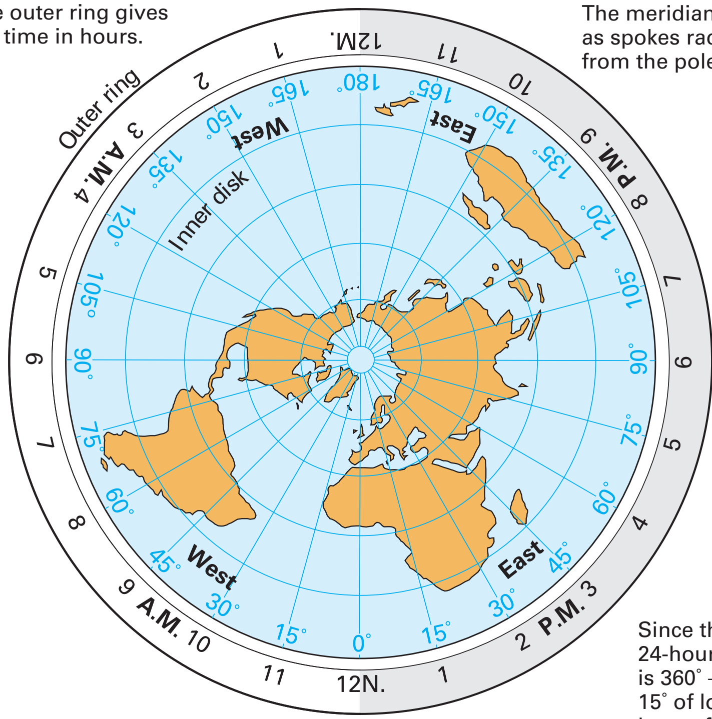
Time and the Sun FIGURE 1.15

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, which is about 1600 km (1000 mi) away, it is also noon. This is because time is determined by longitude, not latitude.

Process Diagram

The relation of longitude to time



This figure shows a polar projection of the northern hemisphere, centered on the North Pole.

Standard time
Time system based on the local time of a standard meridian and applied to belts of longitude extending roughly 7 1/2° on either side of that meridian.

local time at its headquarters—so train timetables were often incompatible.

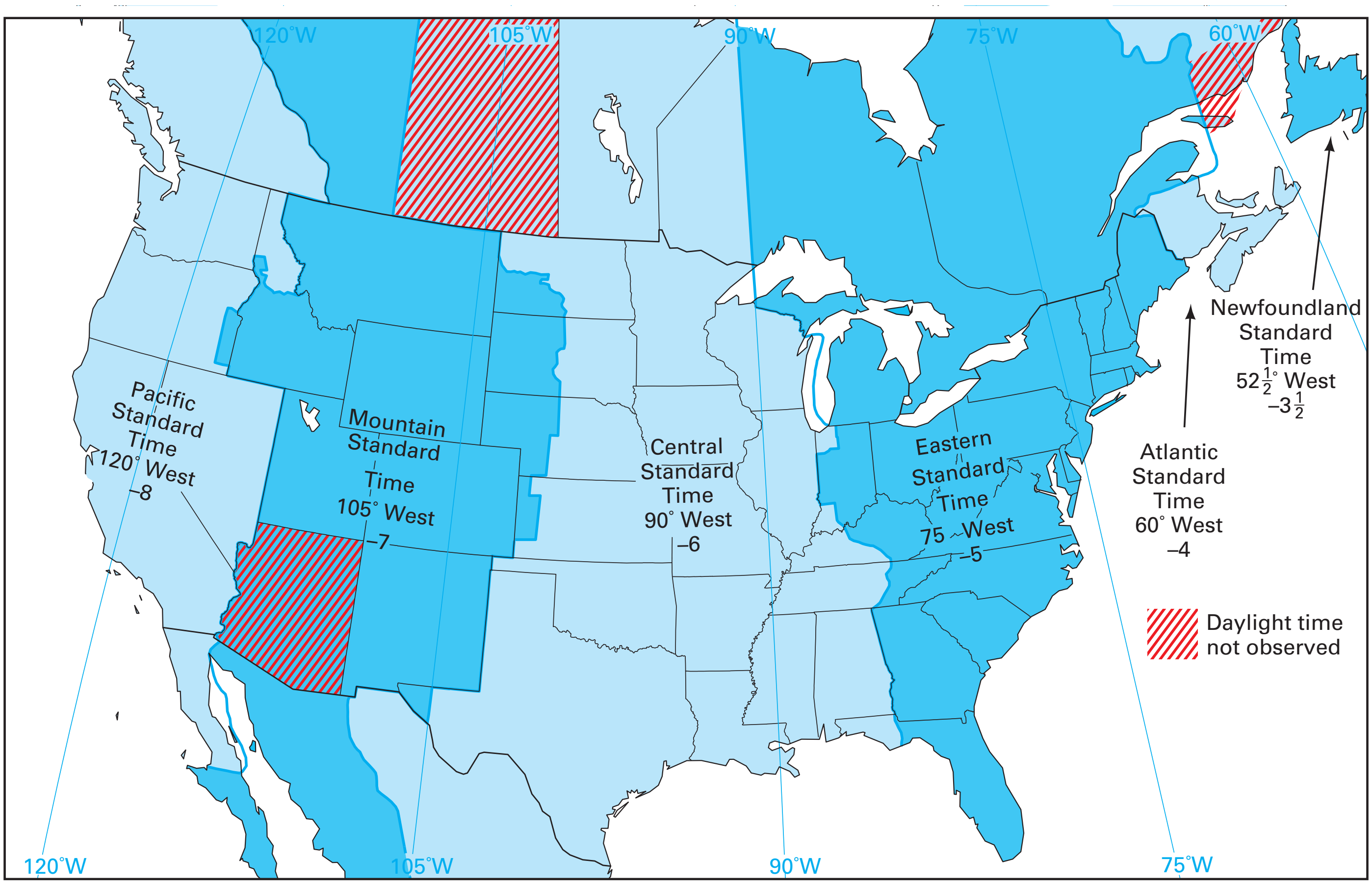
The introduction of **standard time** solved these timekeeping problems. In the standard time system, the globe is divided into time zones. People within a zone keep time according to a standard meridian that passes through their zone. Since the standard meridians are usually 15 degrees apart, the difference in time between adjacent zones is normally one hour, but in some geographic regions,

> **Time zones**
> Zones or belts within which standard time is applied.

the difference is only one-half hour. FIGURE 1.16 shows the **time zones** observed in North America.

The United States and its Caribbean possessions are covered by seven time zones. Their names and standard meridians of longitude are as follows:

U.S. Zones	Meridian
Atlantic	60°
Eastern	75°
Central	90°
Mountain	105°
Pacific	120°
Alaska	135°
Hawaii–Aleutian	150°



Time zones of North America FIGURE 1.16

The name, standard meridian, and number code are shown for each time zone. Note that 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.

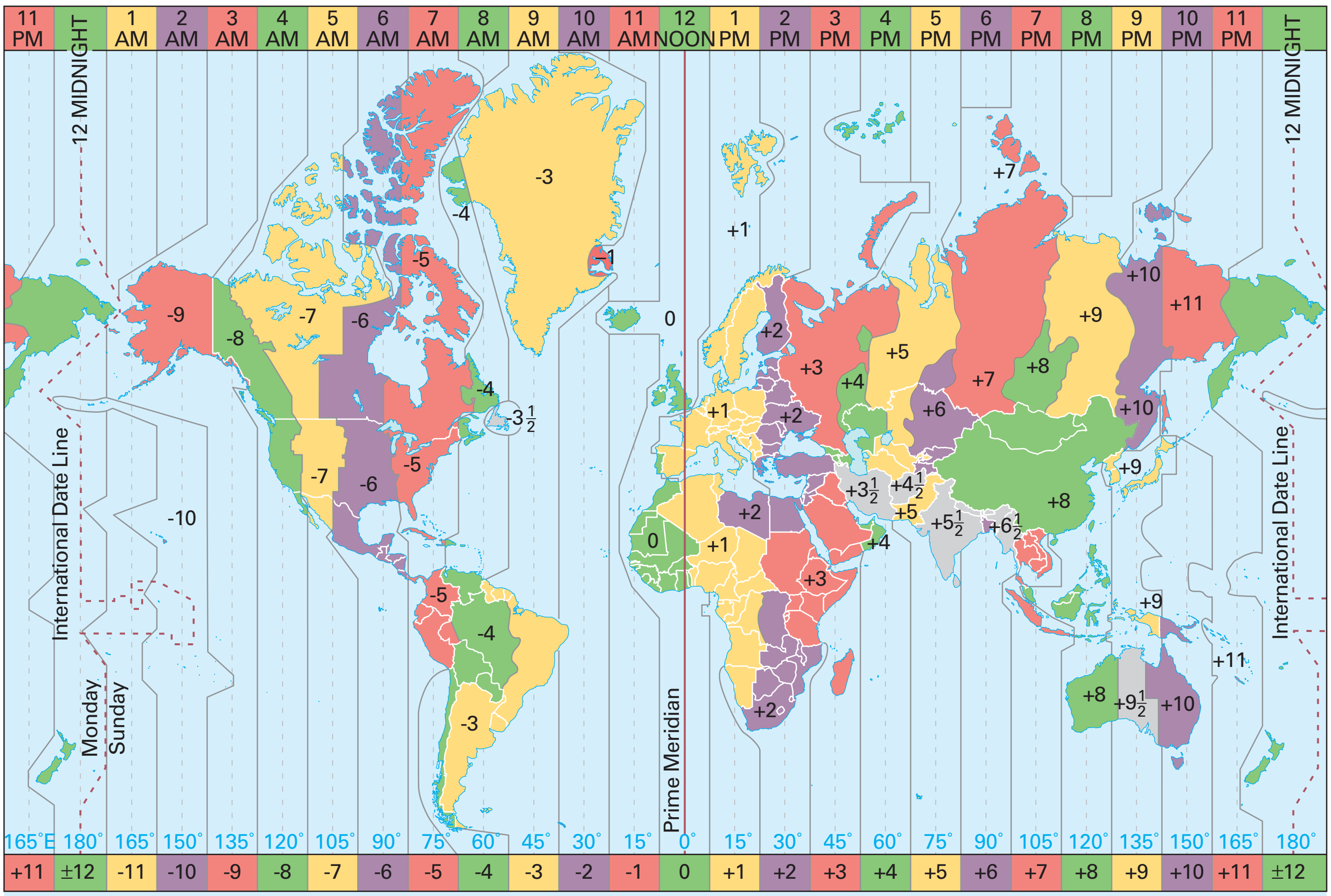
WORLD TIME ZONES

According to our map of the world's time zones (FIGURE 1.17), the country spanning the greatest number of time zones is Russia. From east to west Russia spans 11 zones, but these are grouped 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 regions within countries also keep time by 7 1/2° meridians, such as the Canadian province of Newfoundland and the interior Australian states of South Australia and Northern Territory.

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



Time zones of the world FIGURE 1.17

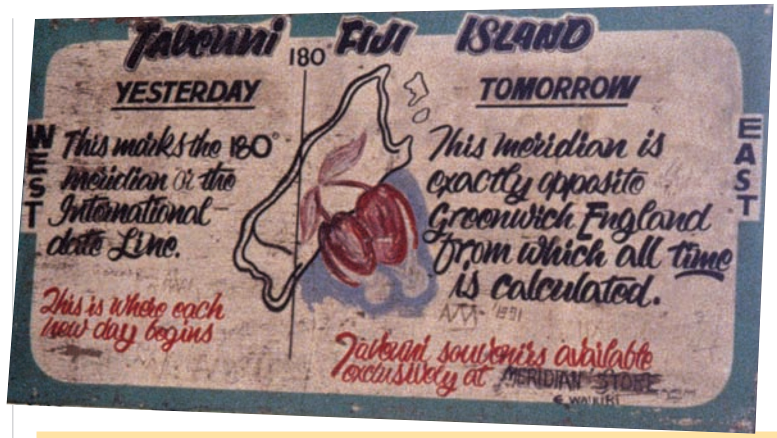
This figure shows the principal standard time zones of the world. World time zones are labeled at the bottom of the figure by the number of hours difference between that zone and Greenwich. So the number −7 tells us that local time is seven hours behind Greenwich time, while a +3 indicates that local time is three hours ahead of Greenwich time. 15° meridians are dashed lines, while the 7 1/2° meridians, which form many of the boundaries between zones, are bold lines. Alternate zones appear in color. The top line shows the time of day in each zone when it is noon at the Greenwich meridian.

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.

Imagine that you are on the 180th meridian on June 26. At the exact instant of midnight, the same 24-hour calendar day covers the entire globe. Stepping east will place you in the very early morning of June 26, while stepping west will place you very late in the evening of June 26. You are in the same calendar day on both sides of the meridian but 24 hours apart in time.

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 (FIGURE 1.18). This means that if you travel westward across the date line, you must advance your calendar by one day. If you are traveling eastward, you set your calendar back by a day.

Air travelers between North America and Asia cross the date line. 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!



International date line FIGURE 1.18

The international date line passes here through Taveuni Island, Fiji. Standing to the left of the sign, the day to the right of the sign is tomorrow. Standing to the right, the day to the left is yesterday.

DAYLIGHT SAVING TIME

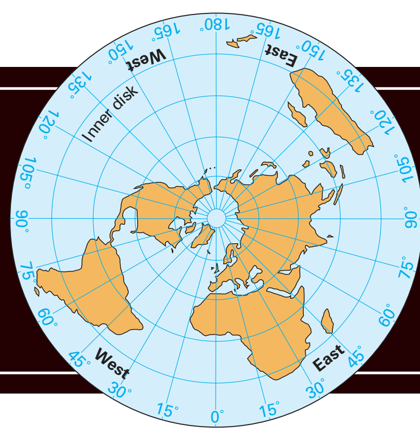
The Daylight Saving Time system allows us to cheat standard time and transfer an hour of light to a time when it will be more useful. In our modern world, we often wake up well after sunrise and continue being active until long after sunset, especially if we live in urban areas. So we adjust our clocks 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.

CONCEPT CHECK STOP

How is longitude related to time?

Why do we need a standard time system?

How is the world divided into time zones?



The Earth's Revolution Around the Sun

LEARNING OBJECTIVES

Explain how the seasons are created.

Define solstice and equinox.

Describe the different conditions at solstice and equinox.

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?

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 (FIGURE 1.19). Every four years, this time adds up to a whole extra day, which we account for by inserting a 29th day into February in leap years.

The point in its orbit at which the Earth is nearest to the Sun is called *perihelion*. The Earth is usually at perihelion on or about January 3. It is farthest away from the Sun, or at *aphelion*, on or about July 4. But this elliptical orbit is still very close to a circle, so the distance between Sun and Earth only varies by about 3 percent during one revolution. For most purposes we can treat the orbit as circular.

Imagine yourself in space, looking down on the North Pole of the Earth. From this position, you would see the Earth traveling counterclockwise around the Sun (FIGURE 1.19). This is the same direction as the Earth's rotation.

The Moon rotates on its axis and revolves about the Sun in the same direction as the Earth. But the Moon's rate of rotation on its axis is synchronized with the time it takes to orbit the Earth. This lock-step synchronization means that one side of the Moon is always permanently directed toward the Earth (FIGURE 1.20A), while the far side of the Moon is always hidden from us. It was only when a Soviet spacecraft passing the Moon transmitted photos back to Earth in 1959 that we caught our first glimpse of this far side (FIGURE 1.20B).

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.

Orbit of the Earth Around the Sun FIGURE 1.19

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

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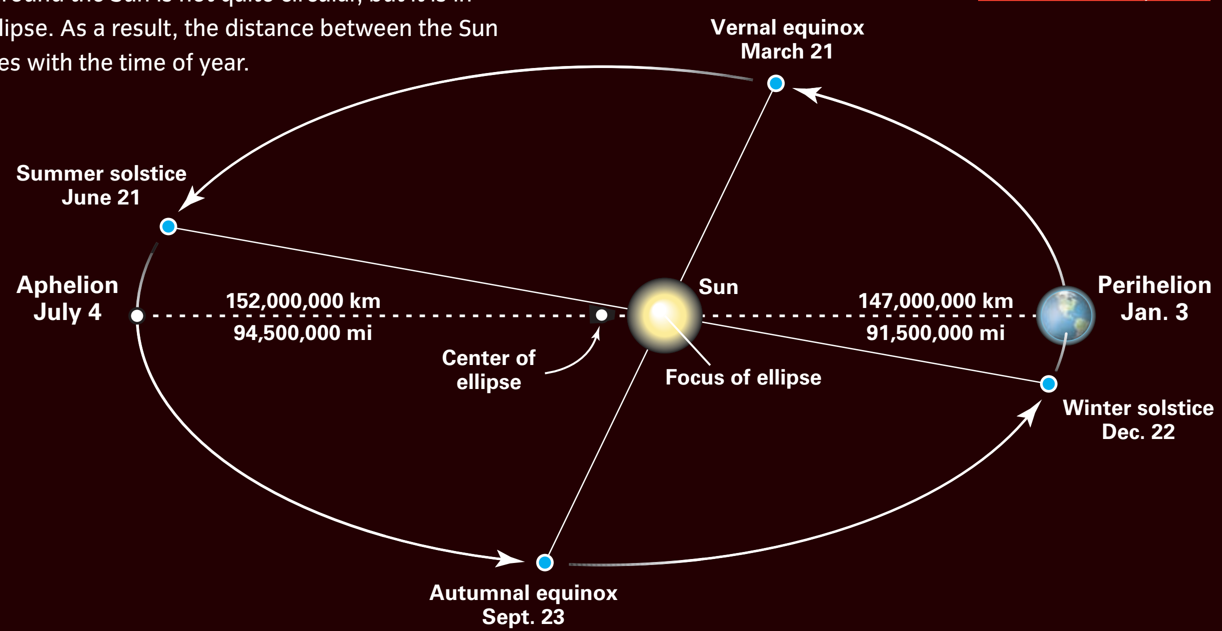


A The near side of the Moon always faces the Earth, although the sunlit portion of the surface we see varies through the lunar month.

B The far side of the Moon can be imaged only by spacecraft.

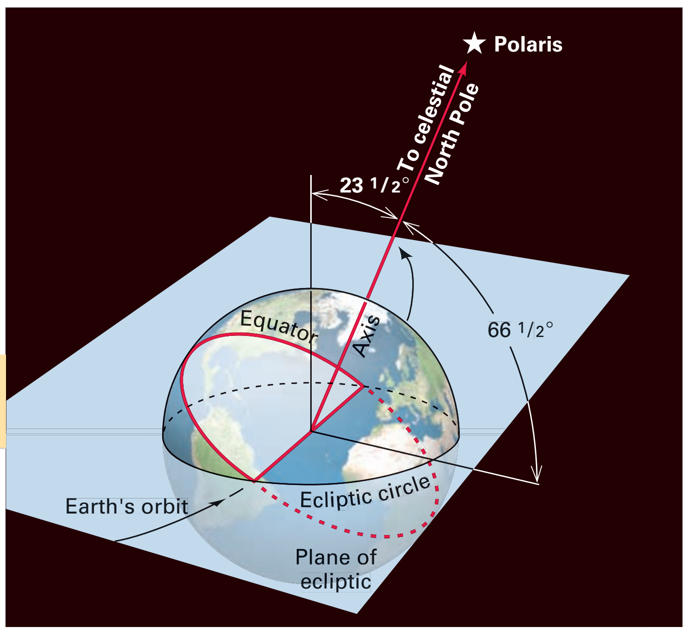
Sides of the Moon FIGURE 1.20

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*. FIGURE 1.21 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.



The tilt of the Earth's axis of rotation with respect to its orbital plane FIGURE 1.21

As the Earth moves in its orbit, its rotational axis remains pointed toward Polaris, making an angle of 66 1/2° with the ecliptic plane. We can see that the axis of the Earth is tilted at an angle of 23 1/2° away from a right angle to the plane of the ecliptic.

THE FOUR SEASONS

Figure 1.22 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, 23 1/2°. This event is called the **winter solstice** in the northern hemisphere. At this time, the southern hemisphere is tilted toward the Sun and enjoys strong solar heating. Because it is summer in the southern hemisphere at this point, we often call this the *December solstice* to avoid confusion.

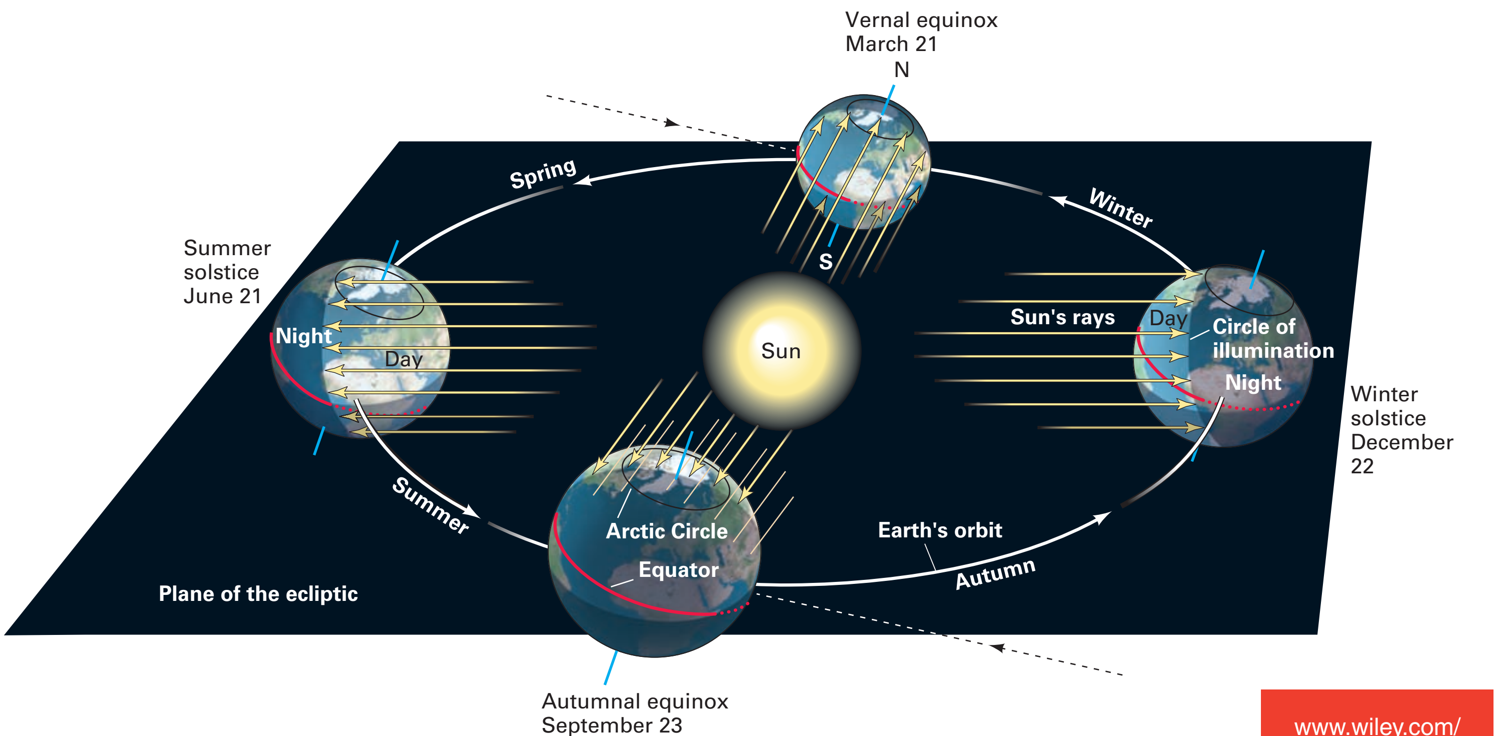
> **Winter solstice** Solstice occurring on December 21 or 22, when the subsolar point is at 23 1/2° S; also termed December solstice.

Six months later, on June 21, the Earth has traveled to the opposite side of its orbit. This is known as the **summer solstice** in the northern hemisphere (*June solstice*). The north polar end of the axis is tilted at 23 1/2° 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. March 21 is known as the *vernal* (*March*) *equinox* and the *autumnal* (*September*) *equinox* occurs on 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 Earth's revolution period is not exactly 365 days.

> **Summer solstice** Solstice occurring on June 21 or 22, when the subsolar point is at 23 1/2° N; also termed June solstice.

> **Equinox** Instant in time when the subsolar point falls on the Earth's equator and the circle of illumination passes through both poles.



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The Four Seasons. Earth-Sun relations through the year **Figure 1.22**

The four seasons occur because the Earth's tilted axis tips the northern hemisphere toward the Sun for the June solstice and away from the Sun for the December solstice. Both hemispheres are illuminated equally at the equinoxes. This figure shows the Earth as it revolves around the Sun over a year, passing through each of its four seasons.

Equinox conditions FIGURE 1.23

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.

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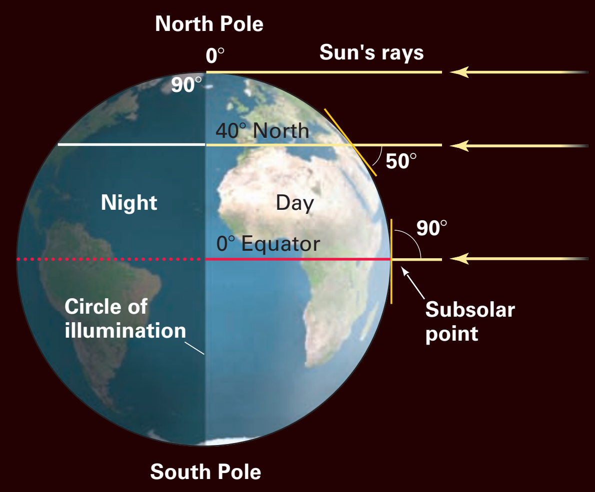


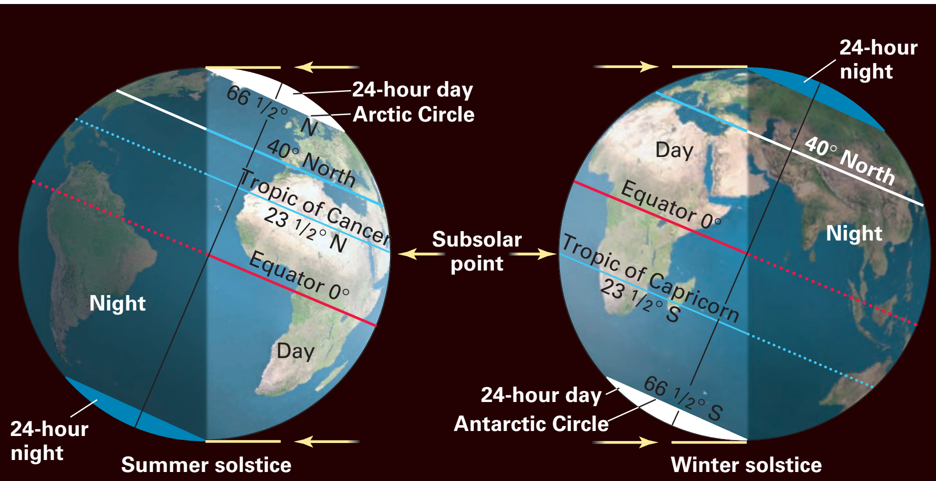
EQUINOX CONDITIONS

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 1.23. 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 the noon angle is equal to 90° minus the latitude, for equinox conditions, 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.

SOLSTICE CONDITIONS

Now let's examine the solstice conditions in FIGURE 1.24. Summer (June) solstice is shown on the left. Imagine that you are back at a point on the lat. 40° N



Solstice Conditions

FIGURE 1.24

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. 23 1/2° N or S.

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.

The farther north you go, the more this effect increases. Once you move north of lat. 66 1/2°, you will find that the day continues unbroken for 24 hours. Looking at FIGURE 1.24, we can see that is because the lat. 66 1/2° 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 23 1/2° 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 winter solstice. Back at lat. 40° N, you will now find that the night is about 15 hours long while daylight lasts about 9 hours. All the area south of lat. 66 1/2° 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. 23 1/2° S, known as the Tropic of Capricorn.

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*.

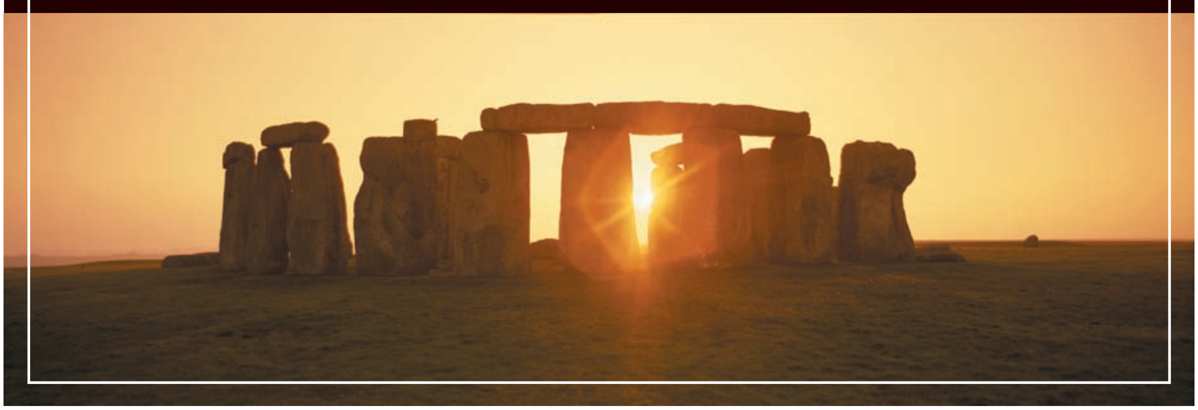
In polar regions, the areas bathed in 24-hour daylight or hooded in 24-hour night shrink and then grow, as the seasonal cycle progresses. At other latitudes, the length of daylight changes slightly from one day to the next, except at the equator, as mentioned above. In this way, the Earth experiences the rhythm of the seasons as it continues its revolution around the Sun.

CONCEPT CHECK **STOP**

What is the main effect of the tilt of the Earth's axis?

When do the solstices and equinoxes occur?

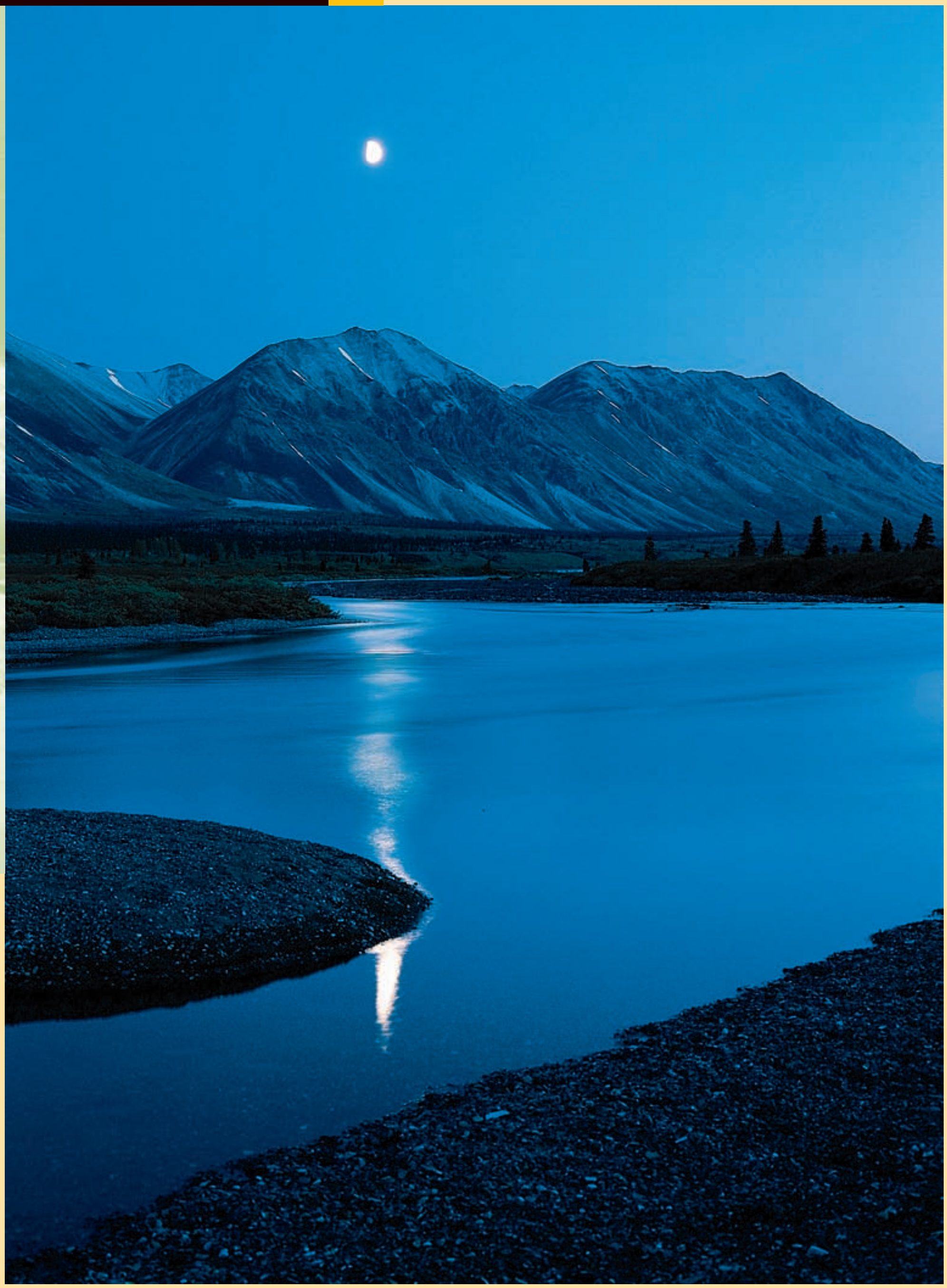
What is the length of daylight at the North Pole on each of the equinoxes and solstices?



What is happening in this picture ?

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.
- What can we tell about the position of the Sun, from the way that the Moon is lit?
- Is it to the left or the right of the picture?



VISUAL SUMMARY

1 The Shape of the Earth

1. We know that the Earth is approximately a sphere from space images.

2. The Earth's shape is closer to an oblate ellipsoid than to a sphere. The geoid is a close approximation of the Earth's exact shape.

2 The Earth's Rotation

1. The Earth rotates on its axis once in 24 hours.

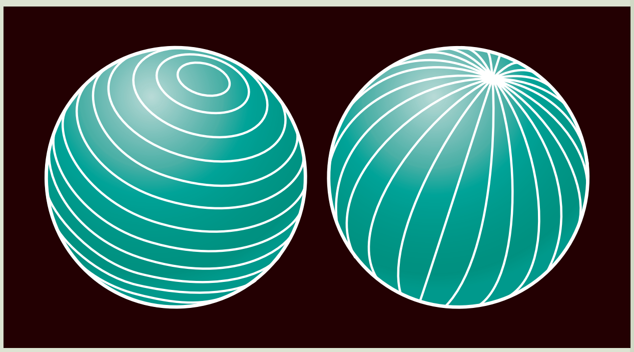
2. The intersection of the axis with the Earth's surface marks the North and South Poles.

3. The daily alternation of sunlight and darkness, the tides, and some curving motions of the atmosphere and oceans are caused by the Earth's rotation.

3 The Geographic Grid

1. The geographic grid, which consists of meridians and parallels, helps us mark location on the globe.

2. Geographic location is labeled using latitude and longitude. The equator and the prime meridian act as reference lines.



4 Map Projections

1. Map projections display the Earth's curved surface on a flat page.

2. The Mercator projection is useful for displaying direction. The Goode projection shows the correct relative areas of land masses. The polar projection is centered on either pole.

5 Global Time

1. We keep time according to standard meridians that are normally 15° apart, so clocks around the globe usually differ by whole hours.

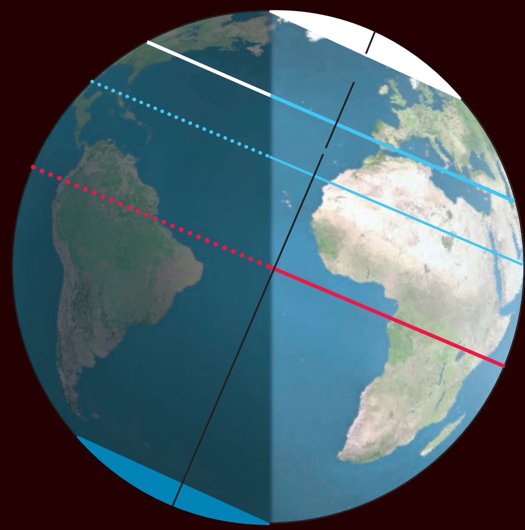
2. As you cross the international date line, the calendar day changes.

3. Daylight Saving Time advances the clock by one hour.

6 The Earth's Revolution Around the Sun

1. The seasons arise from the Earth's revolution around the Sun and the tilt of the Earth's axis.

2. At the summer (June) solstice, the northern hemisphere is tilted toward the Sun. At the winter (December) solstice, the southern hemisphere is tilted toward the Sun. At the equinoxes, day and night are of equal length.



KEY TERMS

- **axis** p. 6
- **poles** p. 6
- **geographic grid** p. 8
- **parallel** p. 8
- **meridian** p. 8
- **equator** p. 8
- **latitude** p. 8
- **longitude** p. 8
- **map projection** p. 14
- **Mercator projection** p. 15
- **Goode projection** p. 16
- **polar projection** p. 17
- **standard time** p. 20
- **time zones** p. 21
- **winter solstice** p. 26
- **summer solstice** p. 26
- **equinox** p. 26

CRITICAL AND CREATIVE THINKING QUESTIONS

1. How do we know that the Earth is approximately spherical? What is the Earth's true shape?

2. Describe three environmental effects of the Earth's rotation on its axis.

3. Discuss the geographic grid, mentioning parallels and meridians. How do latitude and longitude help us determine position on the globe?

4. Name three main types of map projections and describe the advantages and defects of each one briefly.

5. Explain the global timekeeping system. Mention standard time, standard meridians, and time zones in your answer.

6. What is meant by the "tilt of the Earth's axis"? How does this tilt cause the seasons?

7. Sketch a diagram of the Earth at equinox. Show the North and South Poles, the equator, and the circle of illumination. Show the direction of the Sun's incoming rays on your sketch and shade the night portion of the globe.

8. Suppose that the Earth's axis were tilted at 40° to the plane of the ecliptic, instead of 23 1/2°. How would the seasons change at your location? What would be the global effects of the change?

SELF-TEST

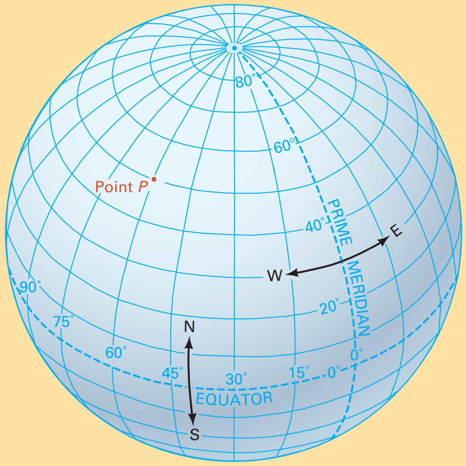
1. The shape of the Earth is best described as a(n) ______________.

a. perfect sphere
b. ellipsoid
c. oblate ellipsoid
d. spherical ellipsoid

2. The Earth ______________ about its axis and ______________ around the Sun.

a. revolves, rotates
b. spins, rotates
c. rotates, revolves
d. revolves, orbits

3. Describe the position of point P, shown here on the geographic grid, in terms of its latitude and longitude.



4. The single major problem all maps have in common is ______________.

a. that they are flat
b. distortion
c. shape distortion
d. area distortion

5. The ______________ projection is normally centered on the North or South Pole and contains meridians that are represented as ______________ lines.

a. Mercator, curved
b. Goode, straight
c. polar, straight
d. Lambert's conic conformal, curved

6. The ______________ projection is a rectangular grid of meridians and parallels depicted as straight vertical and horizontal lines, respectively.

a. polar
b. Goode
c. Mercator
d. conic

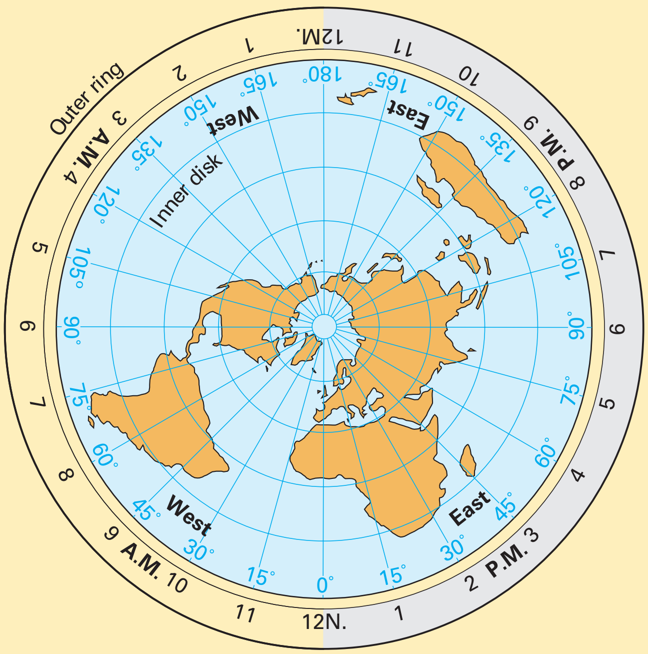
7. While the ______________ projection portrays the relative areas of land masses on the Earth's surface correctly, their shapes become distorted near the poles.

a. Mercator
b. Goode
c. conic
d. polar

8. ______________ time is based on twenty-four, ______________ degree wide time zones.

a. Polar, 7 1/2
b. World, 15
c. Standard, 7 1/2
d. Standard, 15

9. Chicago's latitude is approximately 42° N, and its longitude is approximately 87° W. At 3:00 p.m. in Greenwich, England, what time is it in Chicago? Mumbai is in time zone +5 1/2. Along which meridian does it lie, roughly? Use the diagram to help you.



10. The purpose of Daylight Saving Time is to make the daylight period of the day _______________.

a. correspond more closely with the pace of modern society and is accomplished by moving the clock back one hour
b. longer by moving all clocks ahead by one hour
c. correspond more closely with the pace of modern society and is accomplished by moving the clock ahead one hour
d. longer and results in a slight savings in electricity

11. The Earth completes a(n) _______________ revolution around the sun in _______________ days.

a. circular, 366
b. elliptical, 365
c. elliptical, 365 1/4
d. circular, 365

12. The tilt of the Earth's axis is _______________.

a. 23 1/2 degrees from the plane of the ecliptic
b. 66 1/2 degrees from a perpendicular to the plane of the ecliptic
c. 23 1/2 degrees from the Sun
d. 23 1/2 degrees from a perpendicular to the plane of the ecliptic

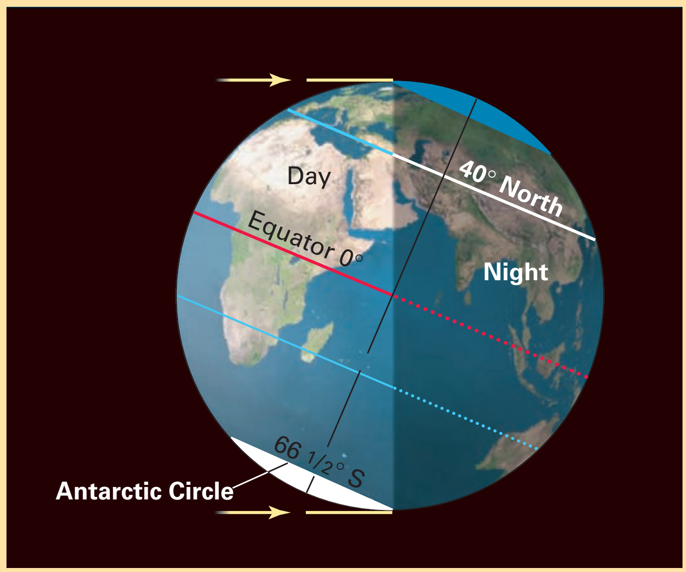
13. The _______________ divides the Earth into a sunlit side and a night side.

a. international date line
b. prime meridian
c. circle of illumination
d. Arctic Circle

14. During an equinox, the circle of illumination passes through the _______________.

a. North and South Poles
b. Antarctic Circle
c. Arctic Circle
d. equator

15. What time of year is represented by this diagram? Label the Tropic of Capricorn and explain its significance during this time.



The Earth's Global Energy Balance

2

Our Sun is a fiery ball of constantly churning gas. This average-sized star is the largest object in our solar system, containing more than 98 percent of the solar system's mass. At its core, the temperature reaches 15 million °C (27 million °F), and the pressure is 340 billion times Earth's air pressure at sea level—conditions intense enough to cause the nuclear reactions that give the Sun its immense power.

Energy generated in the core takes millions of years to reach the Sun's swirling surface, where the temperature is about 6000°C (about 11,000°F). Immense clouds of glowing gas erupt from the turbulent surface, forming towering loops that stretch thousands of kilometers before plunging back down to the surface. Radiant energy speeds out through space, traveling the 150 million km (93 million mi) from the Sun to the Earth in just over eight minutes.

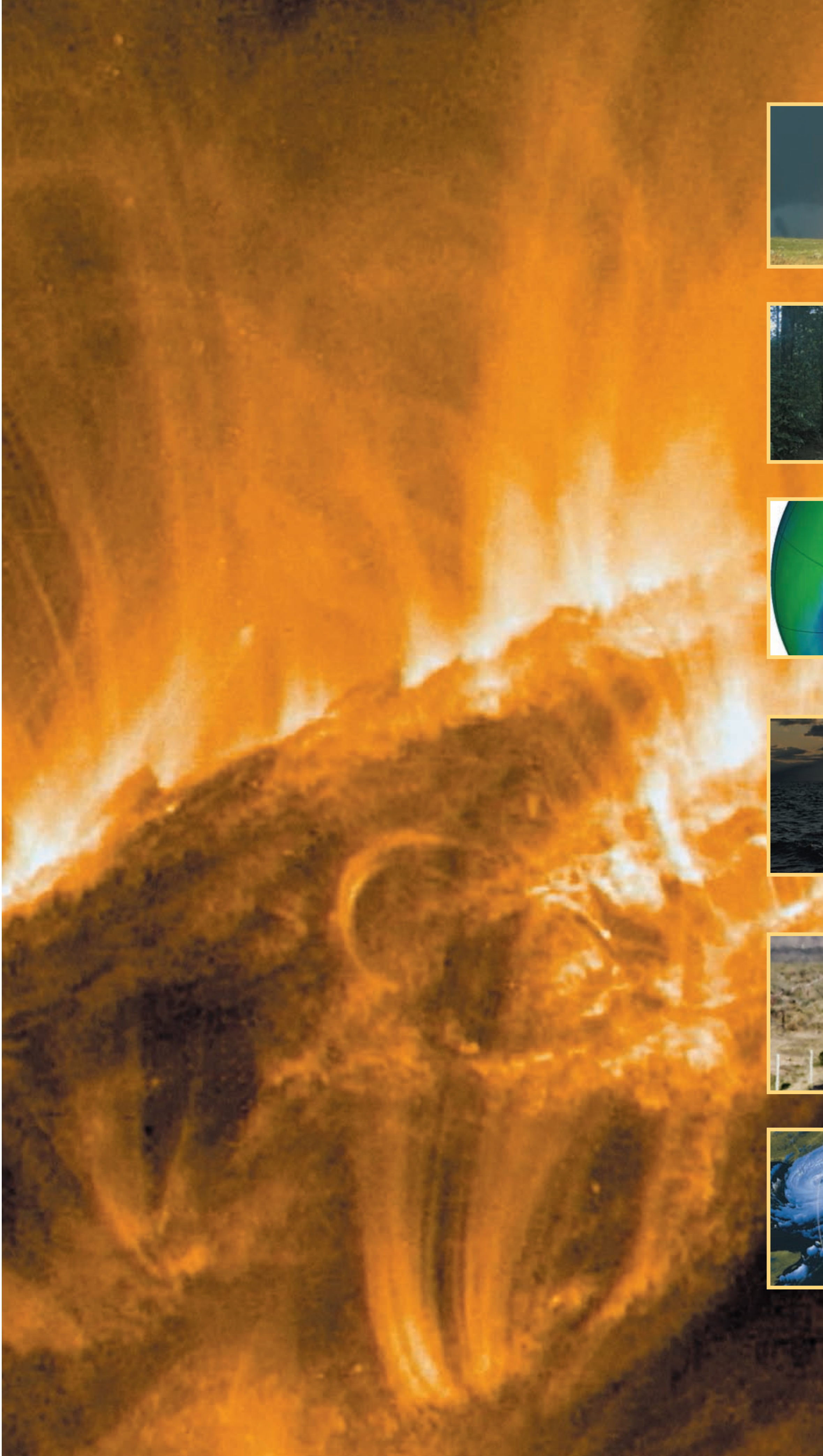
The Earth receives about 28,000 times more energy from the Sun than human society consumes each year—an enormous source of energy that is just waiting to be harnessed.

We are already starting to tap into this resource. Some people place solar heat collectors on their roofs to drive heating systems. Solar panels are used to power a variety of devices, from calculators to outdoor lights. And solar power plants focus sunlight on fluid-filled tubes or reservoirs to ultimately produce steam to generate electricity.

Today, as we become increasingly concerned about our dependence on nonrenewable fossil fuels, it seems likely that the Sun will become an even more important energy provider.

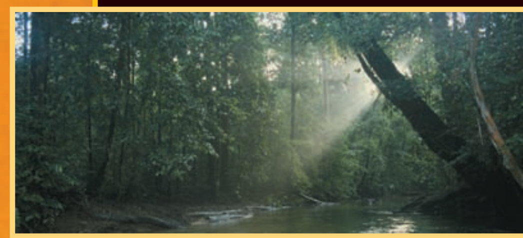
NATIONAL GEOGRAPHIC

Hot gases erupting from the Sun's surface form huge loops that radiate vast amounts of energy to space and toward Earth, as shown in this computer simulation.

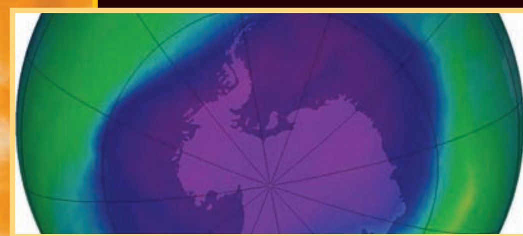


CHAPTER OUTLINE

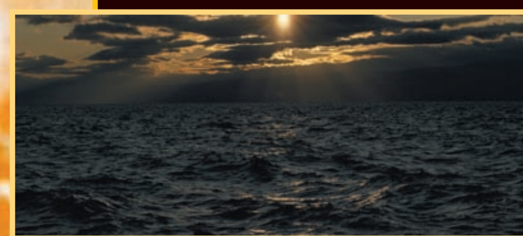
- Electromagnetic Radiation p. 36



- Insolation over the Globe p. 42



- Composition of the Atmosphere p. 46



- Sensible Heat and Latent Heat Transfer p. 49

- The Global Energy System p. 50

- Net Radiation, Latitude, and the Energy Balance p. 56

Electromagnetic Radiation

LEARNING OBJECTIVES

Define and describe different types of electromagnetic radiation.

Contrast shortwave radiation from the Sun and longwave radiation from the Earth.

Describe how radiation is absorbed and scattered in the atmosphere.

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. The Earth receives energy from the flow of the Sun's light—largely visible light, made up of the colors of a rainbow (FIGURE 2.1), and also ultraviolet and infrared light that cannot be seen. All of these emissions are types of **electromagnetic radiation**.

Cooler objects than the Sun, such as Earth surfaces, also emit heat energy. 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, creating a global energy balance.

Electromagnetic radiation Wave-like form of energy radiated by any substance possessing heat; it travels through space at the speed of light.

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

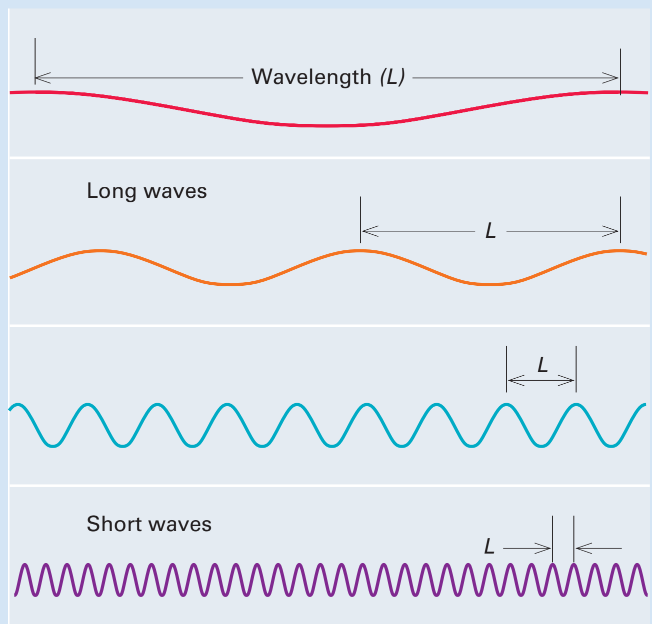
Rainbow FIGURE 2.1

In the rainbow, tiny drops of water refract sunlight, splitting it into its component colors.

Wavelength of electromagnetic radiation

FIGURE 2.2

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



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.

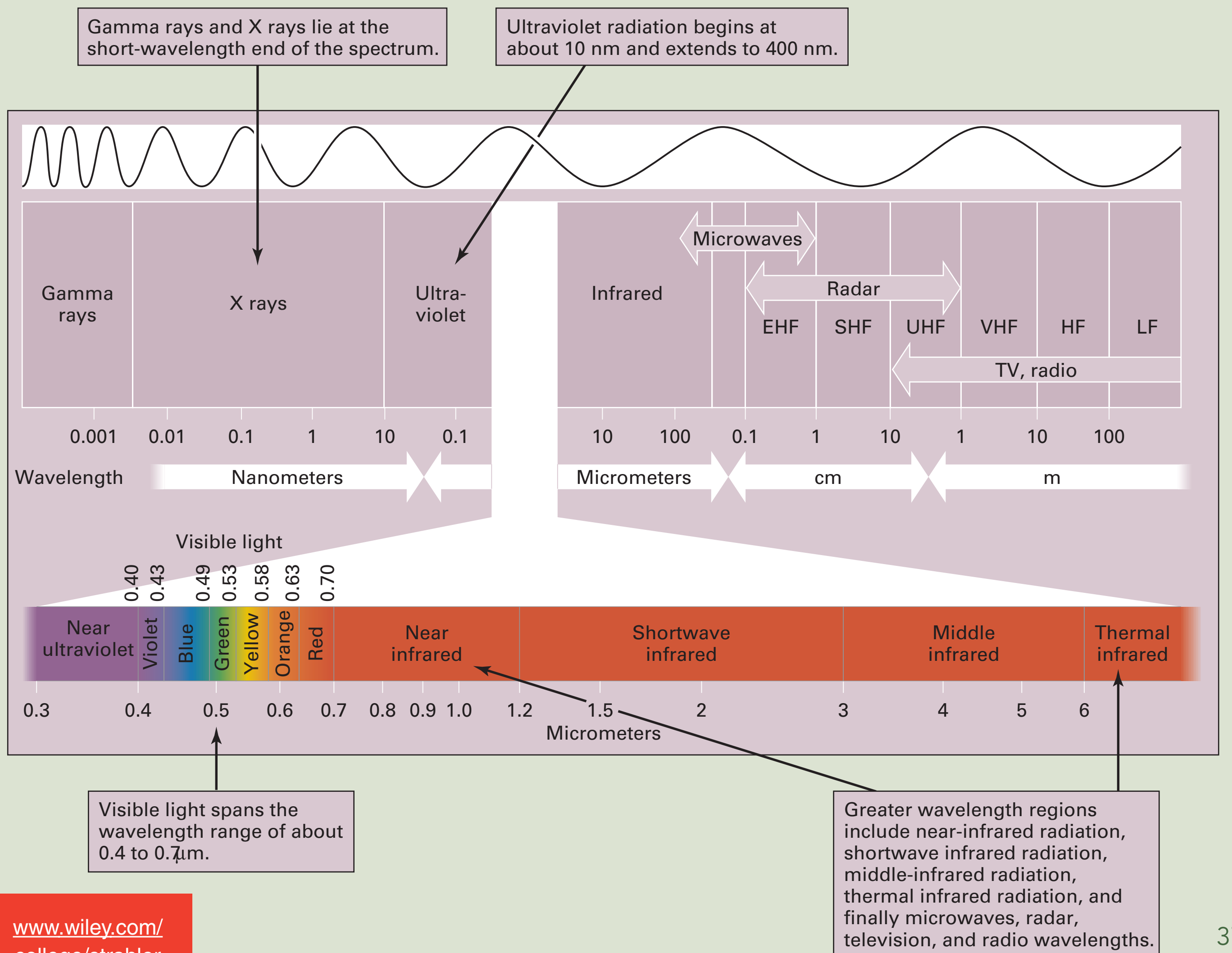
Visible light begins at about 0.4 μm with the color violet. Colors then gradually change through blue, green, yellow, orange, and red, until we reach the end of the visible spectrum at about 0.7 μm. Next is near-infrared radiation, with wavelengths from 0.7 to 1.2 μm. This radiation is very similar to 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 6.0 μm, can come from the Sun or from very hot sources on the Earth, such as forest fires and gas well flames.

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. Following infrared wavelengths we have microwaves, radar, and wavelengths associated with communications transmissions, such as radio and television.

The electromagnetic spectrum FIGURE 2.3

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



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RADIATION AND TEMPERATURE

There are two important physical principles to remember about the emission of electromagnetic radiation. The first is that hot objects radiate much 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. For example, water at room temperature emits about one third more energy than when it is at the freezing point.

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.

SOLAR RADIATION

Our Sun emits energy in straight lines or rays, traveling out 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 1/3 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.

CHARACTERISTICS OF SOLAR ENERGY

Let's look at the Sun's output as it is received by the Earth, shown in **Figure 2.4**. The left side shows how the Sun's incoming electromagnetic radiation varies with wavelength. 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.

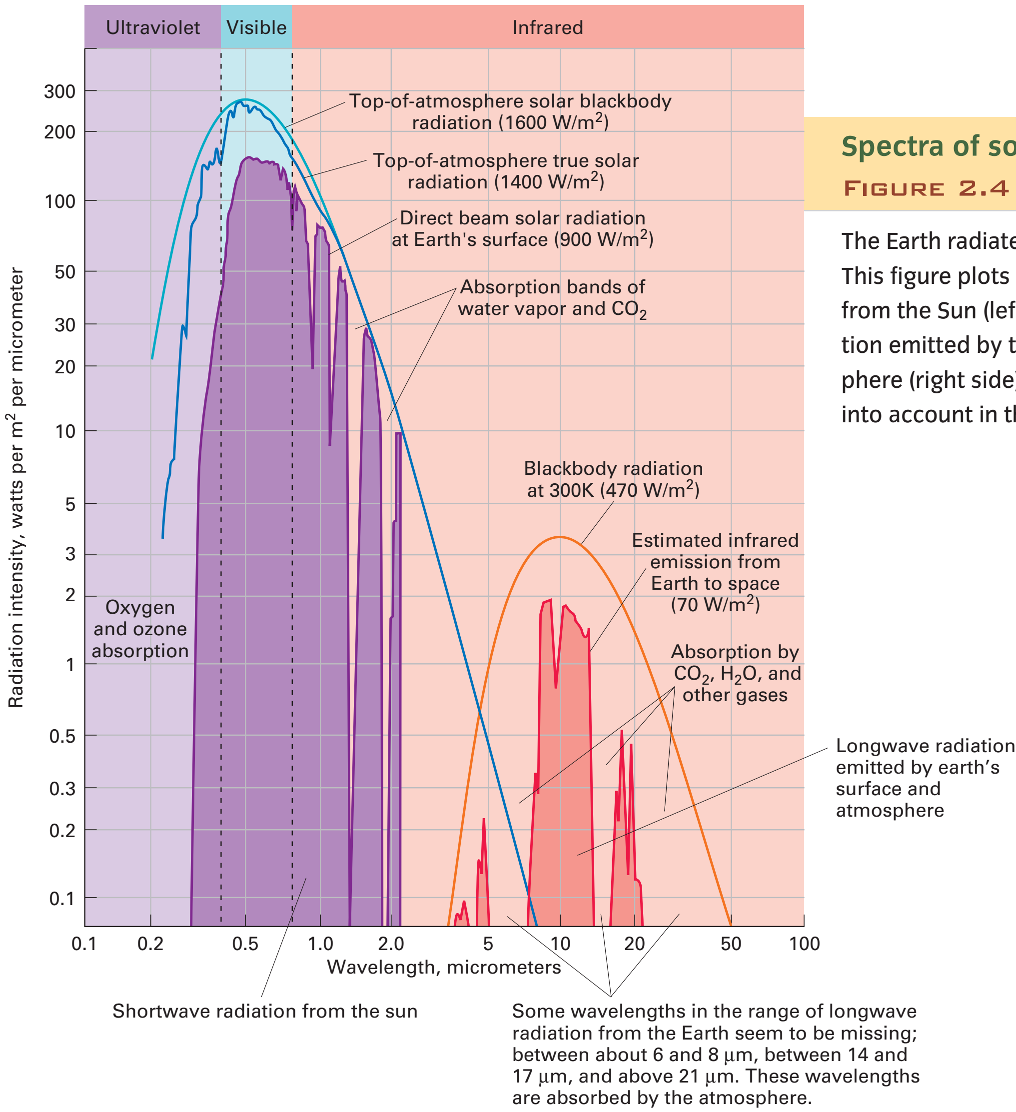
The solar radiation actually reaching the Earth's surface is quite different from the solar radiation measured above the Earth's atmosphere. This is because solar radiation is both absorbed and scattered by varying amounts at different wavelengths as it passes through the atmosphere.

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 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.

Absorption
Process in which electromagnetic energy is transferred to heat energy when radiation strikes molecules or particles in a gas, liquid, or solid.

Scattering
Process in which particles and molecules deflect incoming solar radiation in different directions on collision; atmospheric scattering can redirect solar radiation back to space.



Spectra of solar and Earth radiation

FIGURE 2.4

The Earth radiates less energy than the Sun. This figure plots both the shortwave radiation from the Sun (left side) and the longwave radiation emitted by the Earth's surface and atmosphere (right side). We have not taken scattering into account in this illustration.

Shortwave radiation Electromagnetic energy in the range from 0.2 to 3 µm; most solar radiation is shortwave radiation.

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 an object's temperature controls both the range of wavelengths and the intensity of radiation it emits. The Earth's surface and atmosphere are much colder than the Sun's surface, so we would predict that our planet radiates less energy than the Sun and that this energy is emitted at longer wavelengths.

The right side of Figure 2.4 shows exactly that. The irregular red line shows energy emitted by the Earth and atmosphere, as measured at the top of the atmosphere. It peaks at about 10 µm in the thermal infrared region. This thermal infrared radiation emitted by the Earth is **longwave radiation**.

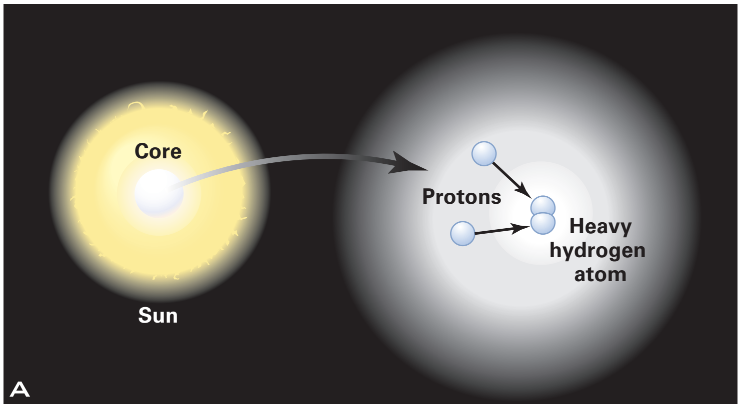
Longwave radiation Electromagnetic radiation in the range 3 to 50 µm; the Earth emits longwave radiation.

We can see that some wavelengths in this range seem to be missing. These wavelengths are almost completely absorbed by the atmosphere before they

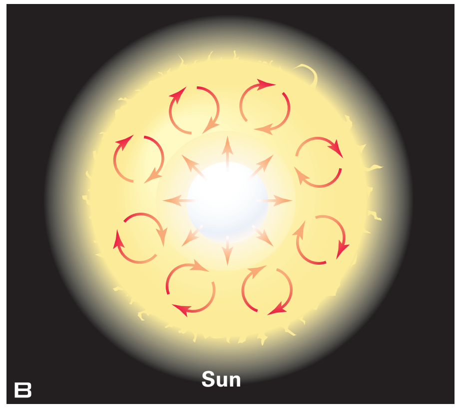
Process Diagram

The global radiation balance

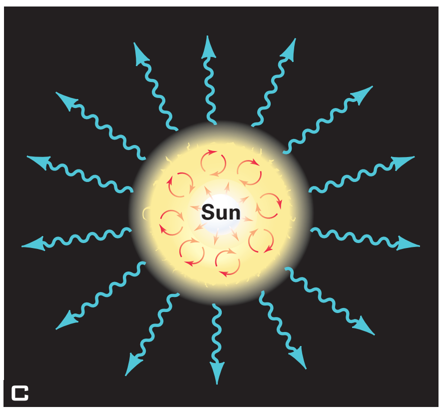
The Sun continually radiates shortwave energy in all directions. The Earth intercepts a tiny portion of this radiation, absorbing it, and in turn emitting longwave radiation. Over time, this gain/loss of radiant energy is balanced, so the Earth's solar-heated surface remains at a constant average temperature. Diagrams A–F show how.



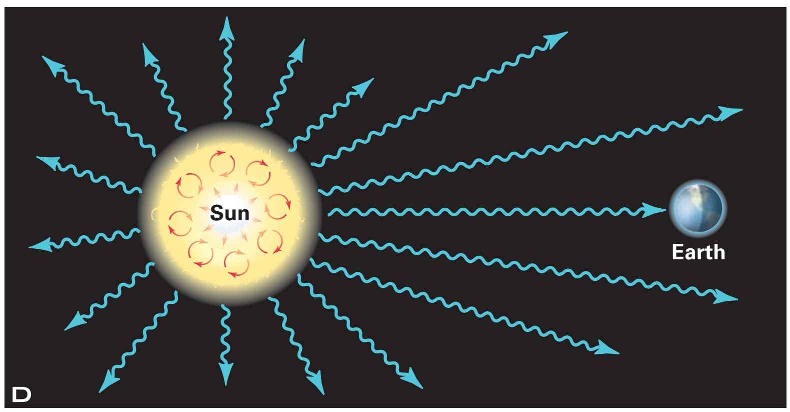
Nuclear reactions in the Sun
Under intense heat and pressure, two hydrogen nuclei (protons) collide to form an atom of heavy hydrogen (deuterium), containing one proton and one neutron. This releases large amounts of energy. Many of these nuclear reactions continually occur, radiating bountiful energy into space.



Internal heat transfer
Heat is transferred from the Sun's core to its surface by slow convection of the dense, hot gases.



Shortwave radiation
The Sun transmits this energy through space in all directions.

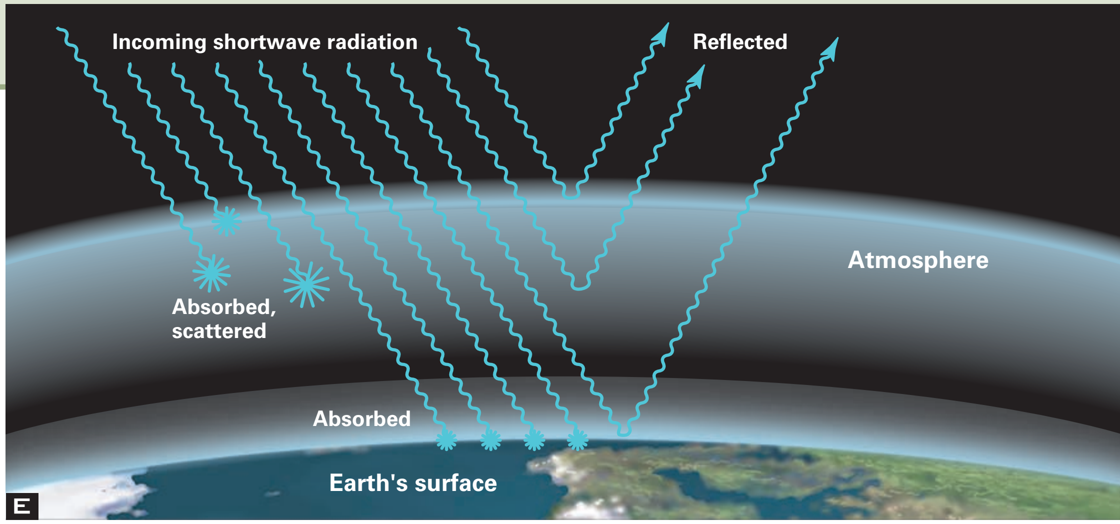


Shortwave radiation reaches the Earth
The Sun provides a nearly constant flow of shortwave radiation to the Earth. The Earth is a tiny target in space, intercepting only about one-half of one-billionth of the Sun's total energy output.

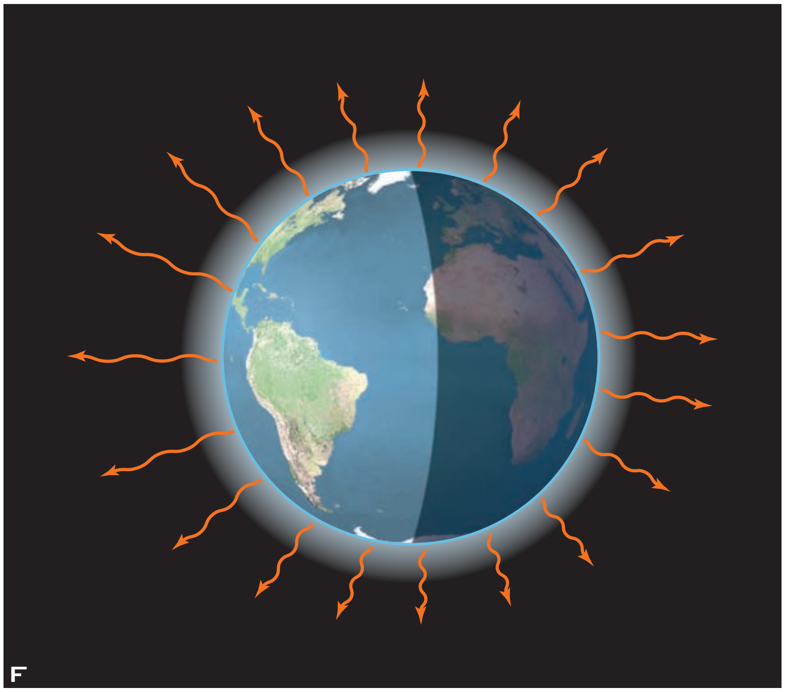
can escape. Water vapor and carbon dioxide are the main absorbers, playing a large part in the greenhouse effect, which we will discuss shortly.

There are still three "windows" where the flow of outgoing longwave radiation from the Earth to space is significant—4 to 6 μm, 8 to 14 μm, and 17 to 21 μm.

We have seen that the Earth is constantly absorbing solar shortwave radiation and emitting longwave radiation. This creates a global radiation balance, which is shown in more detail in the Process Diagram, The Global Radiation Balance.



Some shortwave radiation is reflected
Molecules and particles in the atmosphere absorb and scatter incoming shortwave radiation, as does the Earth's surface. So, some shortwave radiation is directly reflected back to space.



The Earth emits longwave radiation
Shortwave radiation is absorbed by the Earth and the atmosphere, increasing earthly temperatures and generating longwave radiation that radiates back to space.

CONCEPT CHECK **STOP**

What is electromagnetic radiation?

What are the major regions of the electromagnetic spectrum?

How is an object's temperature related to the nature and amount of electromagnetic radiation it emits?

What wavelengths of radiation does the Sun emit?

What wavelengths are emitted by the Earth?

Insolation over the Globe

LEARNING OBJECTIVES

Define insolation and explain why it is important.

Identify the factors that affect daily insolation.

Describe how annual insolation is related to latitude.

Explain how the globe can be divided into latitude zones.

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 driven 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.

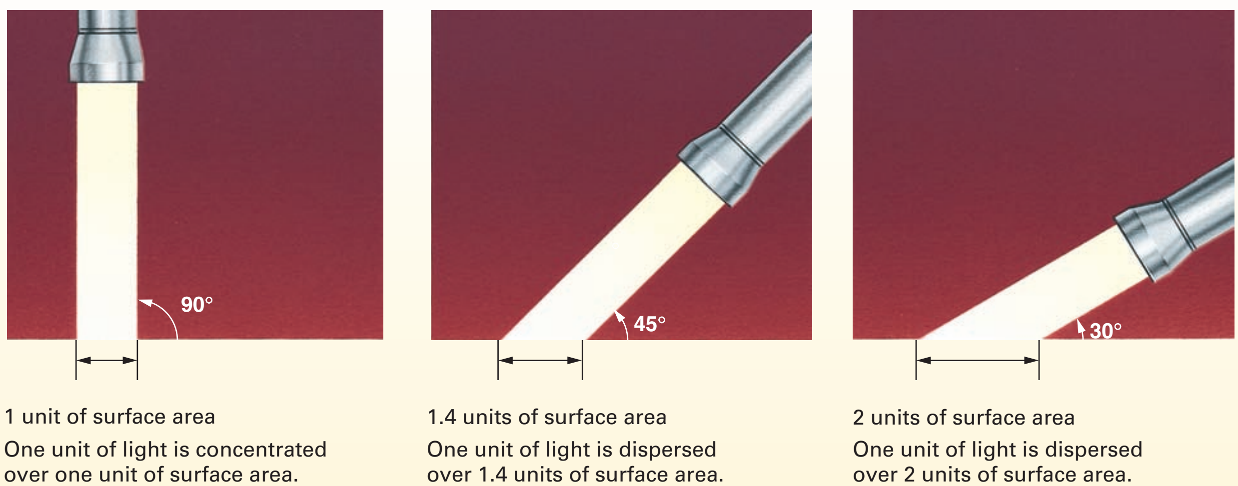
Although the flow of solar radiation to the Earth as a whole remains constant, different places on the planet receive different amounts of energy at different times. What causes this variation?

Incoming solar radiation is known as **insolation**. It is measured in units of watts per square meter (W/m^2), and 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 2.5).

Insolation The flow of solar energy intercepted by an exposed surface assuming a uniformly spherical Earth with no atmosphere.

DAILY INSOLATION THROUGH THE YEAR

Daily insolation is the average insolation over a 24-hour day. At any location it depends on two factors: (1) the angle at which the Sun's rays strike the Earth, and (2) how



A Sunlight (represented by the flashlight) that shines vertically near the equator is concentrated on the Earth's surface.

B-C Toward the poles, the light hits the surface more and more obliquely, spreading the same amount of radiation over larger and larger areas.

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Solar intensity and latitude FIGURE 2.5

The angle at which the Sun's rays strike the Earth varies from one geographic location to another owing to the Earth's spherical shape and its inclination on its axis.

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 2.6 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.

Daily insolation will be greater at the June solstice than at the equinox since the Sun is in the sky longer and reaches a higher angle at noon.

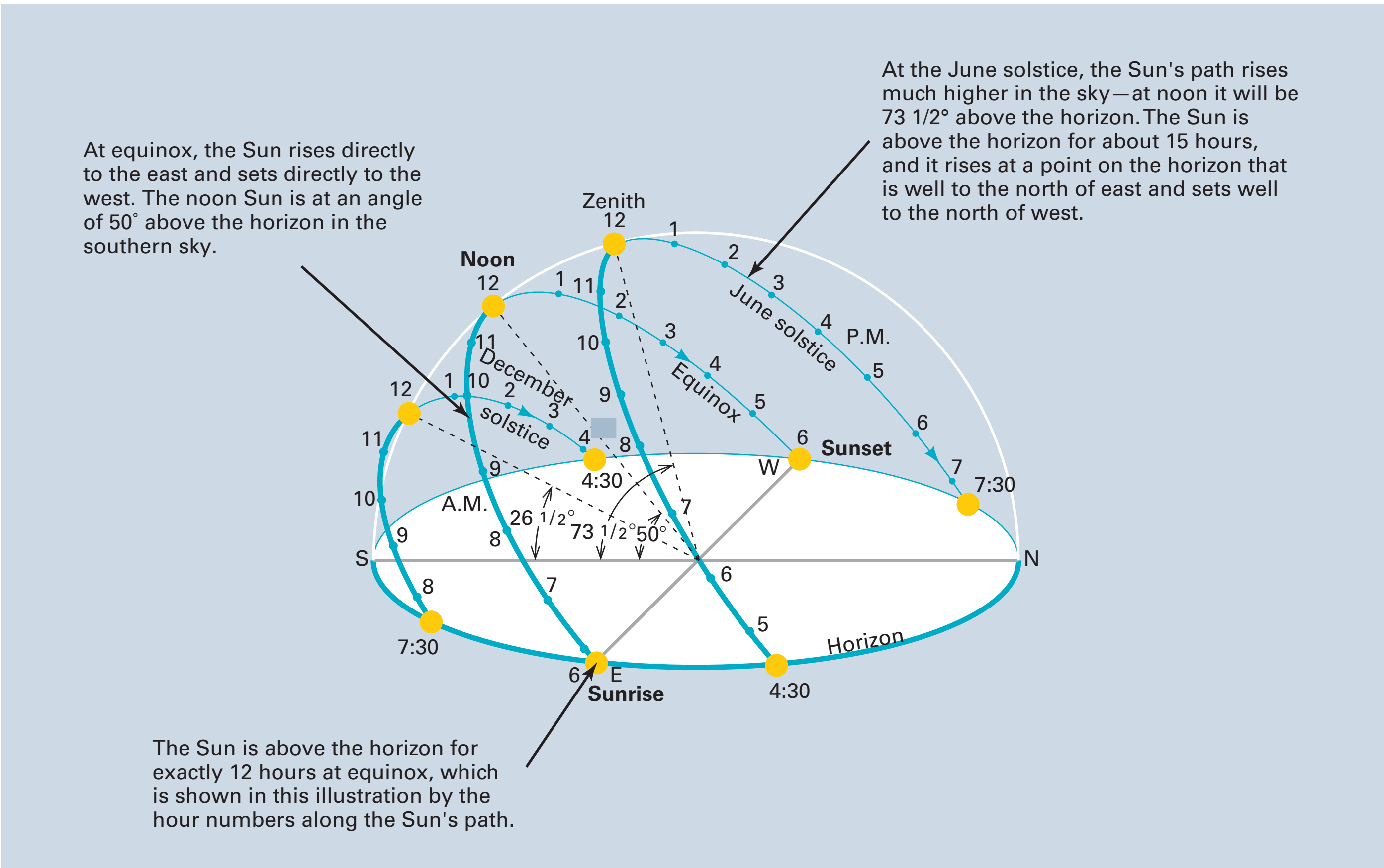
At the December solstice, the Sun's path is low in the sky, reaching only 26 1/2° above the horizon, and is only visible for about 9 hours. Sunrise is to the south of east and sunset is to the south of west. So, daily insolation reaching the surface at the December solstice will be less than at the equinox and much less than at the June solstice.

The actual insolation values confirm these predictions. The daily average insolation at 40°N ranges from about 160 W/m^2 at the December solstice to about 460 W/m^2 at the June solstice. Equinox values are around 350 W/m^2.

Daily insolation measures the flow of solar power available to heat the Earth's surface, so it is the most important factor in determining air temperatures, as we will see in later chapters. The change in daily insolation with the seasons at any location is therefore a major determinant of climate.

The path of the Sun in the sky at 40°N latitude FIGURE 2.6

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



ANNUAL INSOLATION BY LATITUDE

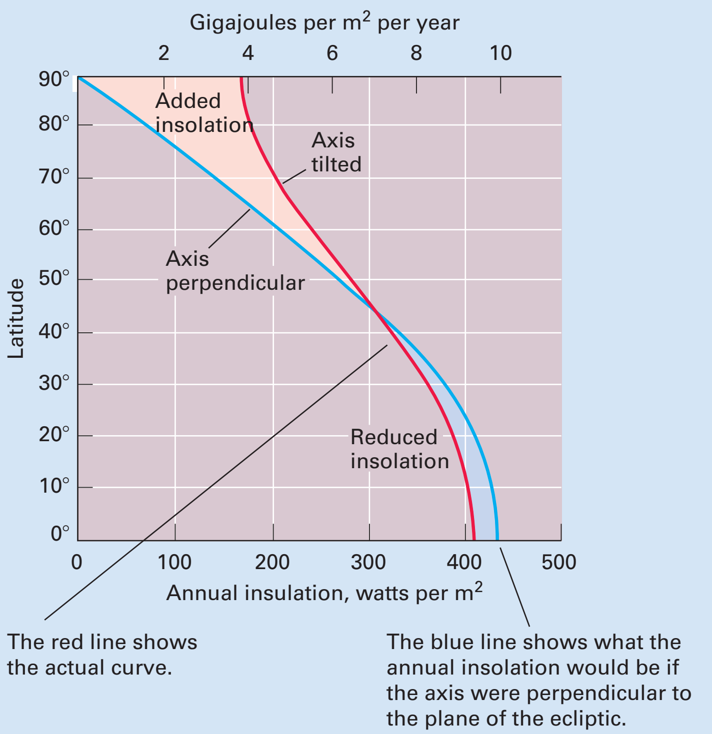
How does latitude affect annual insolation—the rate of insolation averaged over an entire year? FIGURE 2.7 shows two curves of annual insolation by latitude—one for the actual case of the Earth's axis tilted at 23 1/2°, and the other for an Earth with an untilted axis.

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, the situation would be quite different. In this case, 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. But 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.

Annual insolation from equator to pole for the Earth FIGURE 2.7



WORLD LATITUDE ZONES

We can use the seasonal pattern of daily insolation to divide the globe into broad latitude zones (FIGURE 2.8). We do this for convenience in this book, and the zone limits given here should not be taken as rigid definitions.

The equatorial zone covers the latitude belt roughly 10° north to 10° south of the equator. The Sun provides intense insolation here throughout most of the year, and days and nights are of roughly equal length. The tropical zones span the Tropics of Cancer and Capricorn, ranging from latitudes 10° to 25° north and south. They have a marked seasonal cycle and high annual insolation.

Moving toward the poles we come to the subtropical zones. These lie roughly between the latitude belts 25° to 35° north and south. These zones have a strong seasonal cycle and a large annual insolation.

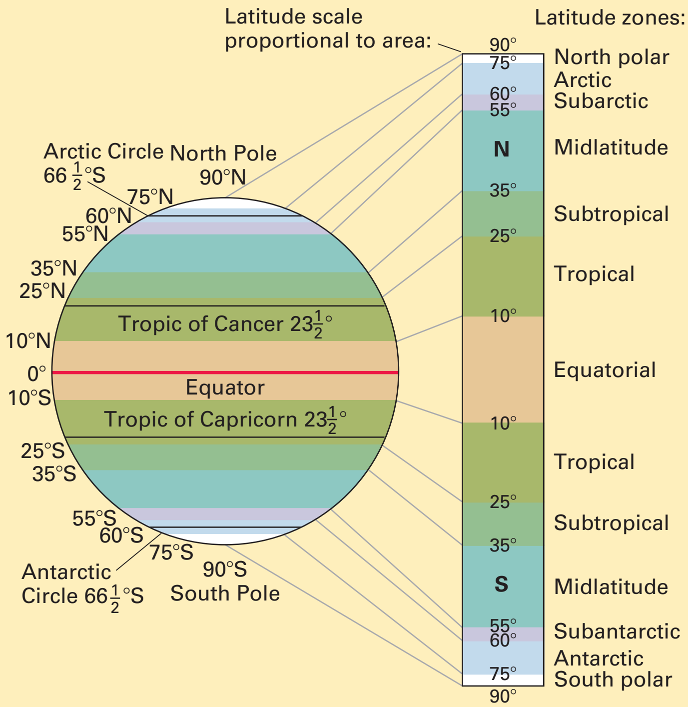
The midlatitude zones are next, between 35° and 55° north and south latitude. The length of a day can vary greatly from winter to summer here, and seasonal contrasts in insolation are quite strong. So these regions experience a large range in annual surface temperature.

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.

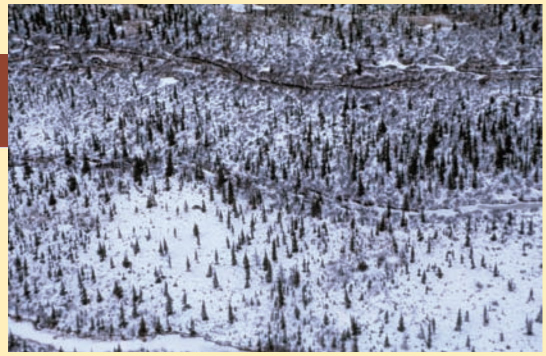
Finally, the north and south polar zones range from about 75° latitude to the poles. They experience the greatest seasonal insolation contrasts of all, and have a six-month day and six-month night.

The Earth's diverse environments by latitude

FIGURE 2.8



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



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.

Midlatitude zone A summer midlatitude landscape in the Tuscany region of Italy.

Tropical zone The tropical zone is the home of the world's driest deserts. Pictured here is Rub' al Khali, Saudi Arabia.

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

CONCEPT CHECK STOP

Which two factors control the amount of daily insolation at a given location on the globe?

How is annual insolation related to latitude?

How can we divide the globe into broad latitude zones?

Composition of the Atmosphere

LEARNING OBJECTIVES

Describe the gases that make up the atmosphere.

Explain the vital role of ozone to Earthly life.

Describe human impact on the ozone layer.

The Earth is surrounded by air—a mixture of various gases that reach up to a height of many kilometers. This envelope of air makes up our atmosphere (FIGURE 2.9). 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 the Earth's diameter.

The proportion of gases in dry air is highly uniform up to an altitude of about 80 km (50 mi). Pure, dry air is mostly made up of nitrogen (about 78 percent by volume) and oxygen (about 21 percent) (FIGURE 2.10). 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 0.035 percent.

Nitrogen molecules in the atmosphere contain two nitrogen atoms (N_2). Nitrogen gas does not easily react with other substances, so we can think of it as a mainly neutral substance. Soil bacteria do extract very small amounts of nitrogen, which can be used by plants, but otherwise nitrogen is largely a "filler," adding inert bulk to the atmosphere.

By contrast, oxygen gas (O_2) is highly chemically 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.

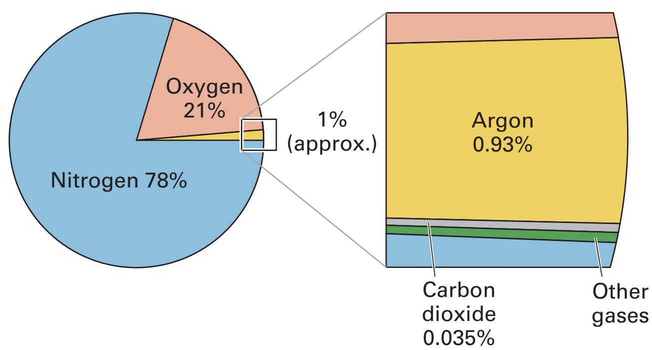
The two main component gases of the lower atmosphere are perfectly mixed, so pure, dry air behaves as if it is a single gas with very definite physical properties. We've already learned that CO_2 absorbs incoming shortwave radiation and outgoing longwave radiation in specific wavelength regions. The 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 CO_2 into its chemical compounds to build up their tissues, organs, and supporting structures during photosynthesis.

Air and sky FIGURE 2.9

Air is a mixture of gases dominated by nitrogen and oxygen. Water vapor, another important constituent, can condense into clouds of liquid water droplets.

Component gases of the lower atmosphere FIGURE 2.10

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.



Water vapor is another important atmospheric gas. Individual water molecules are mixed freely throughout the atmosphere, just like the other gases. But unlike the other component gases, 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. The atmosphere also contains dust and tiny floating particles (ash, pollen, etc.) that absorb and scatter radiation.

OZONE IN THE UPPER ATMOSPHERE

Ozone Form of oxygen with a molecule consisting of three atoms of oxygen O_3.

Another small but important constituent of the atmosphere is **ozone**—a form of oxygen in which three oxygen atoms are bonded together (O_3). Ozone is found mostly in the upper part of the atmosphere, in a layer called the stratosphere, about 14 to 50 km (9 to 31 mi) above the surface.

Ozone is most concentrated in a layer that begins at an altitude of about 15 km (about 9 mi) and extends to about 55 km (about 34 mi) above the Earth. It is produced in gaseous chemical reactions that require energy in the form of ultraviolet radiation. The reactions are quite complicated, but the net effect is that ozone (O_3), molecular oxygen (O_2), and atomic oxygen (O) are constantly formed, destroyed, and reformed in the ozone layer, absorbing ultraviolet radiation with each transformation.

Because the ozone layer absorbs ultraviolet light from the Sun, it protects the Earth's surface from this damaging form of radiation. The presence of the ozone layer is thus essential for life on this planet to survive. If the full intensity of solar ultraviolet radiation ever hit the Earth's surface, it would destroy bacteria and severely damage animal tissue.

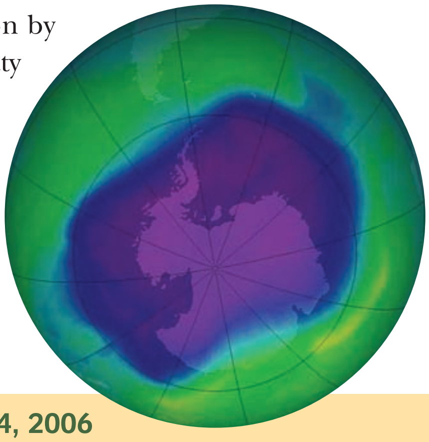
Certain forms of air pollution, such as chlorofluorocarbons, or CFCs, reduce ozone concentrations substantially. CFCs are synthetic industrial chemical compounds containing chlorine, fluorine, and carbon atoms. Although CFCs were banned in aerosol sprays in the United States in 1976, they are still used as cooling fluids in some refrigeration systems. When appliances containing CFCs leak or are discarded, their CFCs are released into the air.

CFC molecules move up to the ozone layer where they decompose to chlorine oxide (ClO), which attacks ozone, converting it to ordinary oxygen by a chain reaction. 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 2.11). In recent years, the ozone layer has thinned 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.

Since 1978, surface-level ultraviolet radiation has been increasing. Over most of North America, the increase has been about 4 percent per decade. 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. By late 1999, scientists confirmed that

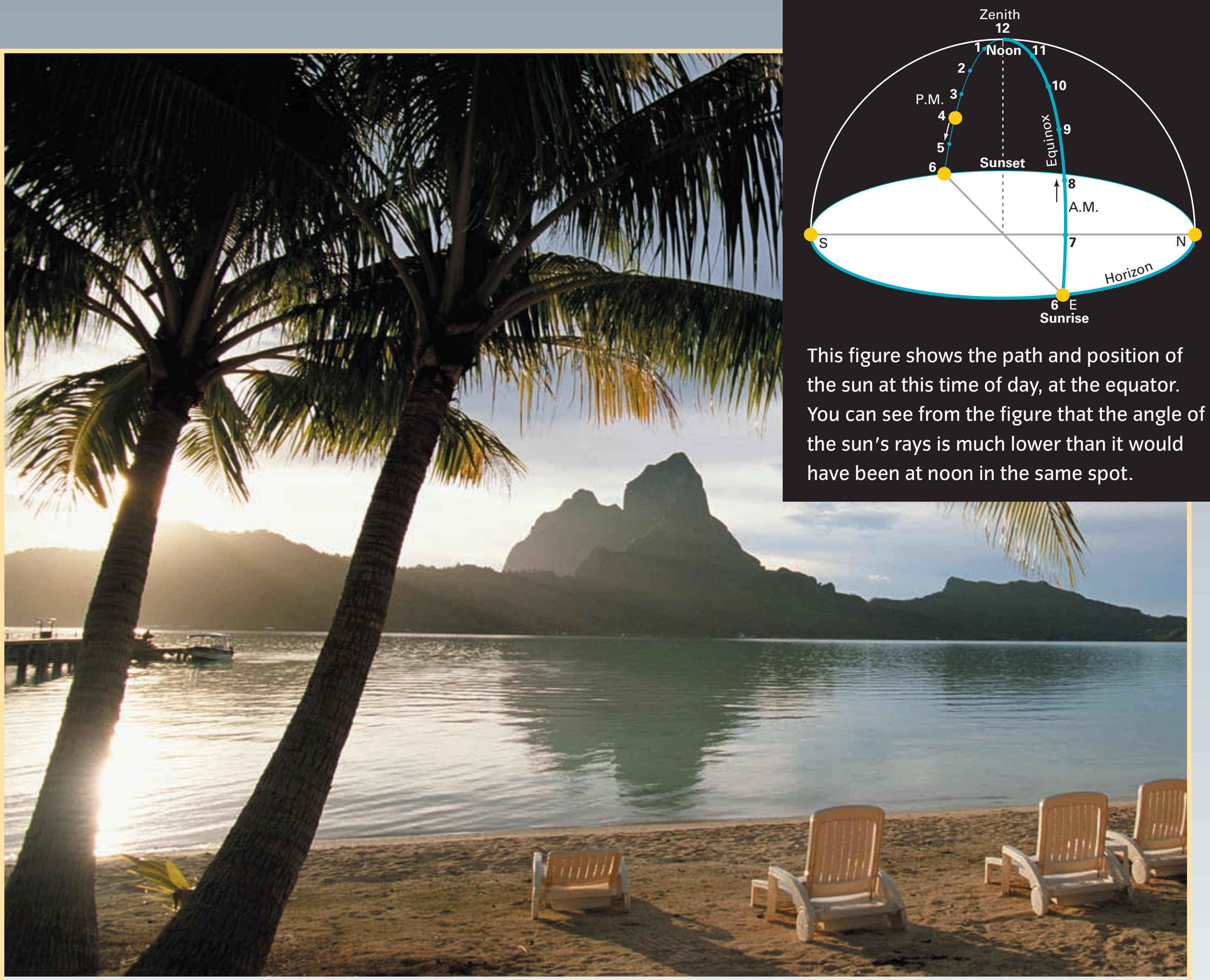


Ozone hole, September 24, 2006

FIGURE 2.11

The Antarctic ozone hole of 2006 was the largest on record, covering about 29.5 million sq km (about 11.4 million sq mi). 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. (NASA)

What a Geographer Sees



This figure shows the path and position of the sun at this time of day, at the equator. You can see from the figure that the angle of the sun's rays is much lower than it would have been at noon in the same spot.

Imagine yourself sitting in a beach chair here on Bora Bora, watching the sunset. Will you be warm or cool?

The beach at sunset will be quite a different place from what it was at noon, a few hours earlier. The long shadows and the position of the glow in the sky show that the Sun is not far from the horizon. As a result, insolation will be much lower than at noon, when the Sun is near the top of the sky.

The Sun will also seem weaker because, at such a low angle, its direct rays pass through more atmosphere. As a result, more of the solar beam will be absorbed or scattered than at noon.

Seated in your chair, directly facing the Sun, however, you will be doubly warmed—first by the direct rays of the Sun on your body and second by the sunlight reflected off the still water.

With this analysis, a geographer would safely conclude that the temperature will be. . . just about perfect!

stratospheric chlorine concentrations had topped out in 1997 and were continuing to fall. Although the ozone layer is not expected to be completely restored until the middle of the twenty-first century, this is a welcome observation.

CONCEPT CHECK **STOP**

Which gases make up the most of the air in our atmosphere?

Why is ozone important in climate change?

Sensible Heat and Latent Heat Transfer

Learning Objectives

Define sensible heat and latent heat.

Describe why latent heat transfer is important in the Earth-atmosphere system.

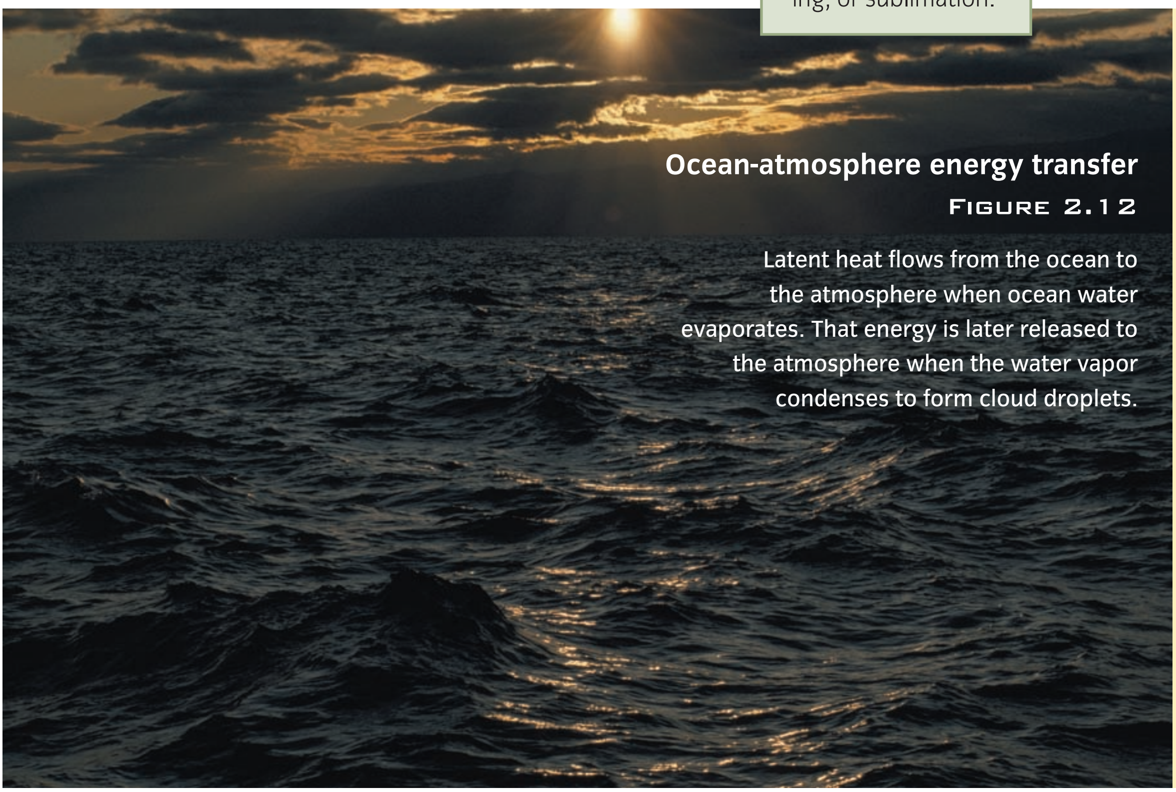
Sensible heat is actually very familiar—it's what you feel when you touch a warm object. We are measuring sensible heat when we use a thermometer. Sensible heat moves from warmer to colder objects, either by conduction or by convection, when they are put into contact.

By 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, to change liquid water to water vapor, or ice to liquid water, you need to put in energy. This energy is stored in free fluid motion of the liquid water molecules or in the fast random motion of free water vapor molecules.

Although we can't measure the latent heat of water vapor in air with a thermometer, energy is stored there just the same. 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 from a moist land surface or from open water evaporates (FIGURE 2.12). On a global scale, latent heat transfer is a very important mechanism for transporting large amounts of energy from one region of the Earth to another.

Sensible heat An indication of the intensity of kinetic energy of molecular motion within a substance; it is measured by a thermometer.

Latent heat Heat absorbed and stored in a gas or liquid during the processes of evaporation, melting, or sublimation.



Ocean-atmosphere energy transfer
FIGURE 2.12

Latent heat flows from the ocean to the atmosphere when ocean water evaporates. That energy is later released to the atmosphere when the water vapor condenses to form cloud droplets.

CONCEPT CHECK STOP

What is sensible heat?

What is latent heat?

How is latent heat transferred from water vapor? Why is this process important on a global scale?

The Global Energy System

Learning Objectives

Describe the fate of solar radiation as it passes through the atmosphere.

Define albedo.

Define counterradiation and explain how it leads to the greenhouse effect.

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

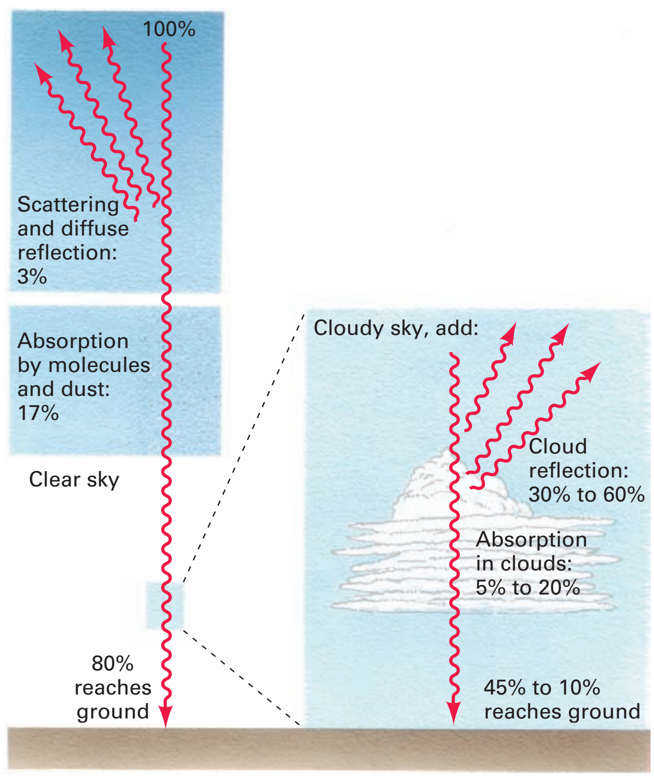
Let's examine the flow of insolation through the atmosphere on its way to the surface. FIGURE 2.13 gives typical values for losses of incoming shortwave radiation in the solar beam as it penetrates the atmosphere. Gamma rays and X rays from the Sun are almost completely absorbed by the thin outer layers 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 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 15 percent of incoming 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.

Fate of incoming solar radiation FIGURE 2.13

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



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.

ALBEDO

The proportion of shortwave radiant energy scattered upward by a surface is called its **albedo** and is measured on a scale of 0 to 1. For example, a surface that reflects 40 percent of incoming shortwave radiation has an albedo of 0.40. 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. By contrast, a black pavement, which has a low albedo (0.03), absorbs nearly all the incoming solar energy (FIGURE 2.14). The albedo of water depends on the angle of incoming radiation. It is very low (0.02) for nearly vertical rays hitting calm water. But when the sun shines on a water surface at a low angle, much of the radiation is directly reflected as Sun glint, producing a higher albedo. 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 high-albedo surfaces. Fields, forests, and bare ground have intermediate albedos, ranging from 0.03 to 0.25.

Albedo Proportion of solar radiation reflected upward from a surface.

Certain orbiting satellites carry instruments that can measure shortwave and longwave radiation at the top of the atmosphere, helping us estimate the Earth's average albedo. The albedo values obtained in this way vary between 0.29 and 0.34. This means that the Earth-atmosphere system reflects slightly less than one-third of the solar radiation it receives back into space.

A Bright snow A layer of new, fresh snow reflects most of the sunlight it receives. Only a small portion is absorbed.

B Blacktop road Asphalt paving reflects little light, and so appears dark or black. It absorbs nearly all of the solar radiation it receives.

Albedo contrasts FIGURE 2.14

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 2.15 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.

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.

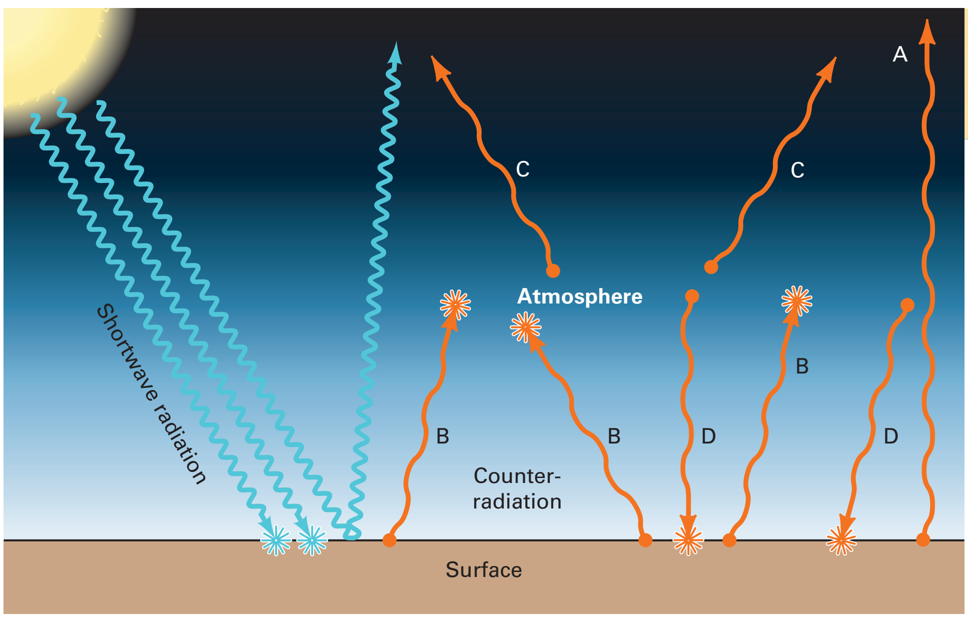
Counterradiation Longwave atmospheric radiation moving downward toward the Earth's surface.

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 is known as the **greenhouse effect**, because it is similar to the principle used in greenhouses to trap solar heat. The process diagram, How a greenhouse works, illustrates how in a greenhouse, the glass windows let in shortwave energy, but absorb and block longwave energy from escaping.

Greenhouse effect Accumulation of heat in the lower atmosphere through the absorption of longwave radiation from the Earth's surface.

The energy flows we have been looking at between the Sun and the Earth's atmosphere and surface must balance over the long term. The global energy budget takes into account all the important energy flows that

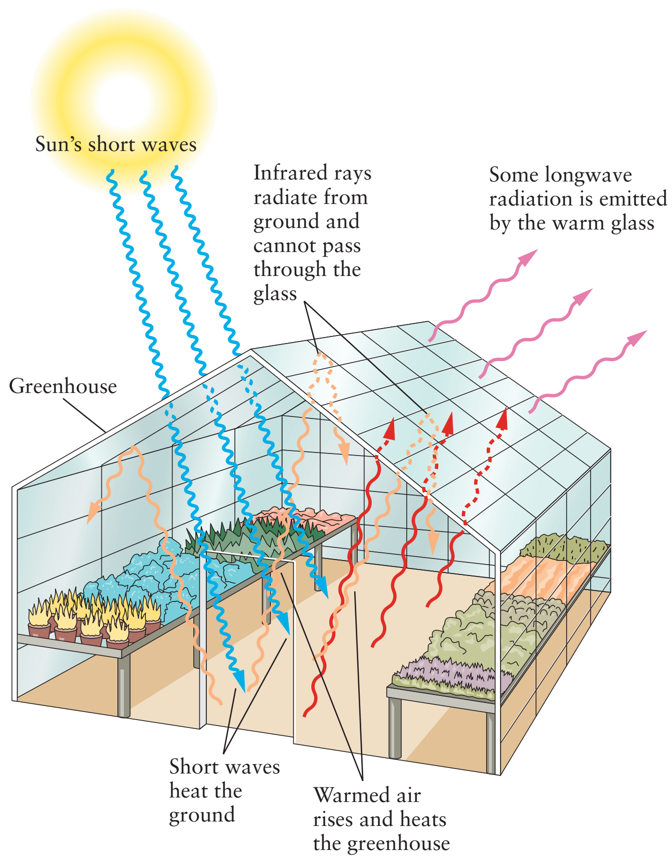


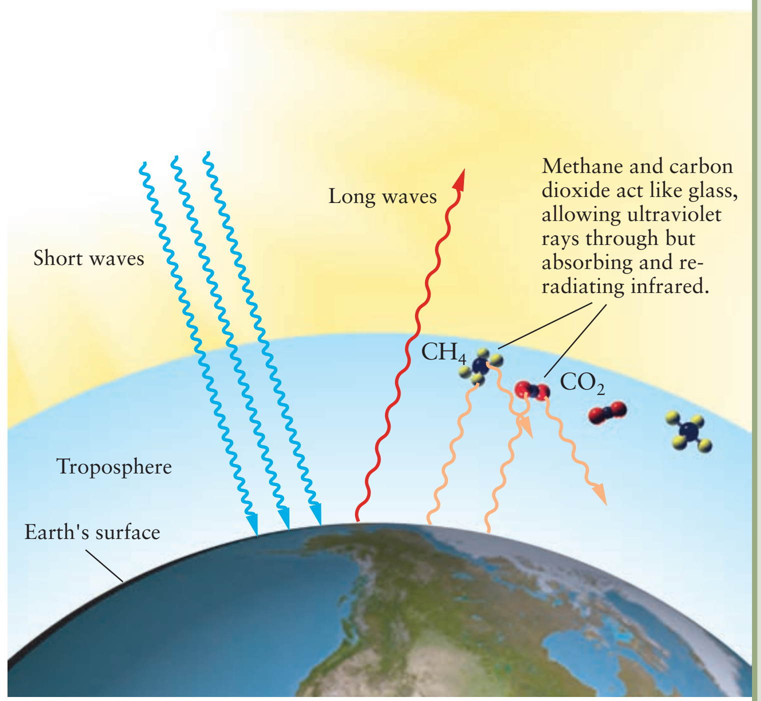
Counterradiation and the greenhouse effect
FIGURE 2.15

Shortwave radiation passes through the atmosphere and is absorbed at the surface. This 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 (D) and also to space (C). The counterradiation is the greenhouse effect.

Process Diagram

How a greenhouse works





The Earth's atmosphere acts like the glass in a greenhouse, admitting solar shortwave radiation but blocking the passage of outgoing longwave radiation.

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we have met so far and helps us to 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 air pollution causes more low, thick clouds to form? Since low clouds increase shortwave reflection back to space, the Earth's surface and atmosphere will cool. What about increasing condensation trails from jet aircraft? These could create more high, thin clouds, which absorb more longwave energy than they reflect shortwave energy. This would 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.

CONCEPT CHECK **STOP**

Describe two processes through which solar energy is lost in the atmosphere.

What is albedo? Give one example of an object with a high albedo and one with a low albedo.

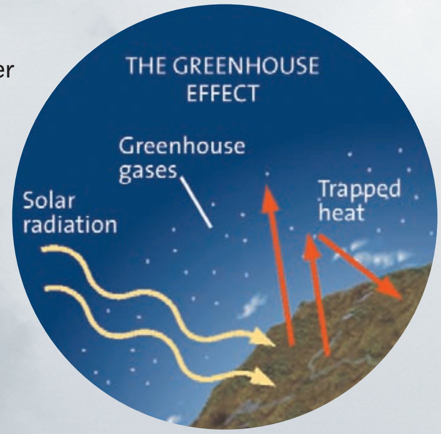
What is counterradiation? How does it lead to the greenhouse effect?

THE GREENHOUSE EFFECT

The Earth's atmosphere acts like a blanket on a cold night, trapping heat to warm the Earth's surface.

▶ Greenhouse heat trap

The atmosphere acts like a greenhouse, allowing sunlight to filter through. Gases such as carbon dioxide, water vapor, methane, ozone, and nitrous oxide help the atmosphere hold heat. This heating is key in the Earth's ability to stay warm and sustain life.

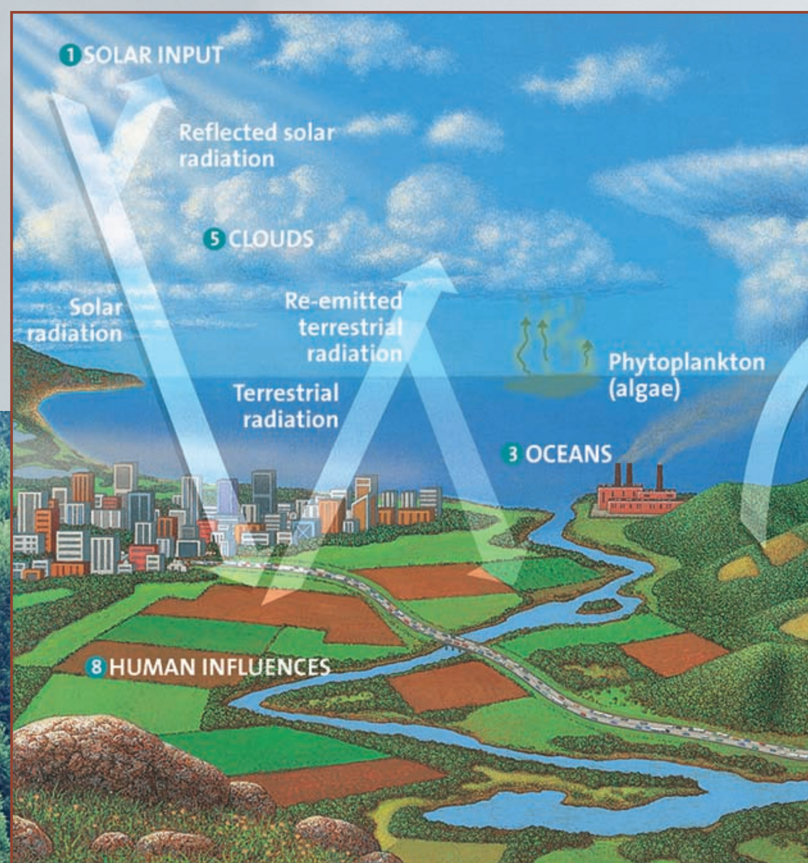


◀ Fossil fuel burning

When fossil fuels are burned to produce power, CO_2 is released. As global CO_2 levels rise, the greenhouse effect is enhanced.

What shapes the Earth's climate ▶

Much of the Sun's heat (1) is held in the atmosphere (2) by greenhouse gases as well as in the top layer of oceans. Oceans (3) distribute heat; evaporation lifts moisture (4). Clouds (5) reflect sunlight and cool the Earth; they also warm it by trapping heat. Ice and snow (6) reflect sunlight, cooling the Earth. Land (7) can influence the formation of clouds, and human use (8) can alter natural processes.



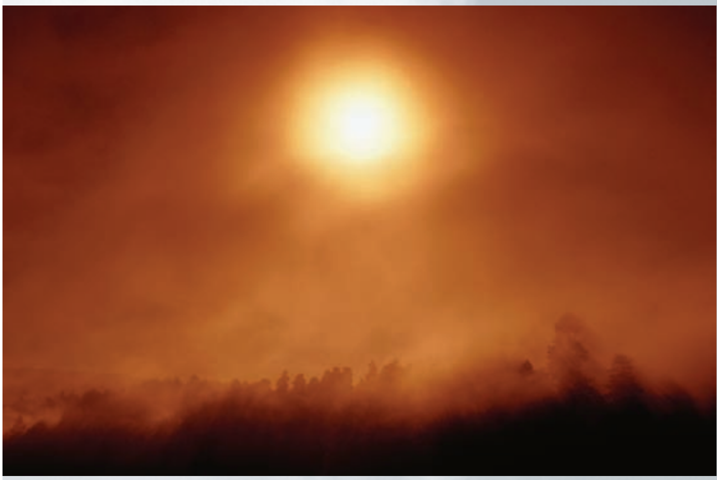
Global vegetation ▶

Plants take up CO_2 in photosynthesis, removing it from the atmosphere. But when the plants die, microorganisms digest the plant matter, returning the CO_2 to the atmosphere. CO_2 is also released by burning.

NATIONAL GEOGRAPHIC

GLOBAL ENERGY FLOWS AND THE EARTH'S CLIMATE

Energy exchanges between oceans, lands, and atmosphere control the Earth's climate system.



◀ **Solar power**

Shortwave radiation from the Sun is the power source that heats the Earth.

▲ **Oceans**

Oceans play a key role in the climate system. Ocean currents carry warm water poleward and cool water equatorward, moving heat around the globe. Ocean waters evaporate, carrying latent heat upward into the atmosphere. When the water vapor condenses, the latent heat is released at a different location.

▲ **Clouds**

Clouds are also an important part of the climate system. Low, thick clouds reflect solar energy back to space, which tends to cool the Earth. High, thin clouds absorb upwelling longwave radiation, enhancing the greenhouse effect and warming the Earth.

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Net Radiation, Latitude, and the Energy Balance

LEARNING OBJECTIVES

Define net radiation.

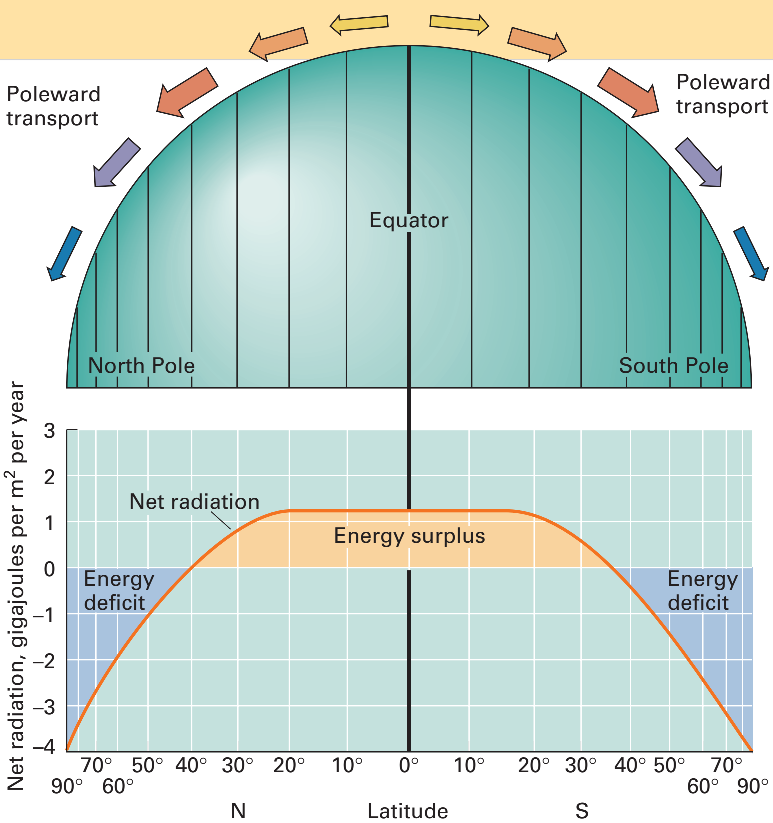
Explain how net radiation depends on latitude.

The heat level of our planet rises as it absorbs solar energy. But at the same time, it radiates energy into outer space, cooling itself. Over time, these incoming and outgoing radiation flows balance for the Earth as a whole. But these flows 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, yet the Earth's surface and atmosphere still emit 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 year.

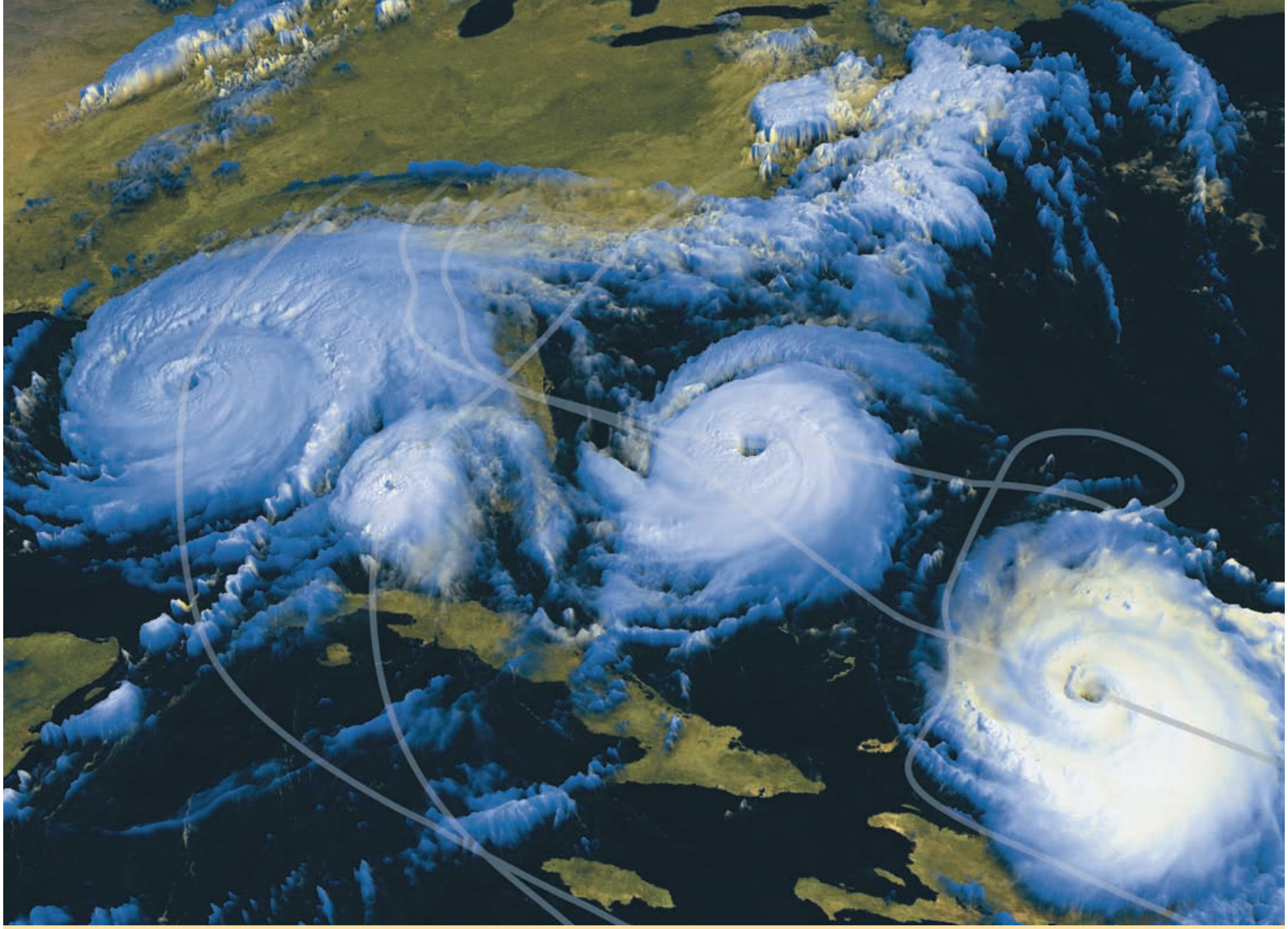
Net radiation The difference in energy flow between all radiant energy coming into a surface and all radiant energy leaving the surface.

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 2.16, which shows the net radiation profile from latitude 90° N to 90° S. The lower part of the figure shows the global profile of net radiation 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



Annual surface net radiation from pole to pole FIGURE 2.16

Where net radiation is positive, incoming solar radiation exceeds outgoing longwave radiation. There is an energy surplus, and energy moves poleward as latent heat and sensible heat. Where net radiation is negative, there is an energy deficit. Latent and sensible heat energy moves from regions of excess to regions of deficit, carried by ocean currents and atmospheric circulation.



Atmospheric circulation and energy transport FIGURE 2.17

Tropical cyclones, such as the four hurricanes from 2004 shown here in a composite image, are formed when atmospheric circulation mixes warm, moist air with cooler, drier air. As the cyclones move poleward, they carry energy from warm tropical oceans to higher latitudes. Global-scale imbalances in net radiation are the primary drivers of atmospheric circulation.

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 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 cool drier air move toward the equator.

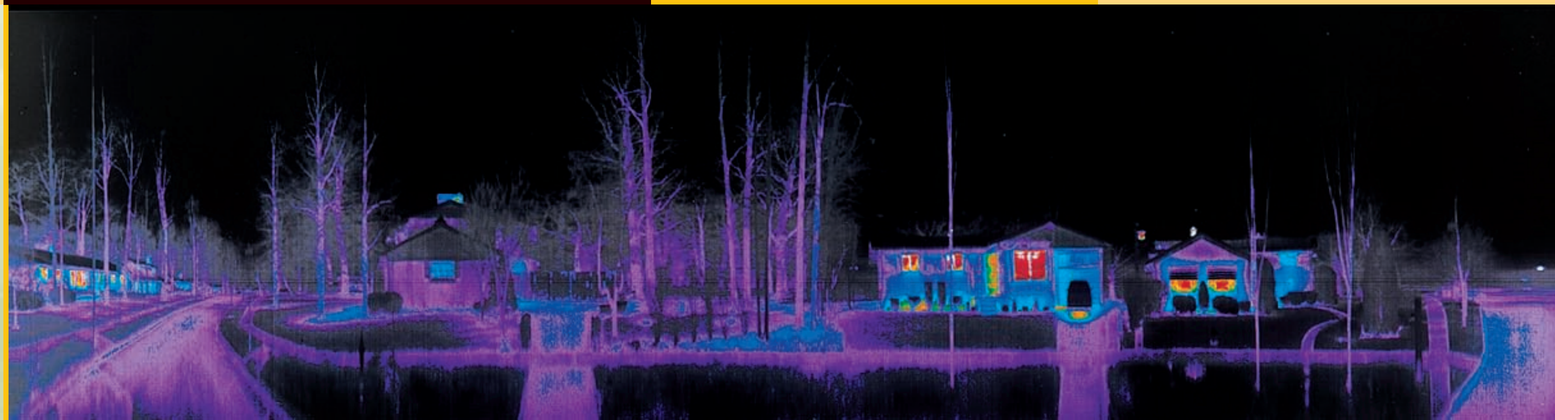
Keep in mind that this poleward heat transfer, driven by the imbalance in net radiation between low and high latitudes, is the power source for broad-scale atmospheric circulation patterns and ocean currents that help sustain marine life by redistributing nutrient rich waters (FIGURE 2.17). Without this 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.

CONCEPT CHECK STOP

What is net radiation?

How do differences in net radiation across the globe drive ocean and atmospheric flow patterns?

What is happening in this picture?



Thermal infrared radiation can be seen using a special sensor. Here we can see a suburban street on a cool night. Different temperatures regions are represented by different colors in the image.

- Which regions would you expect to be the warmest, and which should be the coolest in this scene?

VISUAL SUMMARY

1 Electromagnetic Radiation

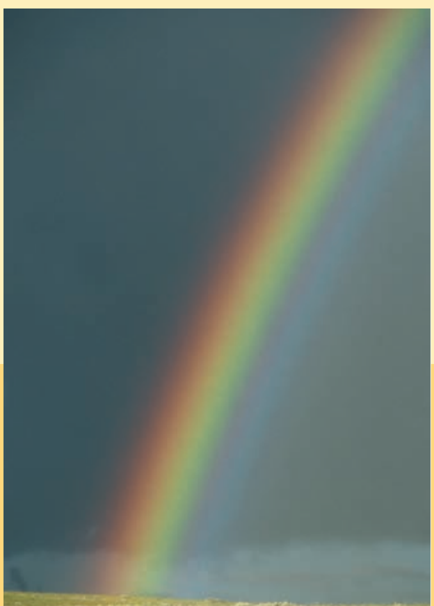
1. All objects give off electromagnetic radiation.
2. Hotter objects emit greater amounts of electromagnetic radiation. They also emit radiation at shorter wavelengths than cooler objects.
3. The Sun emits mostly shortwave radiation, while the Earth gives off longwave radiation.

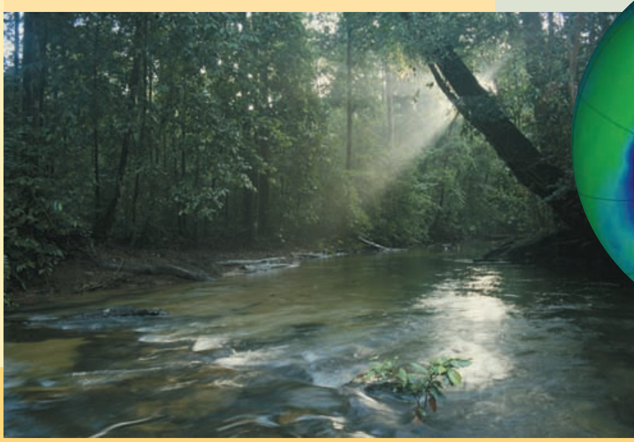
2 Insolation over the Globe

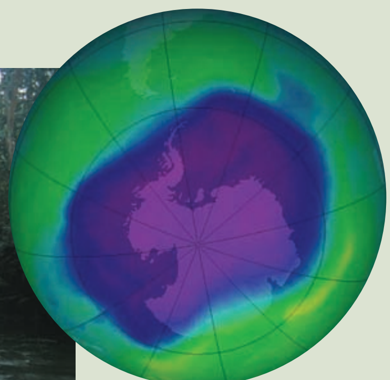
1. Insolation is the rate of solar radiation flow at a location at a given time.
2. Daily insolation is greater when there is more daylight and the Sun is higher in the sky.
3. Annual insolation is greatest at the equator and least at the poles.
4. We can divide the globe into latitude zones according to how much insolation different latitudes receive.

3 Composition of the Atmosphere

1. The Earth's atmosphere is dominated by nitrogen and oxygen.
2. Carbon dioxide and water vapor enhance the greenhouse effect by absorbing longwave radiation.
3. Ozone (O_3) helps absorb ultraviolet radiation, sheltering the Earth from ultraviolet rays.





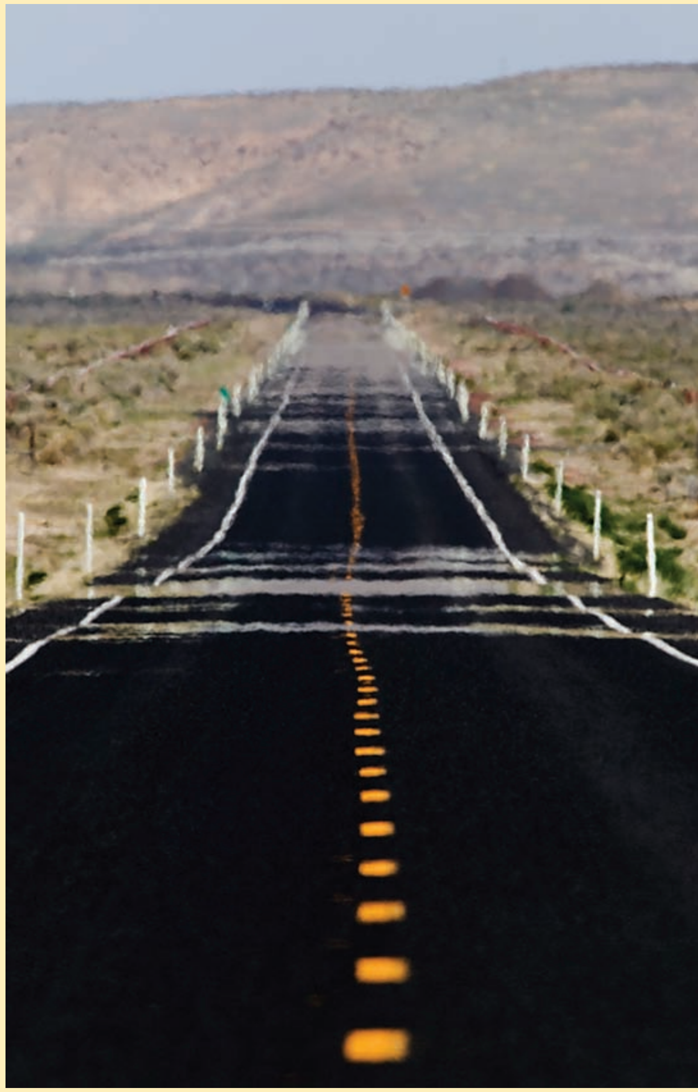


4 Sensible Heat and Latent Heat Transfer

1. Latent heat is taken up or released when substances change between solid, liquid, and gaseous states.
2. Sensible heat is held within a substance and can be transferred by conduction or convection.

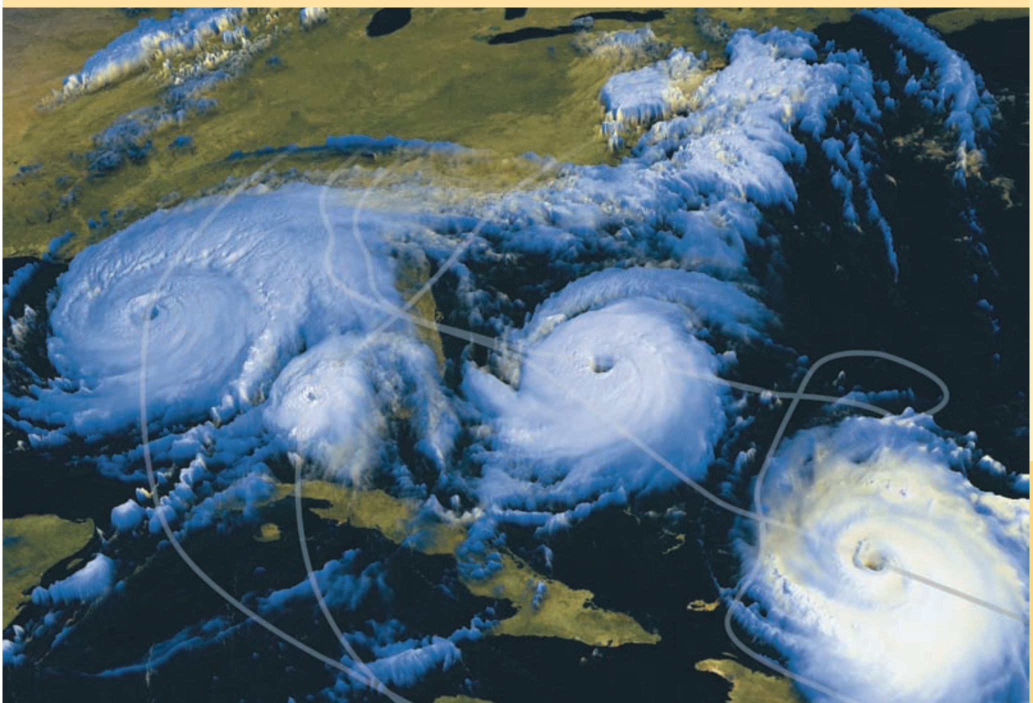
5 The Global Energy System

1. Incoming solar radiation is partly absorbed or scattered by molecules in the atmosphere.
2. The albedo of a surface is the proportion of solar radiation it reflects.
3. The atmosphere absorbs longwave energy from the Earth, and counterradiates some of it back to the Earth, creating the greenhouse effect.



6 Net Radiation, Latitude, and the Energy Balance

1. Net radiation describes the balance between incoming and outgoing radiation.
2. At latitudes below 40 degrees, annual net radiation is positive, while it is negative at higher latitudes.
3. This imbalance drives latent and sensible heat toward the poles, creating broad-scale atmospheric circulation patterns and ocean currents that help sustain marine life.



KEY TERMS

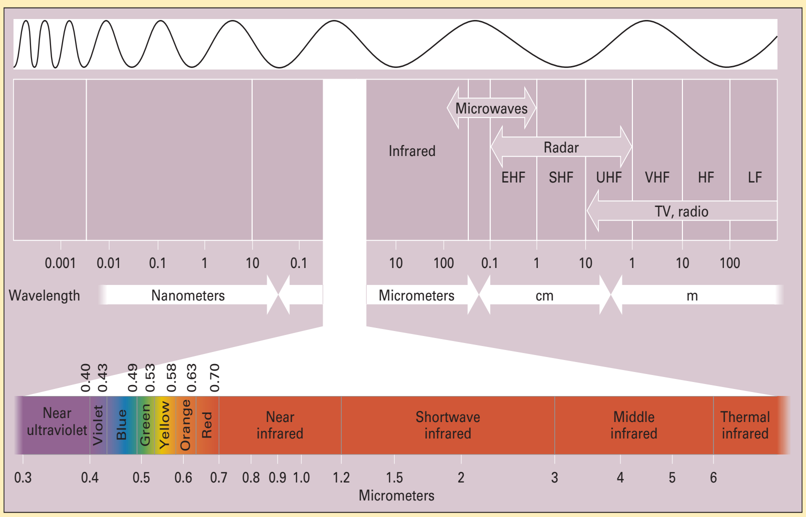
- **electromagnetic radiation** p. 36
- **absorption** p. 38
- **scattering** p. 38
- **shortwave radiation** p. 39
- **longwave radiation** p. 39
- **insolation** p. 42
- **ozone** p. 47
- **sensible heat** p. 49
- **latent heat** p. 49
- **albedo** p. 51
- **counterradiation** p. 52
- **greenhouse effect** p. 52
- **net radiation** p. 56

CRITICAL AND CREATIVE THINKING QUESTIONS

1. What is electromagnetic radiation? How is it characterized? Identify the major regions of the electromagnetic spectrum.
2. What is the Earth's global energy balance, and how are shortwave and longwave radiation involved?
3. Suppose the Earth's axis was not tilted. How would global insolation be affected?
4. Sketch the world latitude zones on a circle representing the globe and give their approximate latitude ranges. How does insolation vary across these zones?
5. Why are carbon dioxide and water vapor levels in the atmosphere important? How does the ozone layer help protect life on Earth?
6. Describe the counterradiation process and how it relates to the greenhouse effect.
7. 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?
8. What is net radiation? What is the role of poleward heat transport in balancing the net radiation budget by latitude?

SELF-TEST

1. Label the regions of the electromagnetic spectrum that correspond to (a) visible light, (b) gamma rays, (c) X rays, and (d) ultraviolet light.

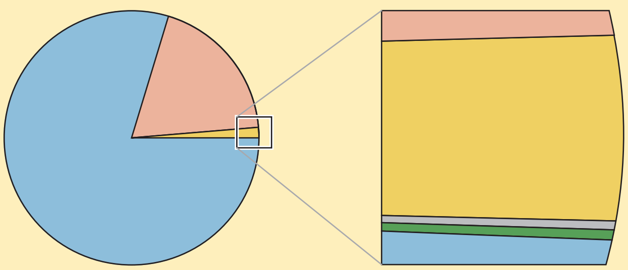


2. In the case of electromagnetic energy, ______________ objects radiate more energy at shorter wavelengths than ______________ objects.
   a. hotter, cooler
   b. rotating, stationary
   c. cooler, hotter
   d. larger, smaller
3. The highest energy, shortest wavelength form of electromagnetic radiation emitted by the sun is:
   a. shortwave infrared
   b. visible light
   c. thermal infrared radiation
   d. ultraviolet radiation
4. The Earth, maintaining a significantly cooler surface temperature than the Sun, emits ______________.
   a. ultraviolet radiation
   b. shortwave infrared radiation
   c. longwave radiation
   d. visible light
5. The amount of incoming solar radiation, or *insolation*, received by the surface of the Earth, is most dependent upon the ______________.
   a. angle at which the insolation is received by the Earth's surface
   b. total solar radiation output of the Sun
   c. amount of glacial coverage in a particular area
   d. amount of ocean surface in a particular region

6. The _______________ regions of the Earth receive the greatest amount of insolation.
   a. polar
   b. equatorial
   c. midlatitude
   d. subtropical

7. The Earth's _______________ regions have the greatest insolation variation.
   a. polar
   b. equatorial
   c. midlatitude
   d. tropical

8. The diagram shows the proportion of gases that make up our atmosphere. Label the following gases on the figure: (a) argon, (b) carbon dioxide, (c) nitrogen, and (d) oxygen.



9. The chemical formula _______________ represents ozone.
   a. O_2
   b. O^2
   c. O_3
   d. CO_2

10. Of the following gases, _______________ result(s) in the most prolific destruction of ozone.
    a. nitrogen
    b. carbon dioxide
    c. chlorofluorocarbons (CFCs)
    d. argon

11. Sensible heat transfer refers to the flow of heat between the Earth's surface and the atmosphere _______________.
    a. that can be measured with a thermometer
    b. by advection
    c. occurring between the various states of water
    d. by conduction and/or convection

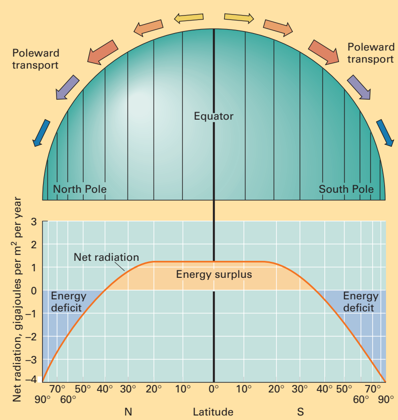
12. Scattered radiation moving in all directions through that atmosphere is known as _______________.
    a. diffuse radiation
    b. diffuse reflection
    c. direct radiation
    d. refracted radiation

13. The percentage of shortwave radiant energy scattered upward by a surface is termed its _______________.
    a. outflow
    b. output
    c. albedo
    d. reflection

14. While the Earth's surface can only radiate longwave radiation _______________, the atmosphere radiates longwave radiation _______________.
    a. upwards, downwards
    b. upwards, in all directions
    c. downwards, upwards
    d. upwards, at right angles to the upwards flow

15. _______________ from the atmosphere helps to warm the Earth's surface through a process known as the _______________.
    a. Outbound longwave radiation, ozone effect
    b. Insolation, greenhouse effect
    c. Counterradiation, greenhouse effect
    d. Counterradiation, ozone effect

16. _______________, driven by the imbalance in net radiation between low and high latitudes, is the power source for ocean currents and broad-scale atmospheric circulation patterns.
    a. Midlatitude heat transfer
    b. Poleward heat transfer
    c. Surface net radiation
    d. Energy balance



Air Temperature 3

In 1991, a sleeping giant awoke with a roar. Mount Pinatubo, a volcano in the Philippines that had lain dormant for more than 500 years, produced one of the most violent eruptions of the twentieth century. At its climax, the eruption blew off the top of the mountain, ejecting between 8 and 10 square kilometers of material. Floods of lava spewed out, and hundreds of cubic meters of sand- and gravel-sized debris rained down on the mountain's upper slopes.

Before the eruption, many people lived on the mountain's forested lower slopes. Early rumblings warned geologists of the impending eruption, and more than 50,000 people were evacuated. But several hundred people died as roofs collapsed under the weight of falling ash. Villages were destroyed and tens of thousands suffered the effects of mudslides, ash-clogged rivers, and crop devastation.

Reverberations were also felt globally. The volcano sent a vast plume of sulfur dioxide gas and dust high into the atmosphere—some 15 to 20 million tons. A haze of sulfuric acid droplets spread throughout the stratosphere over the year following the eruption. These particles, though tiny, had an important impact on the global climate. They reduced the sunlight reaching the Earth's surface by 2 to 3 percent for the year, and average global temperatures fell by about 0.3°C (0.5°F).

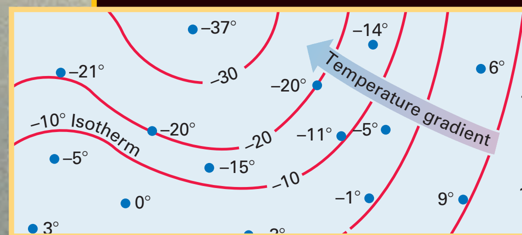
Our planet's atmosphere is a dynamic system that responds readily to many types of change, and we must keep a close watch on the natural and artificial phenomena that can perturb it.

As Philippine farmers plow their fields, Mount Pinatubo erupts on July 8, 1991.

CHAPTER OUTLINE

Surface and Air Temperature p. 64

Daily and Annual Cycles of Air Temperature p. 71



World Patterns of Air Temperature p. 76

Temperature Structure of the Atmosphere p. 80

Global Warming and the Greenhouse Effect p. 83

Surface and Air Temperature

LEARNING OBJECTIVES

Explain how air temperatures close to the ground are related to surface temperatures.

Explain how surface type affects urban and rural temperatures.

Explain how and why conditions change at high elevation.

Define temperature inversion.

Turn on the evening news and you are bound to hear about the threat of global warming. The Earth is becoming increasingly warmer, bringing with it a rise in sea level and more frequent bouts of severe weather, and strong scientific evidence points to human activity as the cause.

Global warming, its causes, and its effects, are a complicated story. We have already touched on some of the issues related to climate change, and we will return to them again later in this chapter. But first we need to understand the interplay between surface and air temperatures and examine how and why air temperature changes from day to day, month to month, and year to year.

SURFACE TEMPERATURE

Temperature is a very familiar concept. We all know that when a substance—gas, liquid, or solid—receives a flow of radiant energy, such as sunlight, its temperature rises. Similarly, when a substance loses energy, its temperature falls.

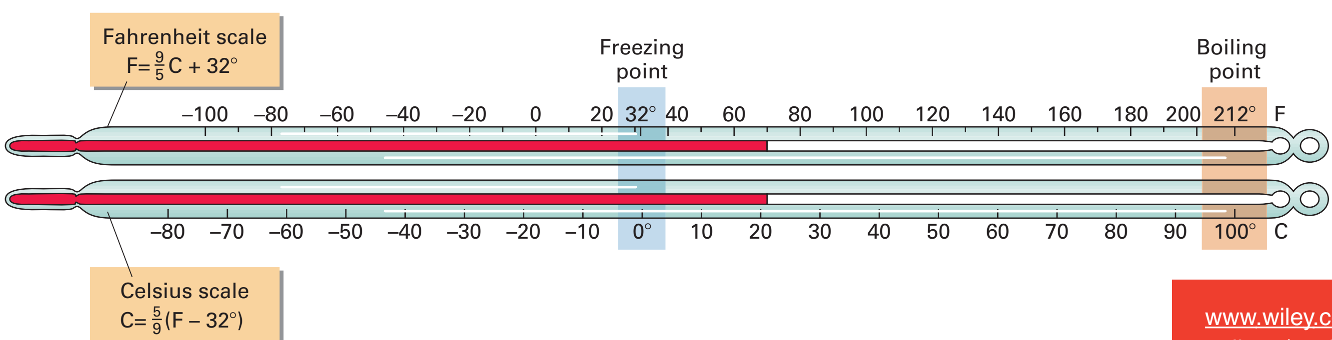
In the United States, temperature is still widely measured and reported using the Fahrenheit scale. The freezing point of water on the Fahrenheit scale is 32°F, and the boiling point is 212°F. In this book, we use the Celsius temperature scale, which is the international standard. On the Celsius scale, the freezing point of water is 0°C and the boiling point is 100°C (FIGURE 3.1).

Let's think about what happens when sunlight hits the ground surface (FIGURE 3.2). The flow of energy moves in and out of the surface. The solar shortwave radiation is quickly absorbed by a very thin layer of soil, which then radiates longwave radiation out to space. Recall from Chapter 2 that we use the term *net radiation* to describe the balance between the solar shortwave radiation absorbed and the longwave radiation emitted.

Energy can also move to or from a surface by conduction, latent heat transfer, and convection. Sensible heat flows by conduction from warm objects to colder ones when they are placed in contact. This is how heat is transferred deeper into soil, from its warm surface during the day. During the night, the soil surface becomes colder than the inner layers, so heat is conducted back up to the soil surface from below.

Temperature scales FIGURE 3.1

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



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Solar energy flow FIGURE 3.2

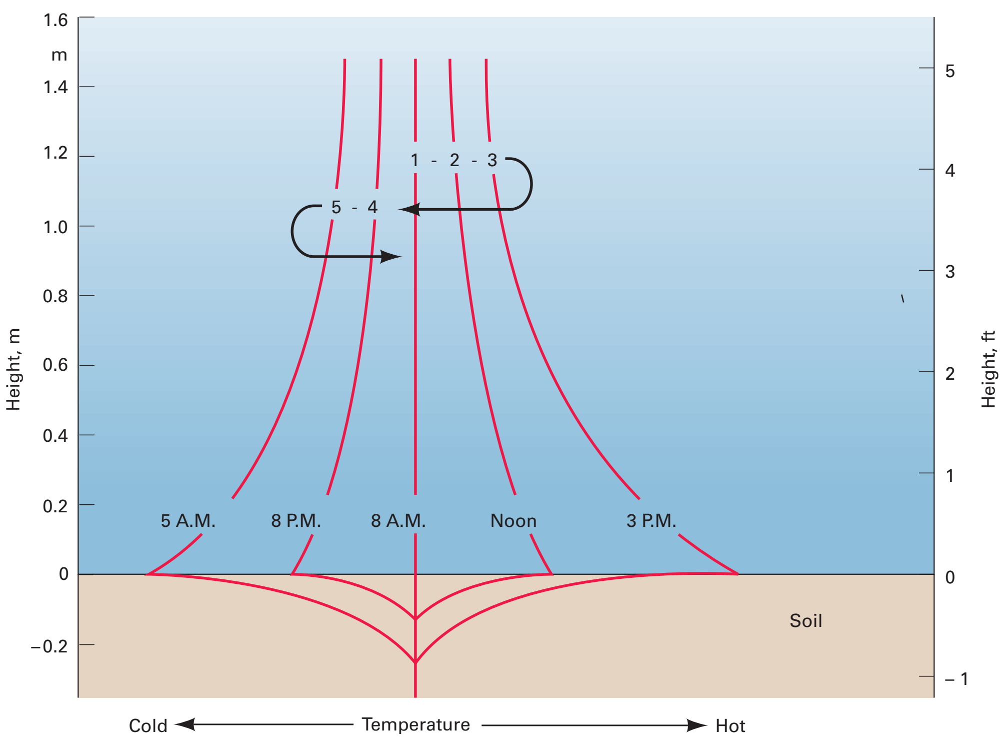
Solar light energy strikes the Earth's surface and is largely absorbed, warming the surface.

Latent heat transfer is also important. When water evaporates at a surface, changing from a liquid to a gas, it takes away latent heat. This cools the surface. Similarly, when water condenses at a surface, latent heat is released, giving a warming effect. Finally, convection redistributes heat in a fluid by mixing. Let's look at how these processes affect temperatures near the ground.

TEMPERATURES CLOSE TO THE GROUND

The air temperature is one piece of weather information that affects us daily. So far we have looked at surface temperatures. We will see shortly that air temperature can be 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 measured at the standard height of 1.2 m (4.0 ft) above a surface reflect the same trends as ground surface temperatures, but ground temperatures are likely to be more extreme.

Soil, surface, and air temperatures within a few meters of the ground change through the day (FIGURE 3.3). 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.



Daily temperature profiles close to the ground FIGURE 3.3

The red curves 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. At 8 a.m. (curve 1), the temperature of air and soil is the same, producing a vertical line on the graph. By noon (curve 2), the surface is considerably warmer than the air at standard height, and the soil below the surface has been warmed as well. By 3 p.m. (curve 3), the soil surface is much warmer than the air at standard height. By 8 p.m. (curve 4), the surface is cooler than the air, and by 5 a.m. (curve 5), it is much colder.

ENVIRONMENTAL CONTRASTS: URBAN AND RURAL TEMPERATURES

So far we have looked at the movement of heat through a soil surface. But are temperature patterns different when we look at artificial surfaces? Human activity has altered much of the Earth's land surface. Vegetation has been removed to build cities, and soils have been covered with pavement.

When you walk across a parking lot on a hot day, the ground can become hot enough to burn your bare feet. It is different when you step across a grassy field—the ground does not feel as hot, even if the air temperature is similar. The reason is the surface material, which plays a large part in determining temperature. "What a Geographer Sees: Rural Surfaces and Urban Surfaces" discusses these effects on temperature. We see that two of the key processes that help to keep rural surfaces cool are **transpiration** and *evaporation*, which together are known as **evapotranspiration**.

Transpiration The process by which plants lose water to the atmosphere by evaporation through leaf pores.

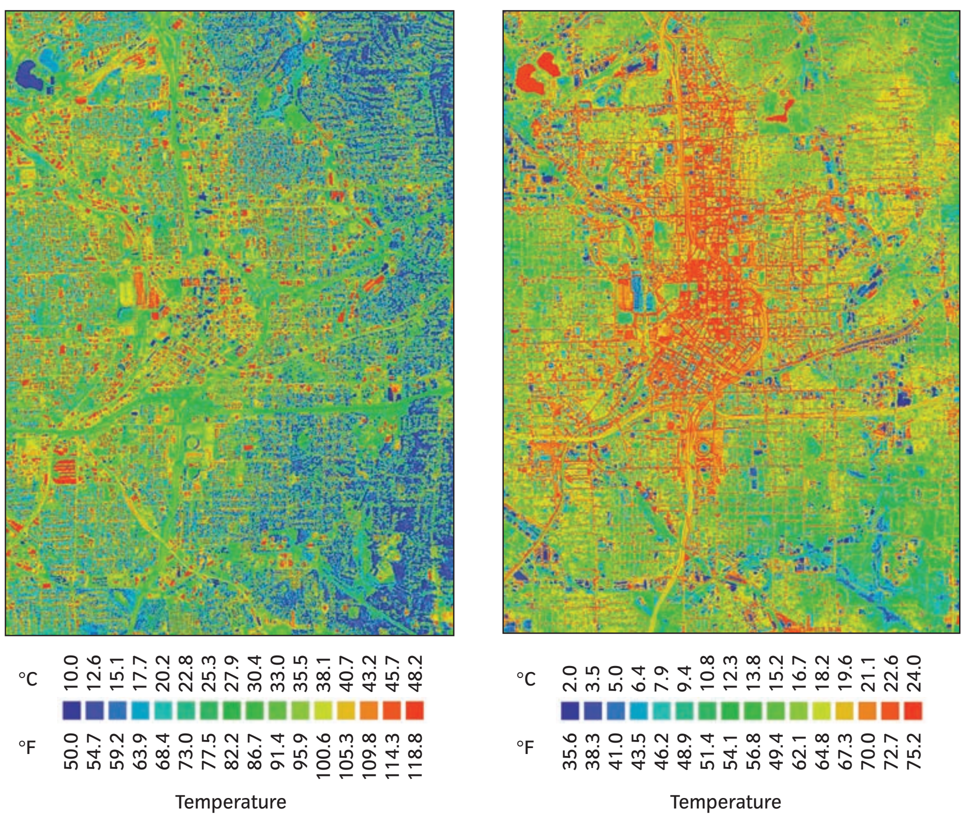
Evapotranspiration The combined water flow to the atmosphere by evaporation from soil and transpiration from plants.

THE URBAN HEAT ISLAND

Because urban surfaces tend to be warmer than rural ones, city centers tend to be several degrees warmer than the surrounding suburbs and countryside. We call this center 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 (FIGURE 3.4).

The urban heat island effect has important economic consequences. We use more air conditioning and more electric power to combat higher temperatures in the city center. And smog is more likely to form

Urban heat island Area at the center of a city that has a higher temperature than surrounding regions.



Thermal infrared images of downtown Atlanta

FIGURE 3.4

These thermal infrared images of the Atlanta central business district in May 1997 demonstrate the heat island effect. On the left is a daytime image, on the right a nighttime image. Note that the heat island effect is strongest at night.

in warm temperatures. Many cities are now planting more vegetation in an attempt to counteract these problems.

HIGH-MOUNTAIN ENVIRONMENTS

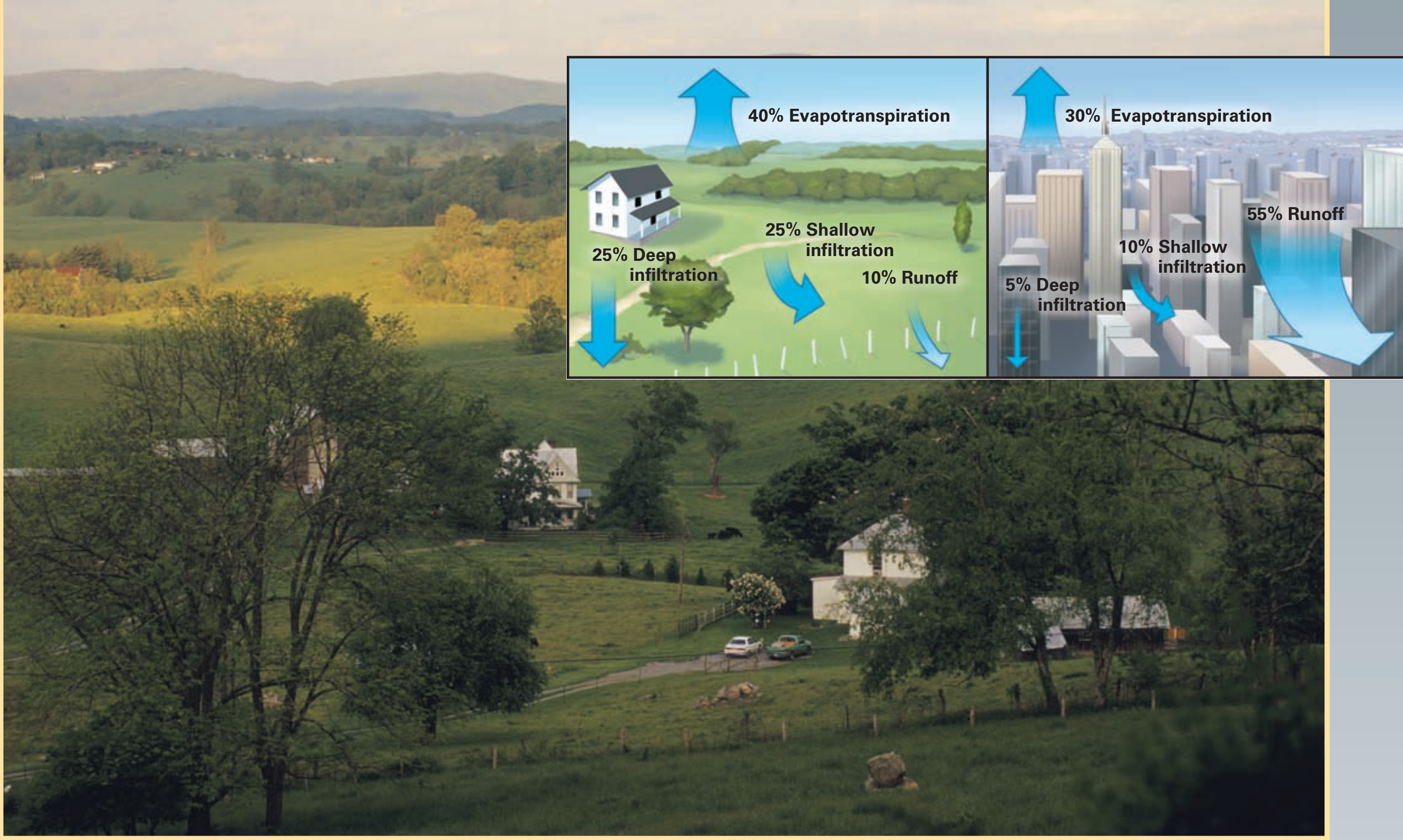
We have seen that the ground surface affects the temperature of the air directly above it. But what happens as you travel to higher elevations? For example, as you climb higher on a mountain, you may become short of breath and you might notice that you sunburn more easily (FIGURE 3.5). You also feel the temperature drop, as you ascend. If you camp out, you'll see that the nighttime temperature gets lower than you might 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 breathe 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 be stronger as they beat down on you. 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.

High elevation FIGURE 3.5

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.

What a Geographer Sees



Rural surfaces and urban surfaces

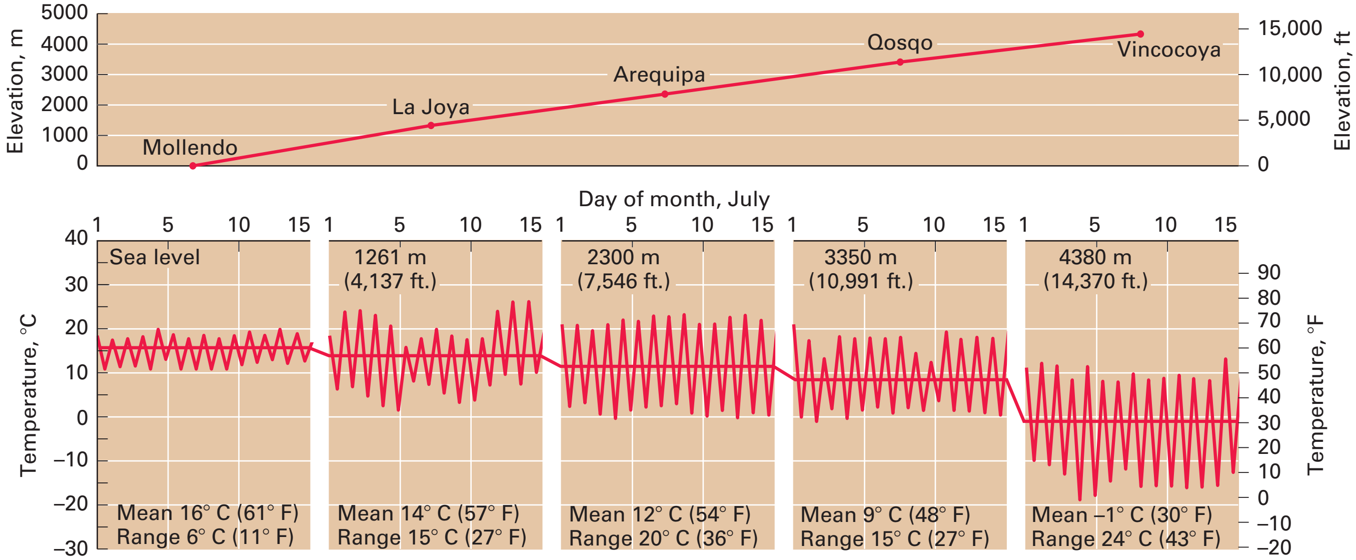
On a hot day, the rural ground will feel far cooler to your bare feet than a city sidewalk. How would a geographer explain the cooling effect?

In rural areas, water is taken up by plant roots and moved to the leaves, in a natural 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. The inset figure illustrates the difference between a natural ground cover and a typical urban ground cover (pavement) on evapotranspiration, runoff, and infiltration.

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.

What else might you notice about the city's layout? The buildings of the city provide many vertical surfaces that reflect radiation between surfaces. This traps solar energy, which bounces back and forth until most of it is absorbed.



The effect of elevation on air temperature cycles FIGURE 3.6

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.

FIGURE 3.6 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 (FIGURE 3.7).

Qosqo by night FIGURE 3.7

Urban power consumption in Qosqo (formerly Cuzco) keeps nighttime temperatures higher than in the surrounding areas.

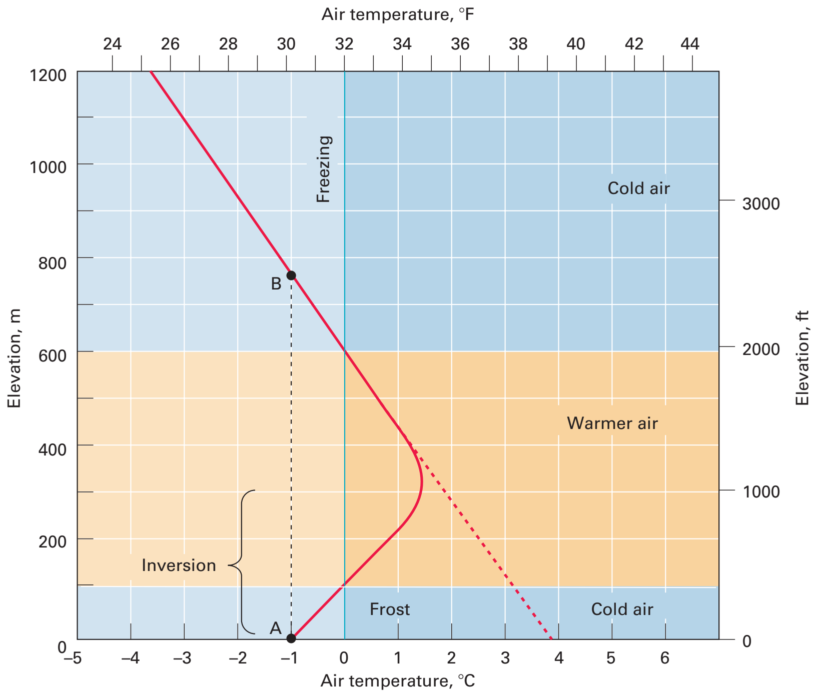
TEMPERATURE INVERSION

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. 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 3.8. This is a **temperature inversion**.

Temperature inversion Reversal of normal temperature pattern so that air temperature increases with altitude.

In a temperature inversion, the temperature of the air near the ground can fall below the freezing point. This temperature condition can cause 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.



Temperature inversion FIGURE 3.8

While air temperature normally decreases with altitude (dashed line), in an inversion, temperature increases with altitude. In this example, the surface temperature is at −1°C (30°F), and temperature increases with altitude (solid line) for several hundred meters (1000 ft or so) above the ground. Temperature then resumes a normal, decreasing trend with altitude.

CONCEPT CHECK STOP

How is the air temperature directly above a surface related to the temperature of the ground?

How does surface type affect air temperature in the city and in rural areas? What is an urban heat island?

How does temperature depend on elevation? What causes this effect?

What is a temperature inversion? Why is it bad for crop growers?

Daily and Annual Cycles of Air Temperature

LEARNING OBJECTIVES

Describe the connection between cycles of insolation, net radiation, and air temperature.

Explain why temperature patterns in maritime and continental regions differ.

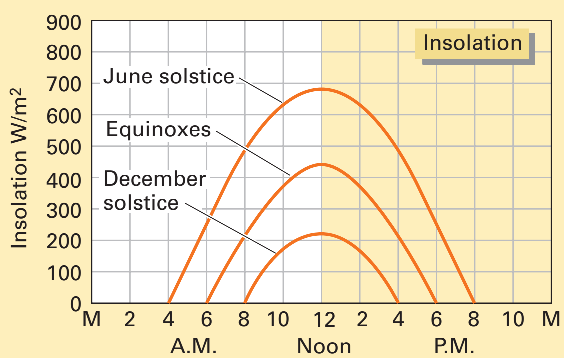
Explain how latitude affects annual air temperature cycles.

THE DAILY CYCLE OF AIR TEMPERATURE

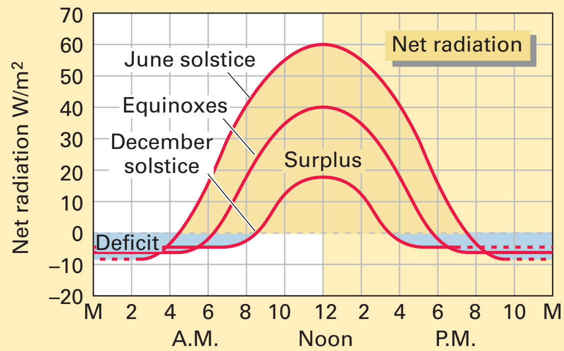
Let's turn to how, and why, air temperatures vary around the world. Insolation from the Sun varies across the globe, depending on latitude. Net radiation at a given place is positive during the day, as the surface gains heat from the Sun's rays. At night, the flow of incoming shortwave radiation stops, but the Earth continues to radiate longwave radiation, so 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 3.9).

Daily cycles of insolation, net radiation, and air temperature FIGURE 3.9

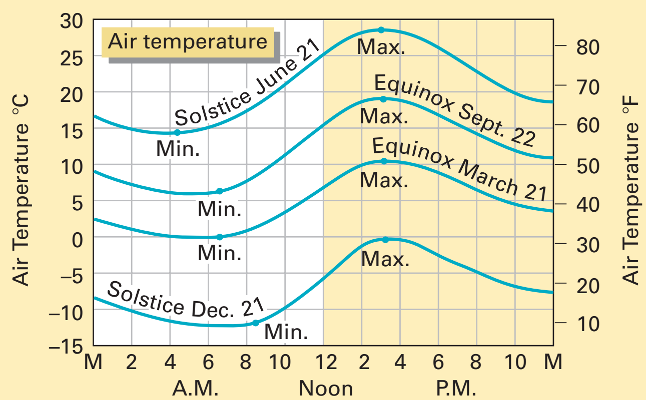
These three graphs show idealized daily cycles for a midlatitude station at a continental interior location and illustrate how insolation, net radiation, and air temperature are linked.



A 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.



B 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.



C 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.

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 3.10 shows a typical temperature record for a week in the summer. Temperatures in San Francisco 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 much warmer on the average—about 28°C (82°F). Clearly, no ocean cooling is felt in Yuma! The daily

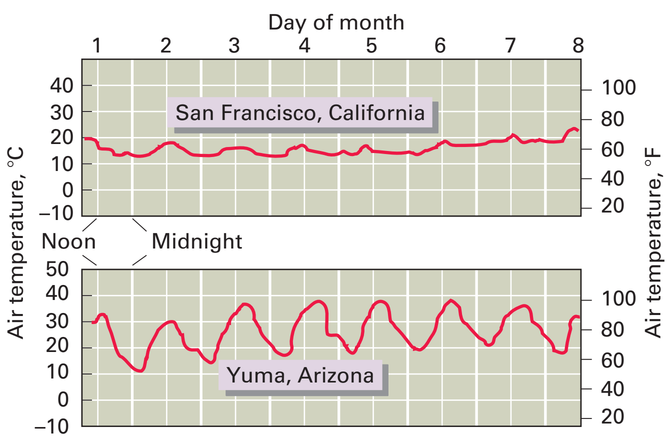
Maritime and continental temperatures

FIGURE 3.10

A 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.

B At San Francisco, on the Pacific Ocean, the daily air temperature cycle is very weak.

C At Yuma, a station in the desert, the daily cycle is strongly developed.



A

B

C

Process Diagram

Land-water contrasts

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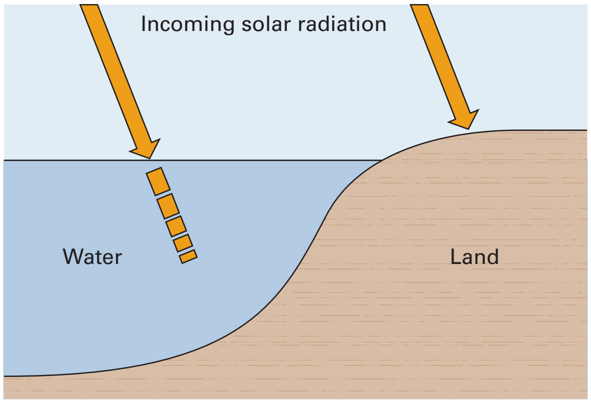
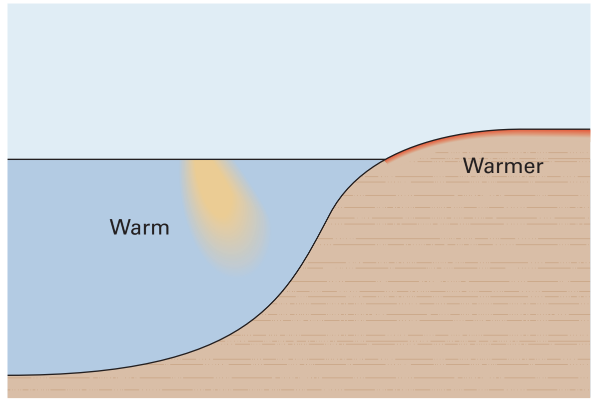
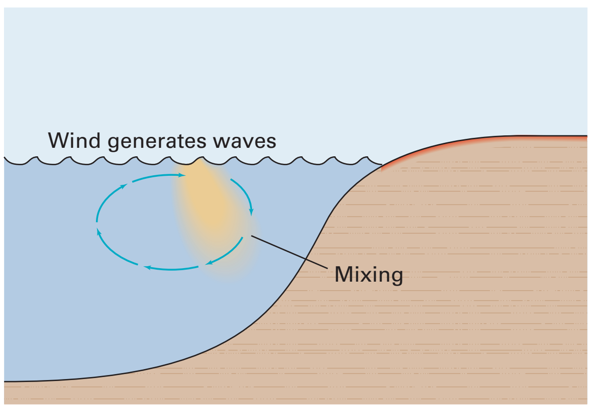
There are four key thermal differences that make land heat faster than water. These differences explain why a coastal city has more moderate, uniform temperatures, but a city inland has more extremes. The seacoast city's summer heat is moderated by the presence of water, and so is cooler. Similarly, the seacoast city's winter chill is moderated by the water, and so is warmer.



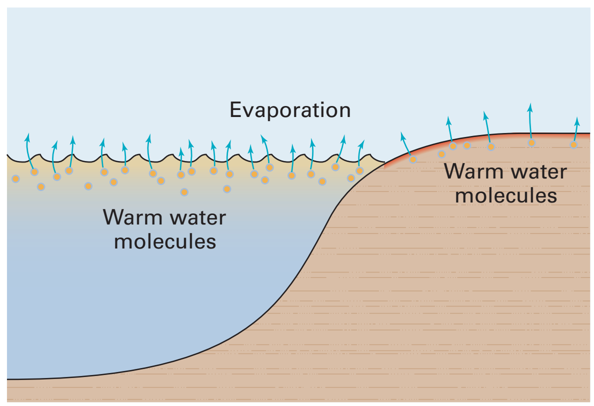
Incoming solar radiation
Solar rays strike the land and water surfaces equally. On land, the radiation cannot deeply penetrate the soil or rock, so heating is concentrated at the surface. On water, much of the radiation penetrates below the surface, distributing heat to a substantial depth.



Heat capacity of water and rock is very different
Heat capacity is the amount of heat that a substance can store. Rock (and soil) have a low specific heat capacity, requiring less energy to increase temperature. But water has a high specific heat capacity, requiring much more energy to raise its temperature. It can take as much as five times the heat energy to raise water temperature one degree as it takes to raise the same volume of rock's temperature one degree. The same is true for cooling—after losing the same amount of energy, water temperature drops less than rock temperature. Thus, water temperature remains more uniform than land temperature.



Mixing
Water allows mixing, whereas rock is essentially immobile, preventing mixing. In water, the warming surface water mixes with cooler water at depth to produce a more uniform temperature throughout. This mixing is driven by wind-generated waves. In rock and soil, no such mixing can occur.



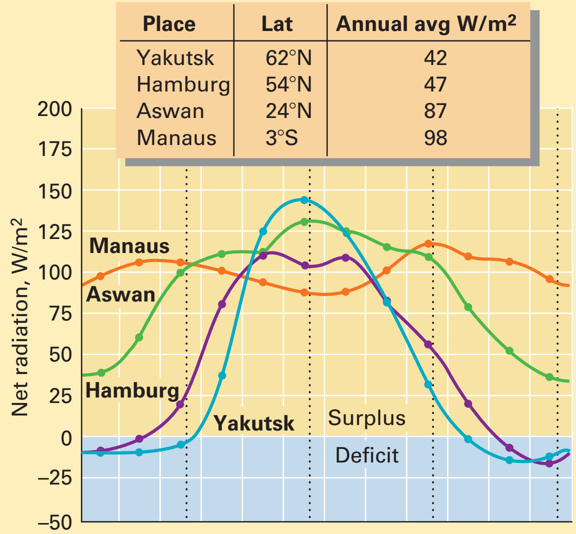
Evaporation
As water molecules evaporate, exposed water surfaces are easily cooled, absorbing heat from the surroundings. Land surfaces also can be cooled by evaporation if water exists near the soil surface, but once the land surface dries, evaporation stops, and so does cooling.

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.

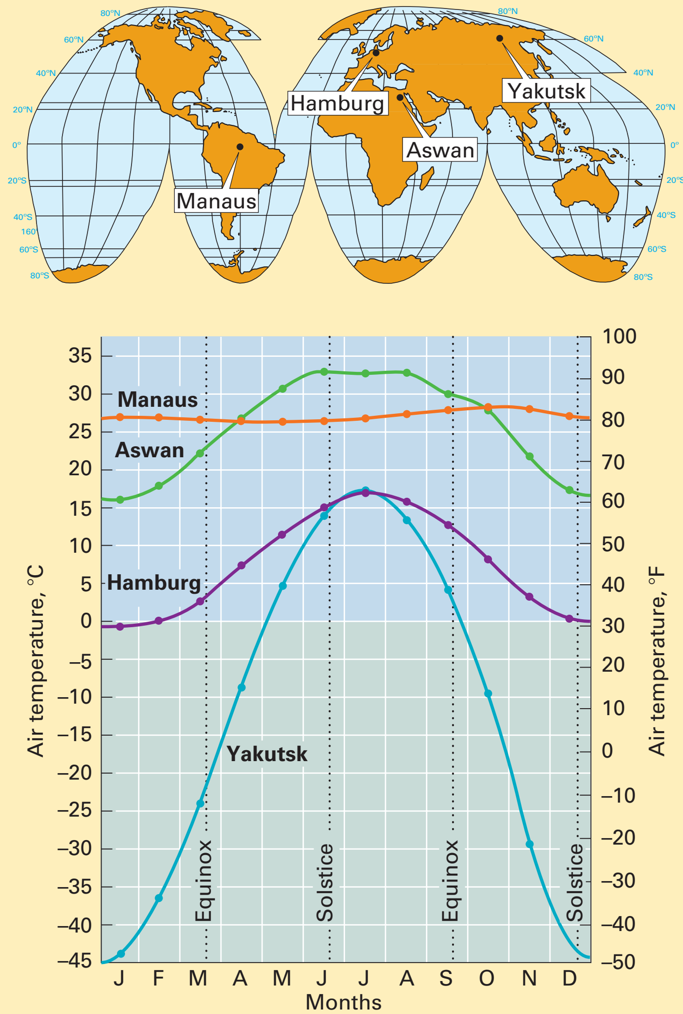
What is behind these differences? The important principle is this: the surface layer of any extensive, deep body of water heats more slowly and cools more slowly than the surface layer of a large body of land when both are subjected to the same intensity of insolation. Because of this principle, daily 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.

The relationship between net radiation and temperature FIGURE 3.11

Place	Lat	Annual avg W/m²
Yakutsk	62°N	42
Hamburg	54°N	47
Aswan	24°N	87
Manaus	3°S	98



▲ **A** **Net radiation** At Manaus, Brazil, 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, Egypt, 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.



▶ **B** **Monthly mean air temperature** Manaus has uniform air temperatures, averaging about 27°C (81°F) for the year. The temperature is also similar each month, with only a small difference of 1.7°C (3°F) between the highest and lowest mean monthly temperature. This is known as the annual temperature range. There are no temperature seasons. The Aswan data for temperature follows the cycle of the net radiation rate curve, with an annual range of about 17°C (31°F). June, July, and August are terribly hot, averaging over 32°C (90°F). The temperature cycle for Hamburg 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, monthly mean temperatures for three winter months are between −35 and −45°C (about −30 and −40°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—with monthly values of over 13°C (55°F). Because of Yakutsk's high latitude and continental interior location, its annual temperature range is enormous—over 60°C (108°F).

C **Manaus, Brazil**

D **Yakutsk, Siberia**

ANNUAL NET RADIATION AND TEMPERATURE CYCLES

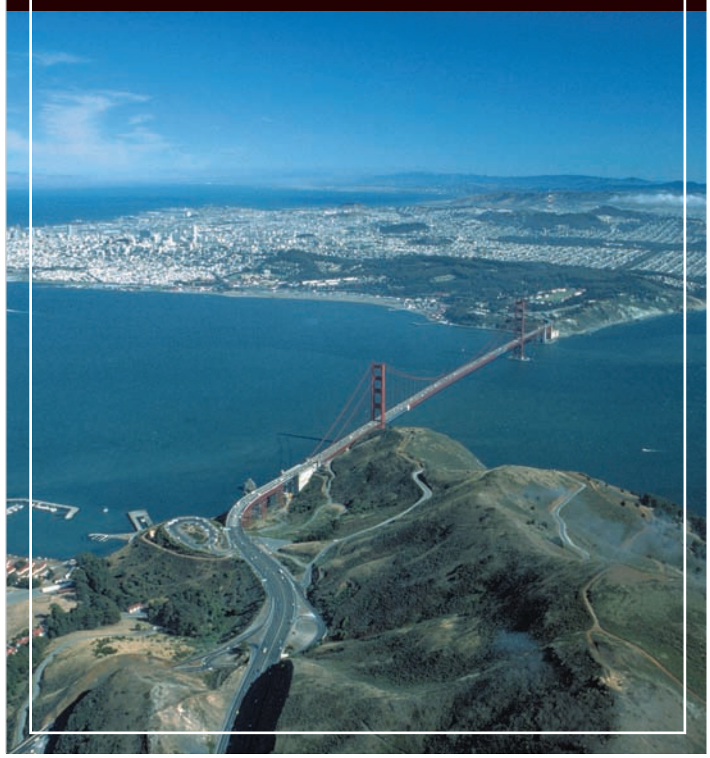
We have seen that location—maritime or continental—has an important influence on annual temperature cycles. But the largest effect is caused by the annual cycle of net radiation. Daily insolation varies over the seasons of the year, owing to the Earth's motion around the Sun and the tilt of the Earth's axis. That rhythm produces a net radiation cycle that, in turn, causes an annual cycle in mean monthly air temperatures (FIGURE 3.11).

CONCEPT CHECK **STOP**

Describe the factors influencing the daily cycle of air temperature.

Why do San Francisco, California, and Yuma, Arizona, have such different daily temperature cycles?

What is the relationship between net radiation and the temperature cycle?



World Patterns of Air Temperature

LEARNING OBJECTIVES

Learn how to read air temperature maps.

Describe what isotherms are and why they are useful.

Identify and explain world temperature patterns.

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.

First, we need a quick explanation of air temperature maps. FIGURE 3.12 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.

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**.

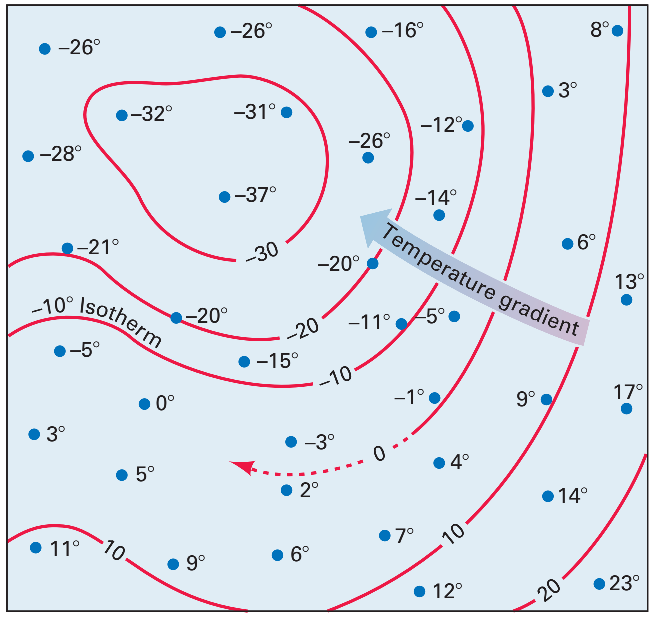
In the winter, isotherms dip equatorward, while in the summer, they arch poleward (FIGURE 3.13). FIGURE 3.14 provides a map of the annual range in temperature, which is greatest in northern latitudes between 60 and 70 degrees.

Isotherm Line on a map drawn through all points with the same temperature.

Temperature gradient Rate of temperature change along a selected line or direction.

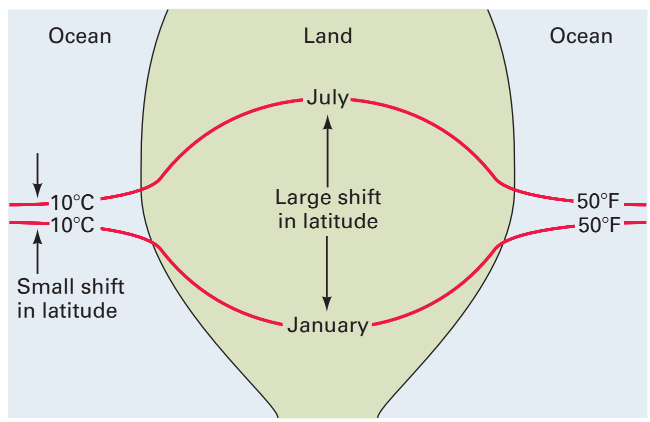
FACTORS CONTROLLING AIR TEMPERATURE PATTERNS

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



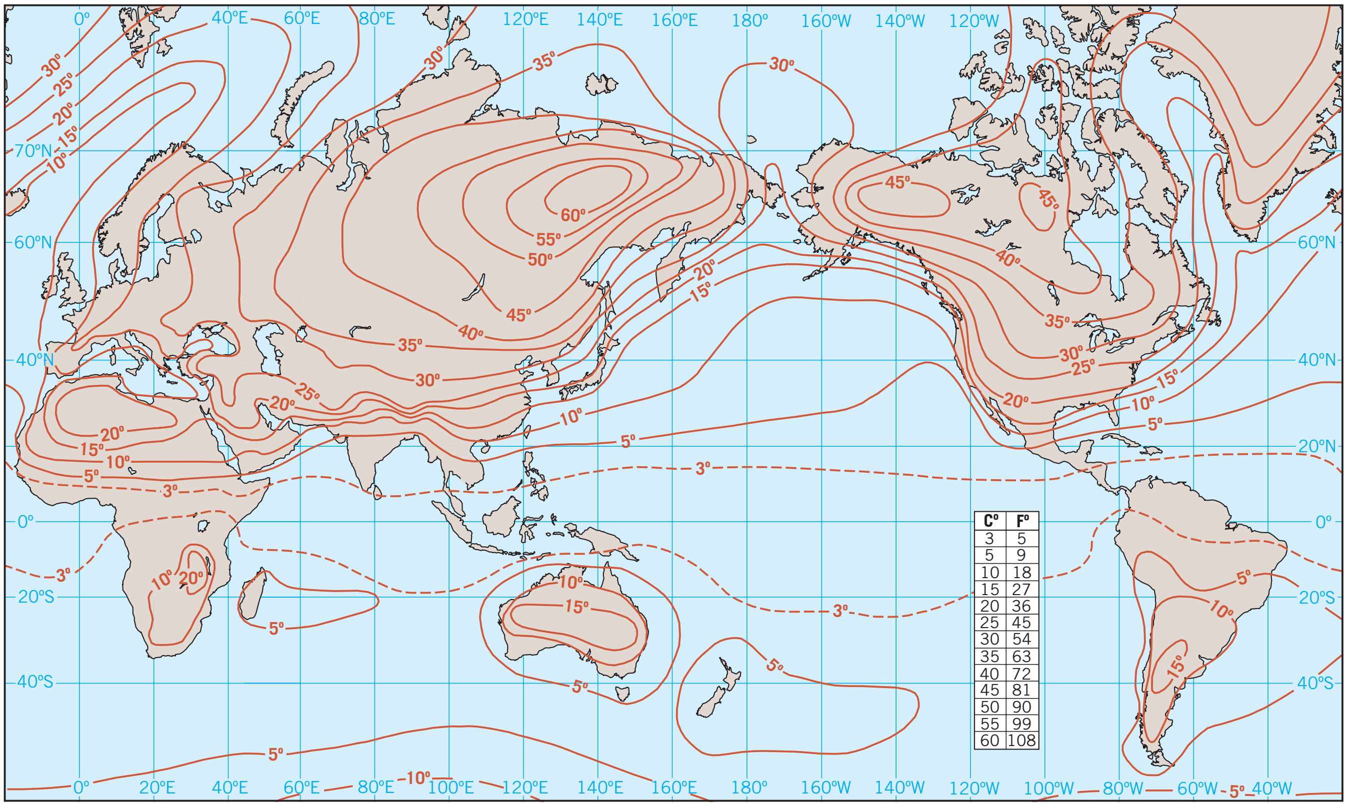
Isotherms FIGURE 3.12

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.



Seasonal migration of isotherms FIGURE 3.13

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.



Annual range of air temperature in Celsius degrees FIGURE 3.14

This figure shows the annual range of air temperature, defined as the difference between January and July means. The inset box shows the conversion of Celsius degrees to Fahrenheit for each isotherm value.

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.

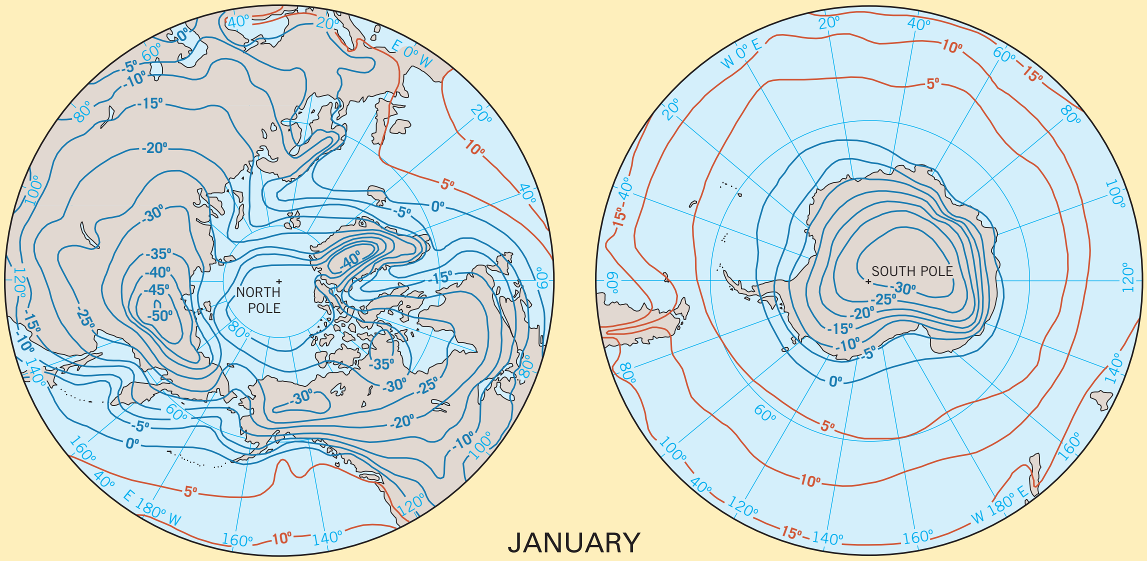
Elevation is the third important factor. At higher elevations, temperatures will be cooler, so we expect to see lower temperatures near mountain ranges.

WORLD AIR TEMPERATURE PATTERNS FOR JANUARY AND JULY

In this section, we'll look at world temperature maps for two months, January and July. First we'll examine polar projections (FIGURE 3.15) for these two months, then Mercator projections (FIGURE 3.16). Polar maps show higher latitudes well, while Mercator maps are best for illustrating trends from the equator to the midlatitude zones. From the maps, we can make some important points about the temperature patterns.

Look at Figures 3.15 and 3.16. What are the six important features that we can learn by comparing temperature maps from January and July?

Mean monthly air temperatures for January and July, polar projections FIGURE 3.15

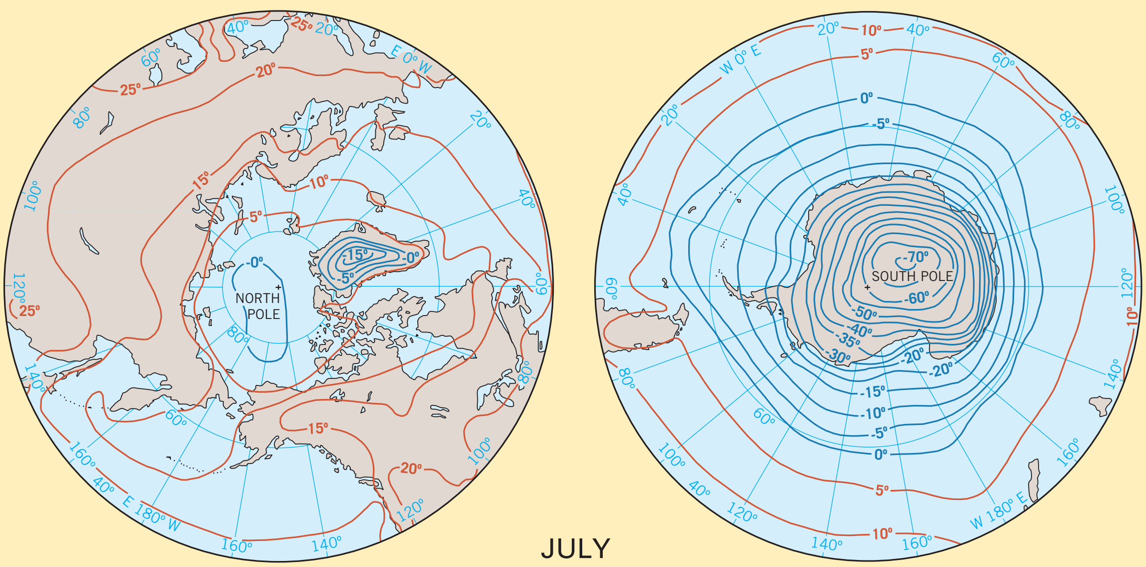


JANUARY

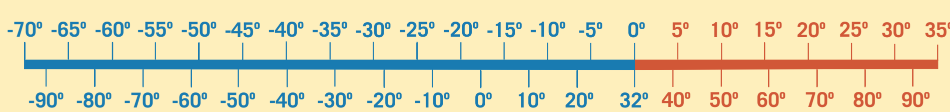
Large land masses located in the subarctic and Arctic zones dip to extremely low temperatures in winter. Look at North America and Eurasia on the January north polar map. These low-temperature centers are very clear. The cold center in Siberia, reaches −50°C (−58°F), while northern Canada is also quite 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, the white snow surfaces reflect much of the insolation.

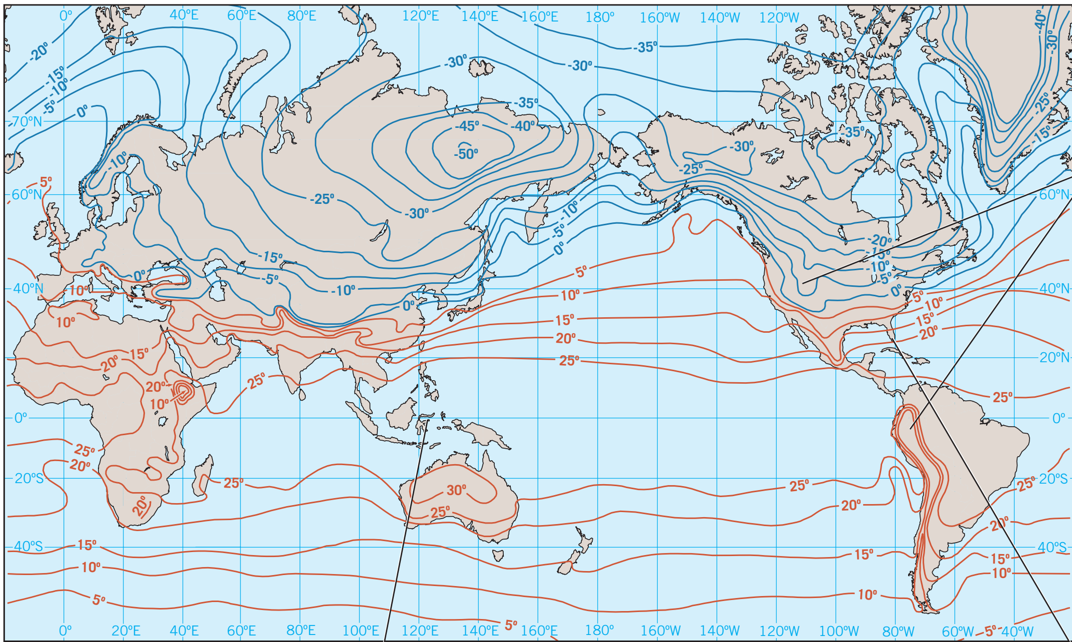


JULY



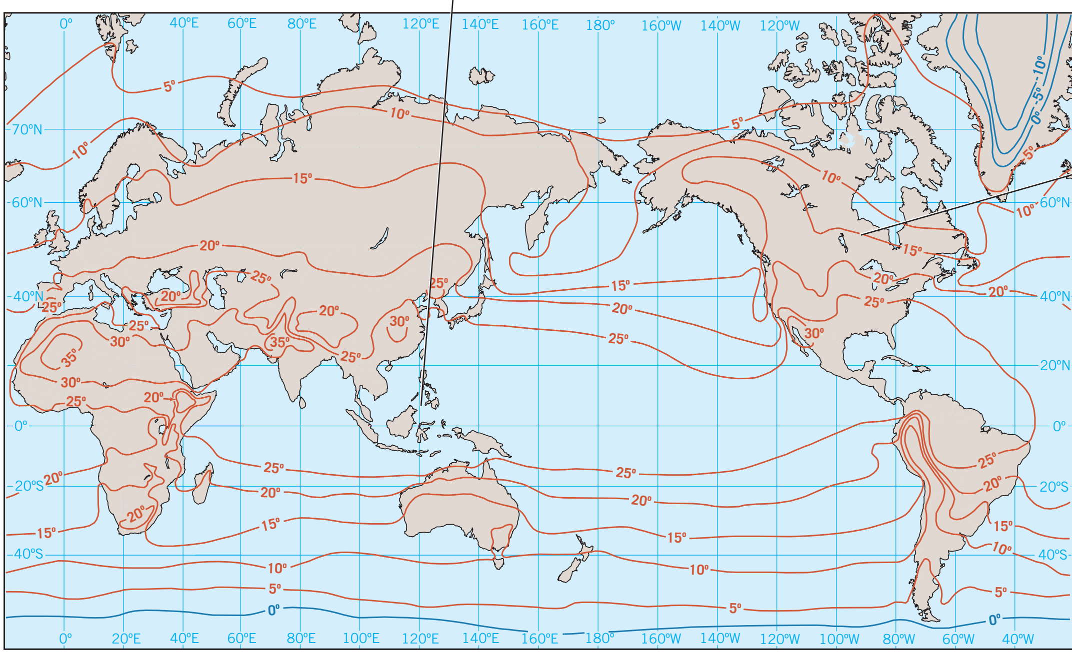
Mean monthly air temperatures for January and July, Mercator projections FIGURE 3.16

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, and at the northern end of the Andes Mountains in South America on the Mercator maps. In both summer and winter, the isotherms dip down around the mountains because of the high elevation.



JANUARY

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.



JULY

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.

CONCEPT CHECK STOP

What is an isotherm? Why are isotherms useful?

Temperature Structure of the Atmosphere

LEARNING OBJECTIVES

Define the different layers of the atmosphere.

Describe how temperature varies between these layers.

Explain what aerosols are, and why they are important.

We have looked at air temperature patterns across the globe pretty thoroughly. But what happens farther up in the sky? We noticed that air temperatures decrease as you climb mountains to higher elevations. Does that pattern extend upward into our atmosphere (FIGURE 3.17)?

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.

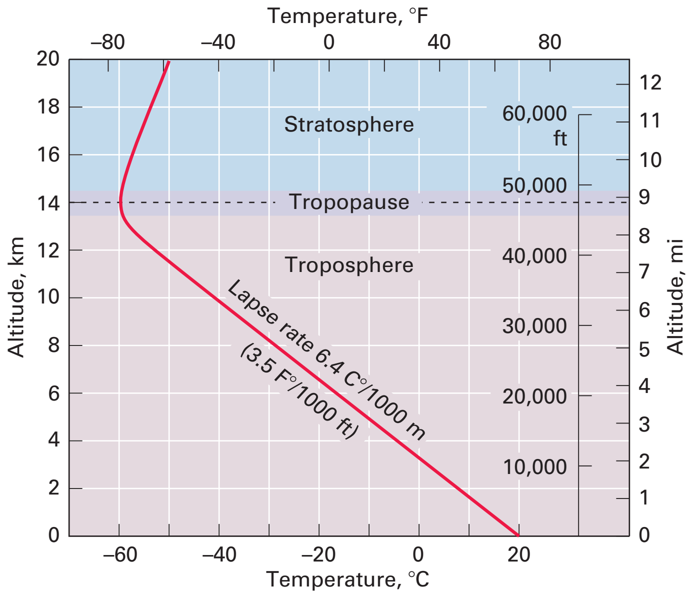
We call the decrease in air temperature with increasing altitude the **lapse rate**. We measure the temperature drop in degrees C per 1000 m (or degrees F per 1000 ft). FIGURE 3.18 shows how temperature varies with altitude for a typical summer day in the midlatitudes. Temperature drops at an average rate of 6.4°C/1000 m (3.5°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.

Lapse rate Rate at which air temperature drops with increasing altitude.

The atmosphere

FIGURE 3.17

The Earth's atmosphere, shown here in profile, is a thin layer surrounding our planet. In the lower layer of clouds and weather (troposphere), air temperatures decrease with height.



A typical atmospheric temperature curve for a summer day in the midlatitudes FIGURE 3.18

Temperature decreases with altitude in the troposphere. The rate of temperature decrease with elevation, or lapse rate, is shown at the average value of 6.48°C/1000 m (3.58°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.

FIGURE 3.18 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 Lowest layer of the atmosphere, in which temperature falls steadily with increasing altitude.

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 Tiny particles present in the atmosphere, so small and light that the slightest air movements keep them aloft.

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 above it 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

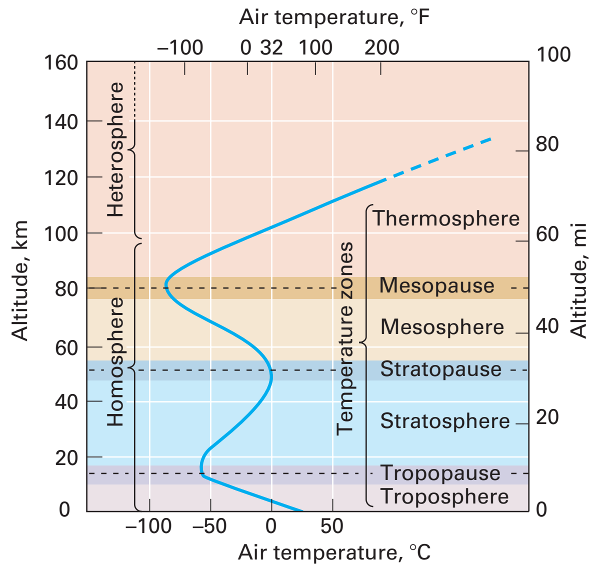
The **stratosphere** lies above the tropopause. Air in the stratosphere becomes slightly warmer as altitude increases. The stratosphere reaches up to roughly 50 km (about 30 mi) above the Earth's surface. It is the home of strong, persistent winds that blow from west to east. Air doesn't really mix between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

> **Stratosphere** Layer of atmosphere directly above the troposphere; here temperature slowly increases with height.

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 3.19. 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*.



Temperature structure of the upper atmosphere FIGURE 3.19

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

CONCEPT CHECK STOP

What are the names of the layers of the atmosphere as defined by temperature?

In general, how does temperature change with elevation? What are the exceptions to this?

What are aerosols? Why are they important?

Global Warming and the Greenhouse Effect

LEARNING OBJECTIVES

Describe the factors that contribute to global warming.

Explain how we know that global temperatures are increasing.

Describe the possible impact of global warming in the future.

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."

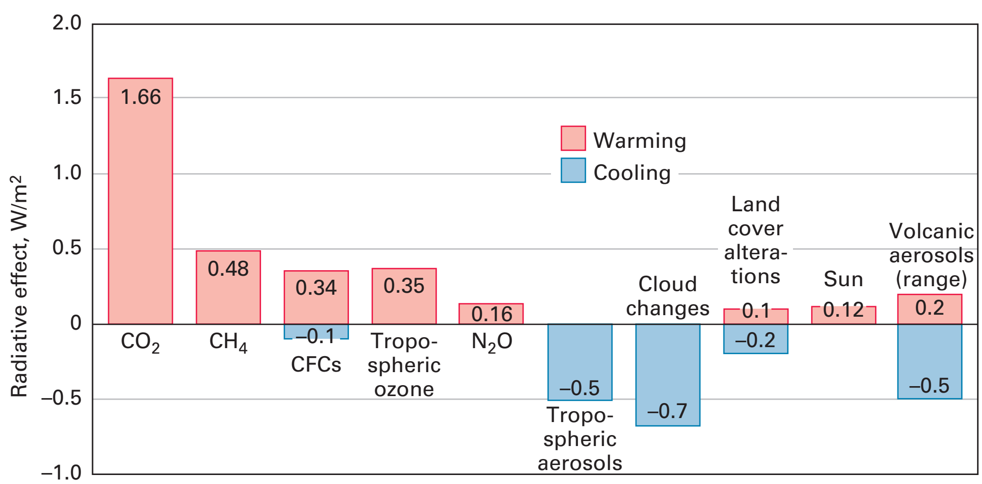
Is this recent warming an effect of human activity? In 1995 the IPCC concluded that human activity has probably caused climatic warming by increasing the concentration of greenhouse gases in the atmosphere. This judgment, which was upgraded to "likely" in 2001 and "very likely" in 2007, was based largely on computer simulations showing 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

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 3.20 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 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



Factors affecting global warming and cooling FIGURE 3.20

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.

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 3.20, 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.

The last two factors in FIGURE 3.20 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

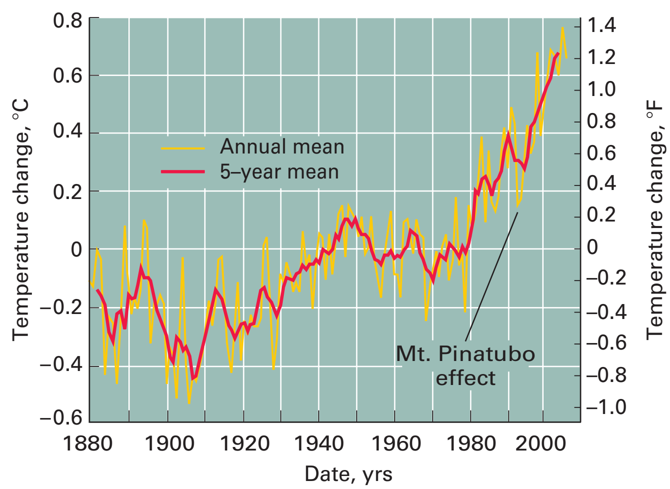
When we add all these factors together, the warming effects of the greenhouse gases outweigh the cooling effects. The result is a net warming effect of about 1.6 W/m^2, which is about 2/3 of 1 percent of the total solar energy flow absorbed by the Earth and atmosphere. Has this made global temperatures 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 1880 to 2006 is shown in FIGURE 3.21. We can see that temperature has increased, especially in the last fifty 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 3.21.

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 3.22).

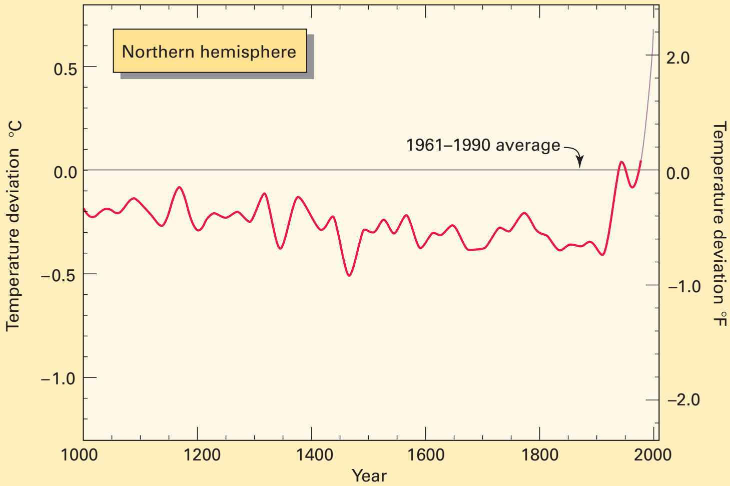
In climates with distinct seasons, trees grow annual rings. For trees along the timberline in North America, the ring width is related to temperature—the trees grow better when temperatures are warmer. Since only one



Mean annual surface temperature of the Earth, 1880–2006 FIGURE 3.21

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.

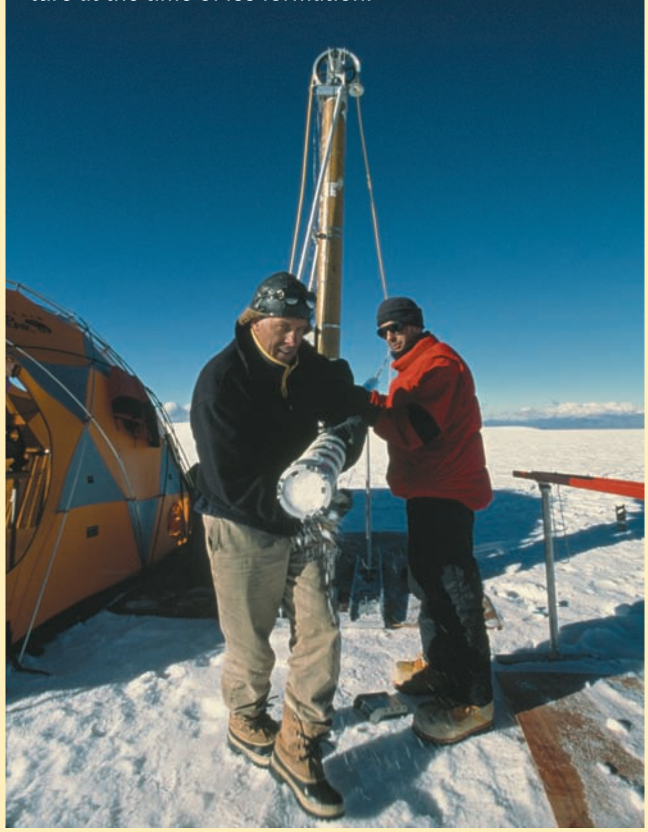
Reconstructing temperature records FIGURE 3.22

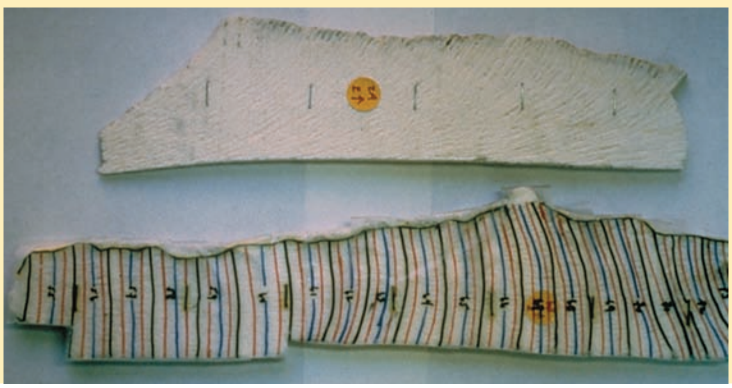


◀ **Temperature variation over the last thousand years** As compared to the reference temperature of the 1961–1990 average, northern hemisphere temperatures trended slightly downward until the beginning of the twentieth century. The line shown is a 40-year moving average obtained from thermometers, historical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

▲ **Tree rings** The width of annual tree rings varies with growing conditions and in some locations can indicate air temperature.

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.





◀ **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.

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.

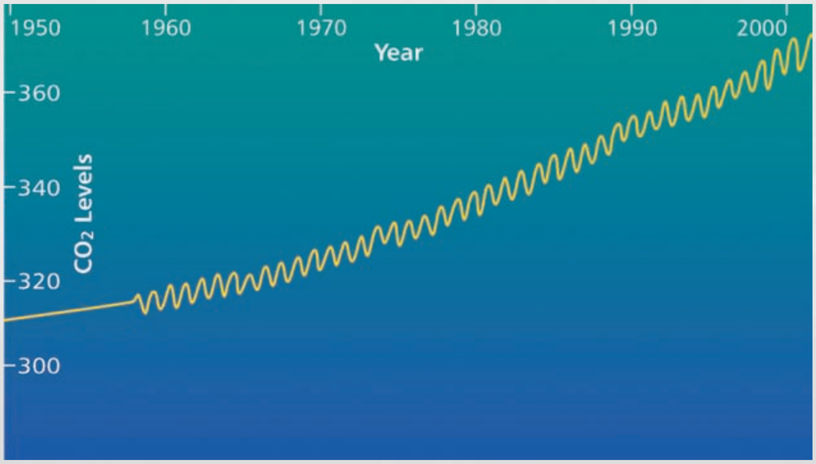
Corals, which survive for hundreds of years, are another living record of past temperatures. As they grow, coral skeletons take up trace elements and atomic isotopes that depend on the temperature of the water.

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

Visualizing
Global Warming

GLOBAL WARMING

Air temperatures are slowly rising as our world warms.



▲ **CO_2 levels are rising** Carbon dioxide levels have been steadily rising since the beginning of the Industrial Revolution. These observations, made at Mauna Loa, Hawaii, show both the rising trend and an annual cycle related to vegetation activity.

▲ **Sea level rise** rising sea levels could drown coral atolls or swamp low islands.

▲ **Arctic thawing** Longer summers and warmer winters could disrupt native people's way of life.

▲ **Habitat loss** Global warming will change habitats and ecosystems around the globe. The risk of habitat loss is greatest at transitional areas, such as the northern and southern boundaries of the boreal forest in North America and Eurasia.

WARMING WORLD

Earth is warming very rapidly at present. Most scientists agree that emissions of CO_2 and other compounds by power plants, factories, and vehicles have enhanced the atmosphere's greenhouse effect, leading to excess warming. Predicted consequences include the loss of boreal forest, more malaria cases, and displacement of peoples by rising sea levels.

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 of Space Science. 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, 1998, 2002, 2003, and 2006 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 calls on 38 industrial nations to reduce their greenhouse gas emissions to about 5 percent below 1990 levels. Nations of the European Union, the United States, and Japan are to reduce average emissions during 2008 and 2012 to levels that are 6, 7, and 8 percent lower, respectively, than 1990 levels. Achieving these reductions could have economic consequences ranging from minor to severe, depending on the analysis.

In 1998, the participating nations met in Buenos Aires and set timetables for greenhouse gas reduction in 1999–2010. The conference adopted a plan to allow countries to trade emission rights, as well as a "clean development" mechanism that permitted industrial nations to invest in emissions-reducing enterprises in developing countries. For the first time, some developing countries pledged specific greenhouse gas reductions of their own.

But this international effort suffered a setback in the spring of 2001, when President George W. Bush rejected American participation in the Kyoto Protocol. Despite this, 178 other nations pledged to join in the effort to reduce greenhouse gas emissions. In 2005, representatives of these nations met in Montreal to finalize the implementation plan for greenhouse gas reductions.

These actions are vital first steps to reducing human impact on global climate. But the ultimate solution will almost inevitably involve our finding ways to safely harness solar, wind, geothermal, and even nuclear energy sources, which produce power without releasing CO_2.

CONCEPT CHECK STOP

What are the main greenhouse gases? What role do they play in global warming?

How do we construct temperature records stretching back many centuries?

What are the risks if global warming continues to escalate?

What is happening in this picture?

These remarkable photos of the Portage Glacier, near Anchorage, Alaska, show a major recession of the glacier between 1950 and 2002. In the earlier photo, the glacier is easily visible in the middle of the image, its sloping surface descending to the meltwater lake in the foreground. By 2002, the sloping tongue of the glacier had retreated into the far background.

- Is the retreat of the Portage Glacier an effect of global warming? It is hard to say for certain that the retreat of an individual glacier is caused by global warming. For example, a drying climate rather than warming climate could reduce the amount of snow that feeds a glacier over a long period of time.
- But a very large number of alpine glaciers are presently retreating in locations ranging from the European Alps to Alaska to Patagonia. Many equatorial zone glaciers, such as those of Mount Kilimanjaro in Tanganyika, are also shrinking. Taken together, the conclusion that the Earth's alpine climates are warming is inescapable.

VISUAL SUMMARY

1 Surface and Air Temperature

1. Energy is transferred through the ground and to and from the air by radiation, conduction, latent heat transfer, and convection.

2. Rural surfaces heat and cool slowly. Urban surfaces easily absorb and emit heat.

3. Air temperatures generally decrease with elevation.

4. When air temperature increases with elevation, it is known as a temperature inversion.

2 Daily and Annual Cycles of Air Temperature

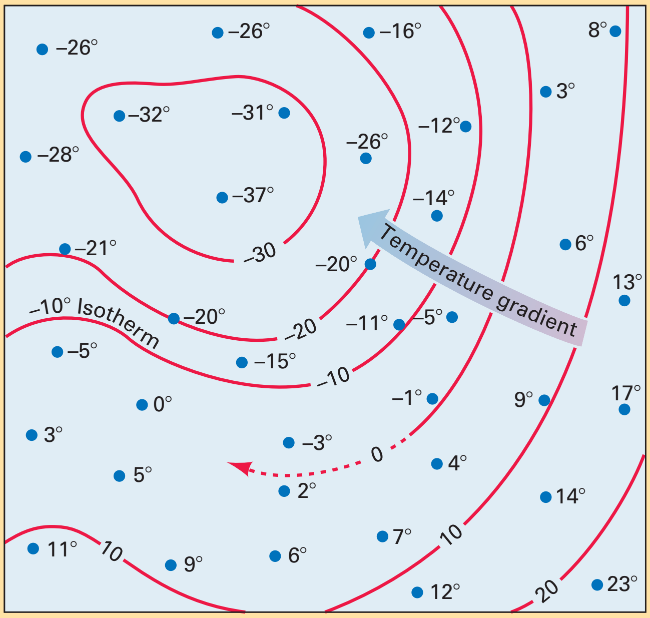
1. Daily and annual air temperature cycles are produced by the Earth's rotation and revolution, which create insolation and net radiation cycles.

2. Maritime locations show smaller ranges of both daily and annual temperature than continental regions. This is because water heats more slowly, absorbs energy throughout a surface layer, and can mix and evaporate freely.

3. Annual air temperature cycles are influenced by annual net radiation patterns, which depend on latitude.

3 World Patterns of Air Temperature

1. Temperatures at the equator vary little from season to season.
2. Poleward, temperatures decrease with latitude, and continental surfaces at high latitudes can become very cold in winter.
3. The annual range in temperature increases with latitude and is greatest in northern hemisphere continental interiors.

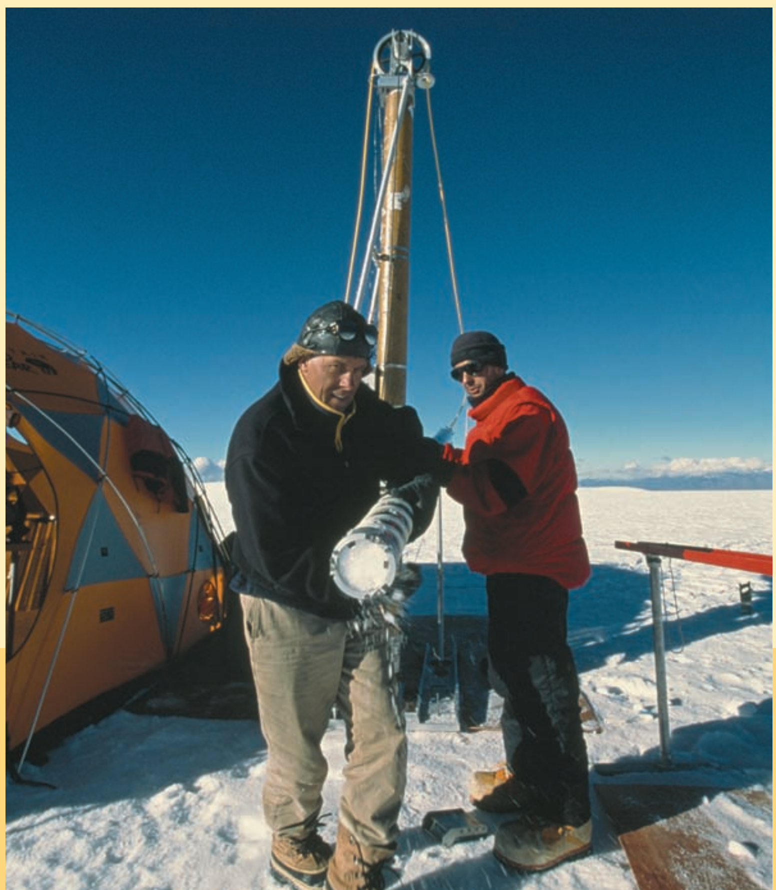


4 Temperature Structure of the Atmosphere

1. Air temperatures normally fall with altitude in the troposphere.
2. In the stratosphere below, temperatures increase slightly with altitude.

5 Global Warming and the Greenhouse Effect

1. Global temperatures have increased over the past few decades. CO_2 released by fossil fuel burning and other greenhouse gases plays an important role in causing warming.
2. Aerosols have a cooling effect because they scatter sunlight back to space and induce more low clouds.
3. A significant rise in global temperatures will be accompanied by increasing sea level.



KEY TERMS

- **transpiration** p. 66
- **evapotranspiration** p. 66
- **urban heat island** p. 66
- **temperature inversion** p. 70
- **isotherm** p. 76
- **temperature gradient** p. 76
- **lapse rate** p. 80
- **troposphere** p. 81
- **aerosols** p. 81
- **stratosphere** p. 82

CRITICAL AND CREATIVE THINKING QUESTIONS

1. How is heat transferred between the ground and the air directly above it? How is heat transferred within the ground? You should mention four processes.
2. Describe the changing conditions that you might notice as you climb higher up a mountain. Explain what causes each of these changes.
3. Explain how latitude affects the annual cycle of air temperature through net radiation by comparing Manaus, Aswan, Hamburg, and Yakutsk.
4. 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?
5. Describe and explain the following features on the maps in Figures 3.15 and 3.16: (a) How annual range varies with latitude; (b) where the greatest ranges occur; (c) how the annual range differs over oceans and over land at the same latitude; (d) the size of the annual range in tropical regions.
6. What are aerosols? How do they enter the atmosphere? Why are they important, in terms of climate?
7. 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 extreme.

SELF-TEST

1. Temperature is ______________.
   a. a measure of the level of sensible heat of matter
   b. only measured with a thermistor
   c. a measure of the level of latent heat of matter
   d. measured only through advection

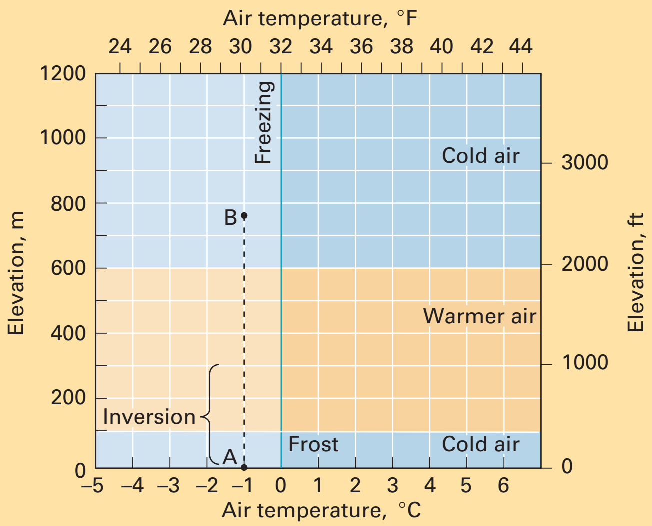
2. Heat in the atmosphere is distributed through a vertical mixing process called ______________.
   a. advection
   b. particle acceleration
   c. convection
   d. conduction

3. In the urban heat island, compared to parks and rural areas, ______________.
   a. downtown areas are warmer during the day and cooler at night
   b. downtown areas are cooler during the day and warmer at night
   c. downtown areas are always warmer
   d. downtown areas are always cooler

4. Urban surface temperatures tend to be warmer than rural temperatures during the day because ______________.
   a. drier surfaces are cooler than wet soils
   b. drier surfaces have less water to evaporate than do moist soils
   c. paved surfaces reflect so much heat away into the air
   d. paved surfaces absorb little solar insolation

5. The urban heat island effect is not a desert environment phenomenon because ______________.
   a. more transpiration is occurring in the city than in the surrounding country side
   b. the surrounding desert is hot too
   c. deserts cool the cities which they surround
   d. atmospheric mixing in the deserts is greater than in other environments

6. Sketch a line showing the relationship between air temperature and elevation in a low-level temperature inversion on the graph. What unwanted consequences can such an inversion have? How do people attempt to combat these effects?



7. Positive net radiation values usually commence ______________.
   a. at noon
   b. shortly after sunrise
   c. in the afternoon
   d. at night

8. Minimum daily temperatures usually occur ______________.
   a. just before sunrise
   b. at midnight
   c. one hour before sunrise
   d. about one-half hour after sunrise

9. Continental locations generally experience _______________ seasonal temperature variations than ocean adjacent locations.

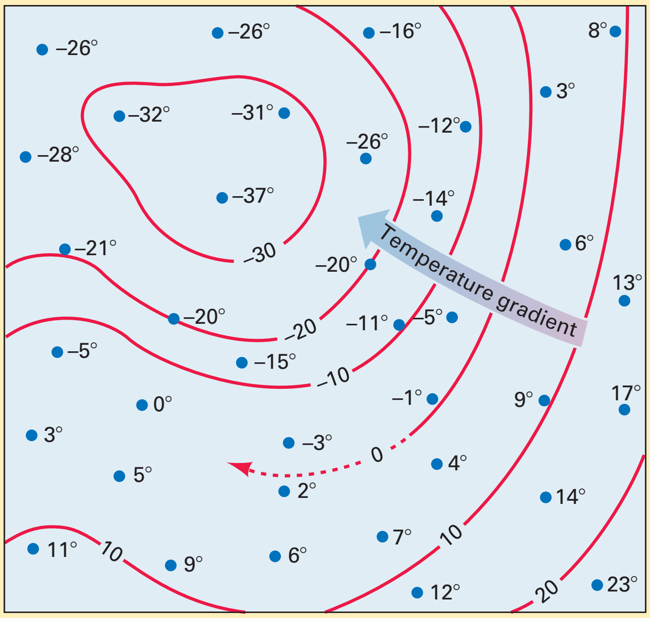
a. weaker
b. stronger
c. more stable
d. unstable

10. Since large bodies of water heat and cool more _______________ compared to land surfaces, monthly temperature maximums and minimums tend to be delayed at coastal stations.

a. slowly
b. rapidly
c. constantly
d. randomly

11. _______________ are lines of equal temperature drawn on a weather map.

a. Isohyets
b. Isobars
c. Isopachs
d. Isotherms



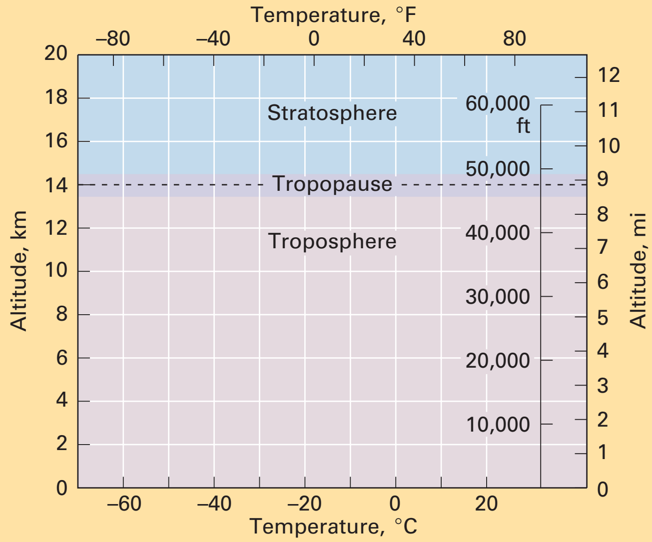
12. The defining characteristic of the troposphere is its _______________.

a. poorly mixed atmospheric gases
b. paucity of weather
c. environmental temperature lapse rate
d. precipitation lapse rate

13. Gases are well mixed in the _______________ region of the atmosphere.

a. homosphere
b. heterosphere
c. mesosphere
d. thermosphere

14. Air temperature changes with altitude in the atmosphere. On the graph, sketch a line showing how air temperature varies as you travel from the troposphere up to the thermosphere.



15. While greenhouse gases such as CO_2, CH_4, and N_2O act primarily to enhance global warming, _______________, cloud changes and land cover alterations caused by human activity act to retard global warming.

a. aerosols
b. chlorofluorocarbons
c. tropospheric ozone
d. water vapor

Atmospheric Moisture and Precipitation

4

Blink. In the instant that your eyes were closed there were 10 flashes of lightning in the Earth's atmosphere. Lightning is one of the most awesome displays in nature—both in terms of its beauty and its power.

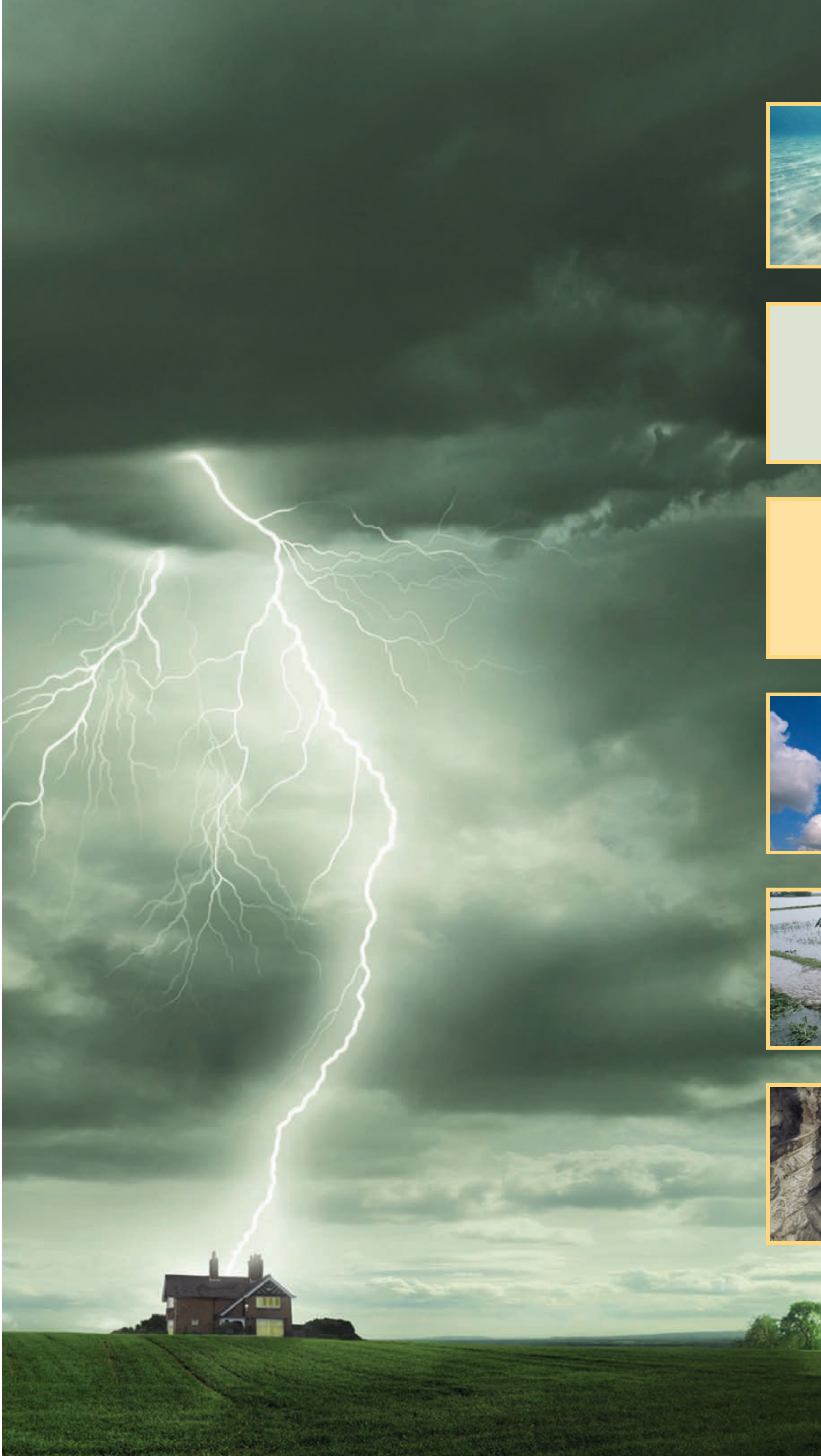
Approximately 90 percent of all lightning flashes are between clouds, but the remaining 10 percent shoot from the clouds to the Earth's surface. In fact, the Earth is struck by lightning about 100 times every second. And when it is, electricity flows between sky and ground, traveling at around a third of the speed of light and packing a punch of 60,000 to 100,000 amps—thousands of times as much as a household circuit.

A lightning bolt is actually an arc of atmospheric gas atoms that is heated as high as 27,000°C (50,000°F)—a temperature hotter than the surface of the Sun—as the current flows through it. The hot gas emits light as a flash and expands explosively to create the familiar crack of thunder.

It is no wonder that lightning is one of the most deadly natural phenomena. In an average year, more people are killed around the world by lightning than by tornadoes or hurricanes. An estimated 400 people survive lightning strikes in the United States annually. Around 200 other people struck by lightning every year do not survive. Between 1940 and 1991, lightning killed 8,316 people in the United States.

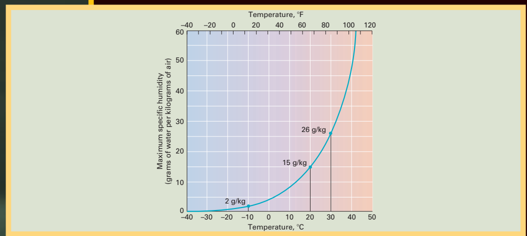
Lightning also presents science with one of its greatest mysteries. We still do not know exactly how lightning is caused. But if we hope to find the answer one day, we must look in depth at some of our atmosphere's most elusive processes.

Lightning strikes an isolated house near Inverness, Scotland.

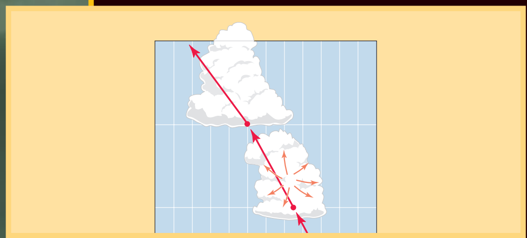


CHAPTER OUTLINE

- Water and the Hydrosphere p. 96



- Humidity p. 101



- The Adiabatic Process p. 103

- Clouds p. 106

- Precipitation p. 108

- Air Quality p. 116

Water and the Hydrosphere

Learning Objectives

Describe the three states of water.

Explain how water changes state.

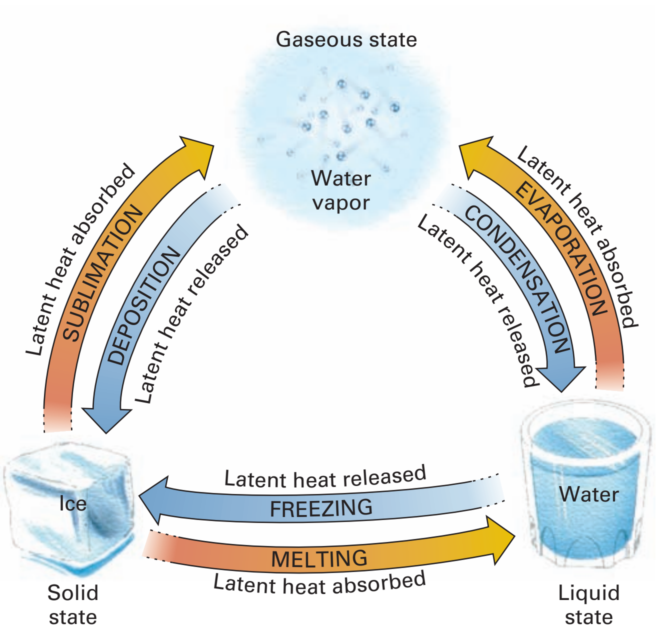
Define hydrosphere.

Explain what precipitation is.

THE THREE STATES OF WATER

Water can exist in three states—as a solid (ice), a liquid (water), or as an invisible gas (water vapor), as shown in FIGURE 4.1. If we want to change the state of water from solid to liquid, liquid to gas, or solid to gas, we must put 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. For example 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 bulk 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.



Three states of water FIGURE 4.1

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.

THE HYDROSPHERE

Hydrosphere Total water realm of the Earth's surface, including the oceans, surface waters of the lands, groundwater, and water held in the atmosphere.

The realm of water in all its forms, and the flows of water among ocean, land, and atmosphere, is known as the **hydrosphere**. About 97.5 percent of the hydrosphere consists of ocean salt water (FIGURE 4.2). The remaining 2.5 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 1.7 percent of total global water.

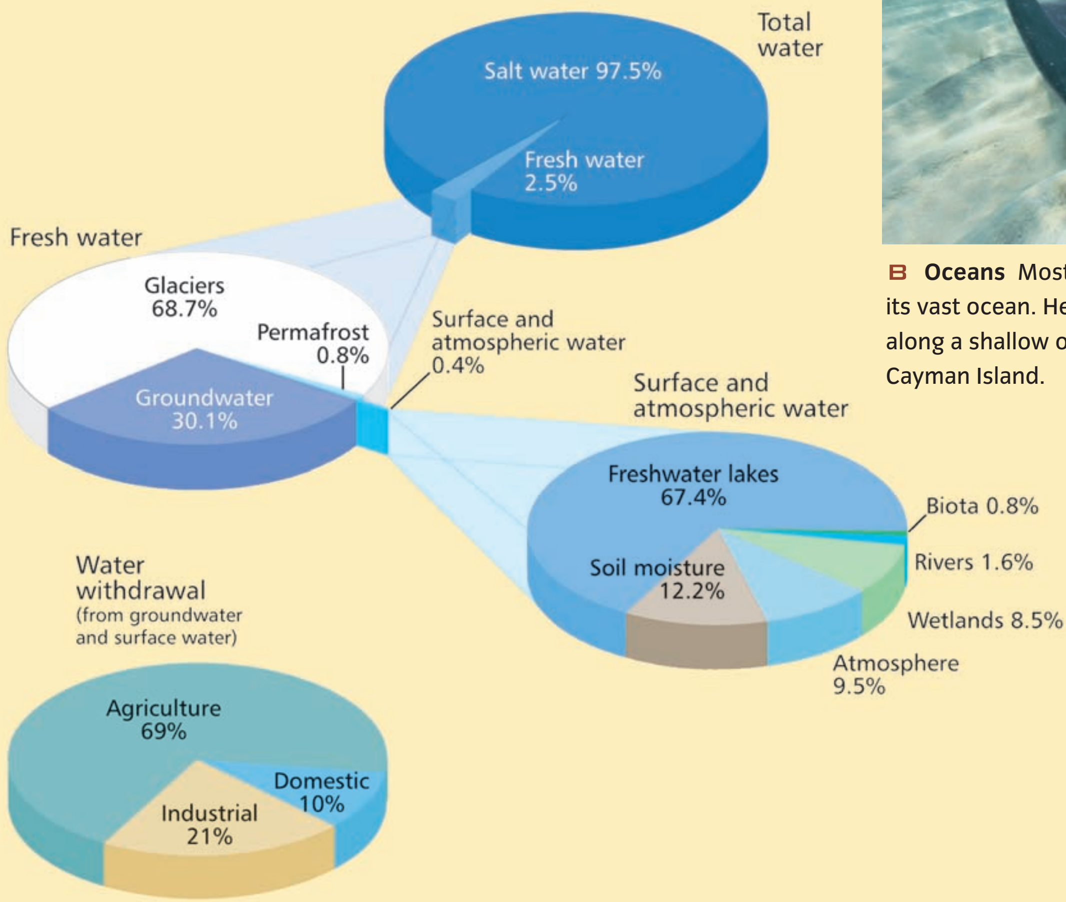
Fresh liquid water is found above and below the Earth's land surfaces. Subsurface water lurks in openings in soil and rock. Most of it is held in deep storage as groundwater, where plant roots cannot reach. Groundwater makes up 0.75 percent of the hydrosphere.

The small remaining proportion of the Earth's water includes the water available for plants, animals, and human use. Soil water is within the reach of plant roots. Surface water is held in streams, lakes, marshes, and swamps. Most of this surface water is in lakes, which are 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. But this small reservoir of

Water reservoirs of the hydrosphere FIGURE 4.2

A Distribution of water Nearly all the Earth's water is contained in the world ocean. Fresh surface and soil water make up only a small fraction of the total volume of global water.



B 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.

C 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.

D 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 a lake in search of tasty aquatic plants.

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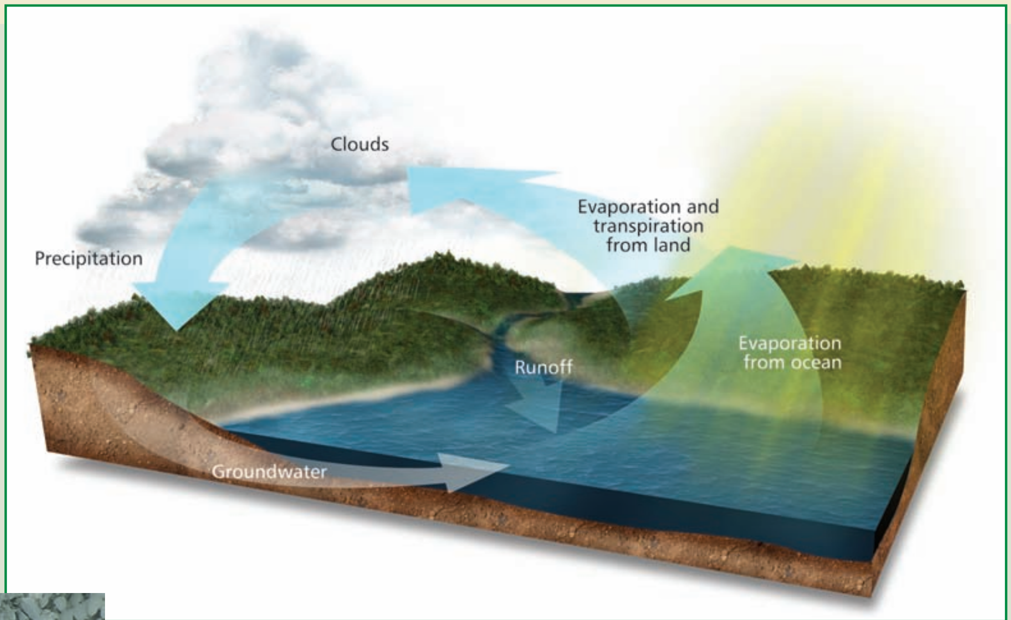
WATER CYCLE

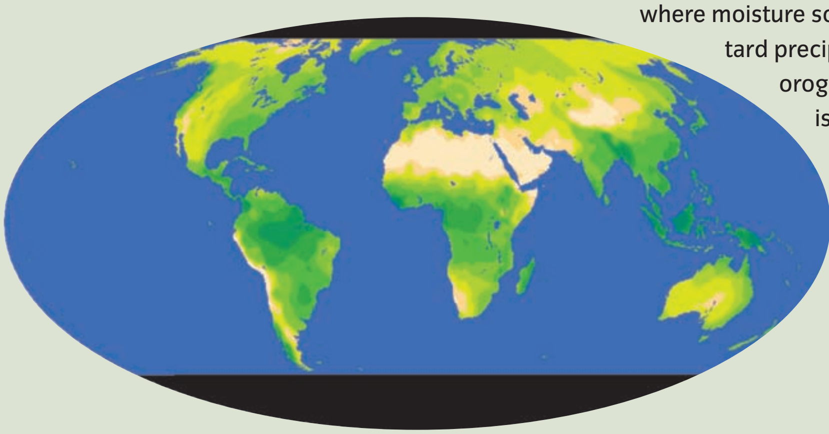
In the water cycle, solar-powered evaporation of water from ocean and moist land surfaces provides atmospheric water vapor that can ultimately fall as precipitation.

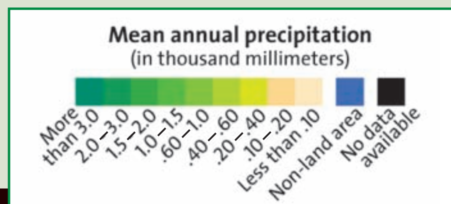
▶ **Water cycle** As the Sun warms the surface of the Earth, water rises from lakes, rivers, oceans, plants, the ground, and other sources. The vapor rises into the atmosphere, providing the moisture that forms clouds. It then returns to Earth in the form of rain, snow, sleet, and other precipitation. It fills lakes and wetlands, flows into rivers and oceans, and recharges underground water reserves. The process endlessly recycles the Earth's water.



◀ **Snow** Where air temperatures are low, precipitation falls as snow. This bison in Yellowstone National Park is well prepared for the region's cold weather.

▼ **Mean annual precipitation** At a global scale, rainfall is greatest in the equatorial regions, where abundant solar energy drives evaporation. The world's deserts, most visible here in a crescent from the Sahara to central Asia, occur where moisture sources are far away or where circulation patterns retard precipitation formation. Mountain chains generate orographic precipitation. At higher latitudes, precipitation is abundant where circulation patterns spawn cyclonic storms.

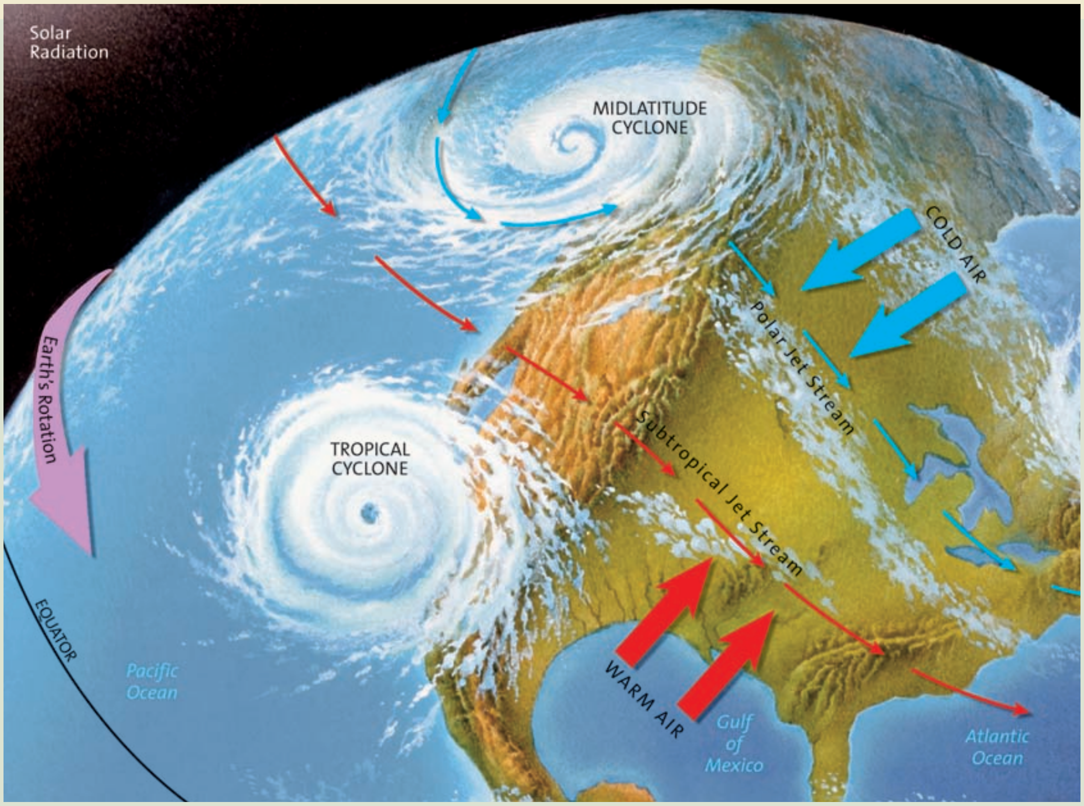




NATIONAL GEOGRAPHIC

GLOBAL CIRCULATION

Water vapor is carried far from its source by atmospheric circulation patterns. Where air currents converge together or rise over mountains, clouds and precipitation form.



◀ **Precipitation and global circulation** The circulation of the atmosphere mixes warm, moist air with cool, dry air in storm systems called cyclones. Where storms are abundant, so is precipitation.

▼ **Deserts** Most deserts are far from moisture sources or lie within the rain shadows of mountain ranges. A herd of camels crosses Australia's Simpson Desert.

◀ **Monsoon rainfall** In tropical and equatorial regions, rainfall can be abundant and in some regions has a strong seasonal cycle. Here rice farmers plant a new crop while sheltered by woven rain shields called *patlas*.

water is enormously important. As we will see later in the chapter, it supplies water and ice to replenish all freshwater stocks on land. And, in the next chapter, we will see that 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

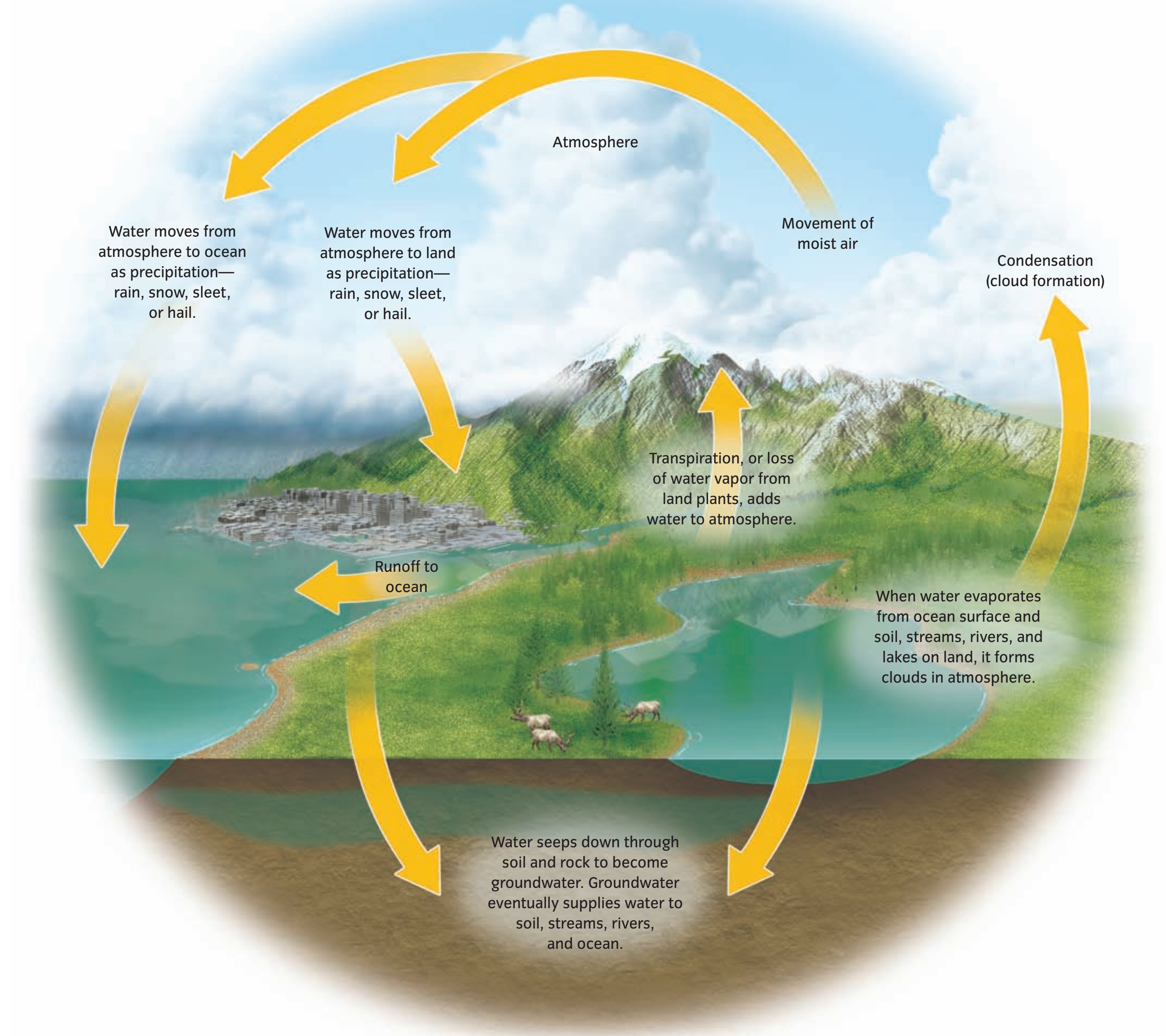
The *hydrologic cycle*, or water cycle, moves water from land and ocean to the atmosphere (FIGURE 4.3). Water from the oceans and from land surfaces evaporates, changing state from liquid to vapor and entering the atmosphere. Total evaporation is about six times greater over oceans than land because oceans cover most of the planet and because land surfaces are not always wet enough to yield much water.

Once in the atmosphere, water vapor can condense or deposit to form clouds and **precipitation**,

Precipitation
Particles of liquid water or ice that fall from the atmosphere and may reach the ground.

The hydrologic cycle FIGURE 4.3

In the hydrologic cycle, water moves among the ocean, the atmosphere, the land, and back to the ocean in a continuous process.



which falls to Earth as rain, snow, or hail. There is nearly four times as much precipitation over oceans than 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*.

CONCEPT CHECK **STOP**

What are the three states of water?

Describe the six processes through which water changes state.

In which processes is latent heat taken in? When is it released?

What is the hydrosphere?

What is precipitation?

Humidity

LEARNING OBJECTIVES

Define humidity.

Describe the difference between specific humidity and relative humidity.

Explain the importance of the dew-point temperature.

Blistering summer heat waves can be deadly, with the elderly and the ill at most risk. But even healthy young people need to be careful, especially in hot, humid weather. High humidity slows the evaporation of sweat from your body, reducing its cooling effect.

Humidity—a general term for the amount of moisture in the air— 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 4 or 5 percent of a given volume of air in the warm wet regions near the equator.

Humidity The amount of water vapor in the air.

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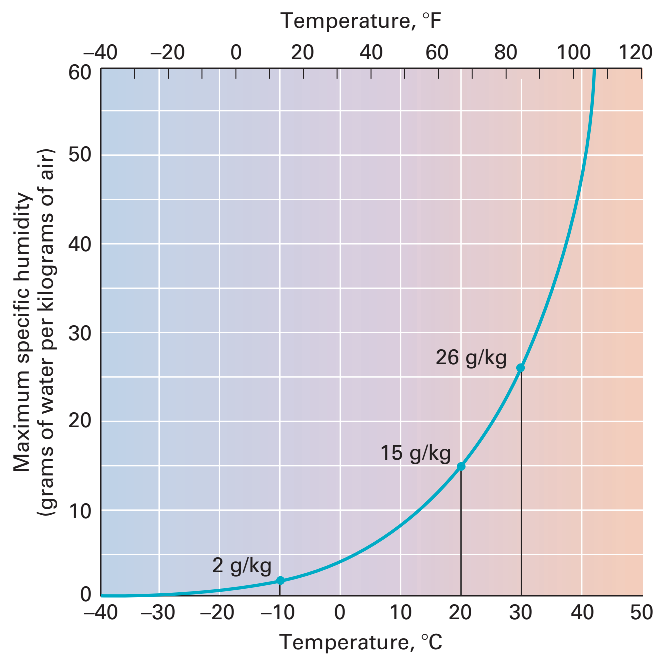
There is an important principle concerning humidity that states that the maximum quantity of moisture that can be held at any time in the air is dependent on air temperature (FIGURE 4.4).



Humidity and temperature FIGURE 4.4

The maximum specific humidity of a mass of air increases sharply with rising temperature.

Warm air can hold more water vapor than cold air—a lot more. Air at room temperature (20°C, 68°F) can hold about three times as much water vapor as freezing air (0°C, 32°F).

RELATIVE HUMIDITY

When radio or television weather forecasters speak of humidity, they are referring to relative humidity. This measure compares the amount of water vapor present to the maximum amount that the air can hold at that temperature. It is expressed as a percentage. So, for example, if the air currently holds half the moisture possible at the present temperature, then the relative humidity is 50 percent. When the humidity is 100 percent, the air holds the maximum amount possible. It is *saturated*.

The relative humidity of the atmosphere can change in one of two ways. First, the atmosphere can directly gain or lose water vapor. For example, additional water vapor can enter the air from an exposed water surface or from wet soil. This is a slow process because the water vapor molecules diffuse upward from the surface into the air layer above.

The second way is through a change of temperature. When the temperature is lowered, the relative humidity rises, even if no water vapor is added. This is because the capacity of air to hold water vapor depends on temperature. When the air is cooled, this capacity is reduced. The existing amount of water vapor will then represent a higher percentage of the total capacity.

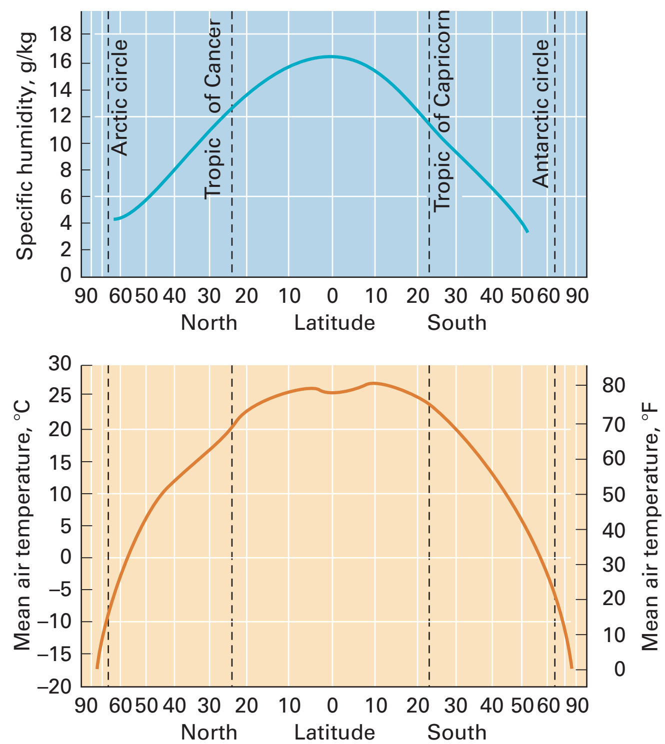
SPECIFIC HUMIDITY

The actual quantity of water vapor held by a parcel of air is known as its specific humidity and is expressed as grams of water vapor per kilogram of air (g/kg).

Climatologists often use specific *humidity* to describe the moisture in a large mass of air. Specific humidity is largest at the equatorial zones, and falls off rapidly towards the poles, as we can see in 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 holds as much as 18 g/kg. More insolation is available at lower latitudes to evaporate water in oceans or on moist land surfaces, so specific humidity values tend to be higher at low latitudes than at high latitudes.

We can see that the global profile of mean (average) surface air temperature, also shown in Figure 4.5, has a similar shape to the specific humidity profile. This is because air temperature and maximum specific humidity vary together.

Specific humidity is also the geographer's yardstick for a basic natural resource—water. It is a measure of the quantity of water in the atmosphere that can be extracted as precipitation. Cold, moist air can supply only a small quantity of rain or snow, but warm, moist air is capable of supplying large amounts.



Global specific humidity and temperature
FIGURE 4.5

Pole-to-pole profiles of specific humidity (above) and temperature (below) show similar trends because the ability of air to hold water vapor (measured by specific humidity) is limited by temperature.

Dew-point temperature Temperature at which air with a given humidity will reach saturation when cooled without changing its pressure.

Another way of describing the water vapor content of air is by its **dew-point temperature**. If air is slowly chilled, it will eventually reach saturation. At this temperature, the air holds the maximum amount of water vapor possible. If the air is cooled further, condensation will begin and dew will start to form. Moist air has a higher dew-point temperature than dry air.

CONCEPT CHECK STOP

What is humidity?

Define specific humidity and relative humidity.

What is the dew-point temperature?

The Adiabatic Process

LEARNING OBJECTIVES

Describe the adiabatic principle.

Explain the role of the adiabatic process in cloud formation.

What makes the water vapor held in the air turn into liquid or solid particles that can fall to 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 air's ability to hold water, forcing some water vapor molecules to change state to form water droplets or ice crystals.

One mechanism for chilling air is nighttime cooling. The ground surface can become quite cold on a clear night, as it loses longwave radiation. But this 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 a higher level in the atmosphere, as we will later see in more detail.

THE ADIABATIC PRINCIPLE

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 is an important law that states that when a gas expands, its temperature drops. And conversely, when a gas is compressed, its temperature increases. So as you pump vigorously, compressing the air, the metal bicycle pump gets hot. In the same way, when a small jet of air escapes from a high-pressure hose, it feels cool.

Adiabatic principle The physical principle that a gas cools as it expands and warms as it is compressed, provided that no heat flows in or out of the gas during the process.

Physicists use the term *adiabatic process* for a heating or cooling process that occurs solely as a result of a pressure change. That is, the change in temperature is not caused by heat flowing into or away from the air, but only by a change in pressure.

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. So, as a parcel of air is uplifted, atmospheric pressure on the parcel becomes lower, and it expands and cools. As a parcel of air descends, atmospheric pressure becomes higher, and the air is compressed and warmed (FIGURE 4.6).

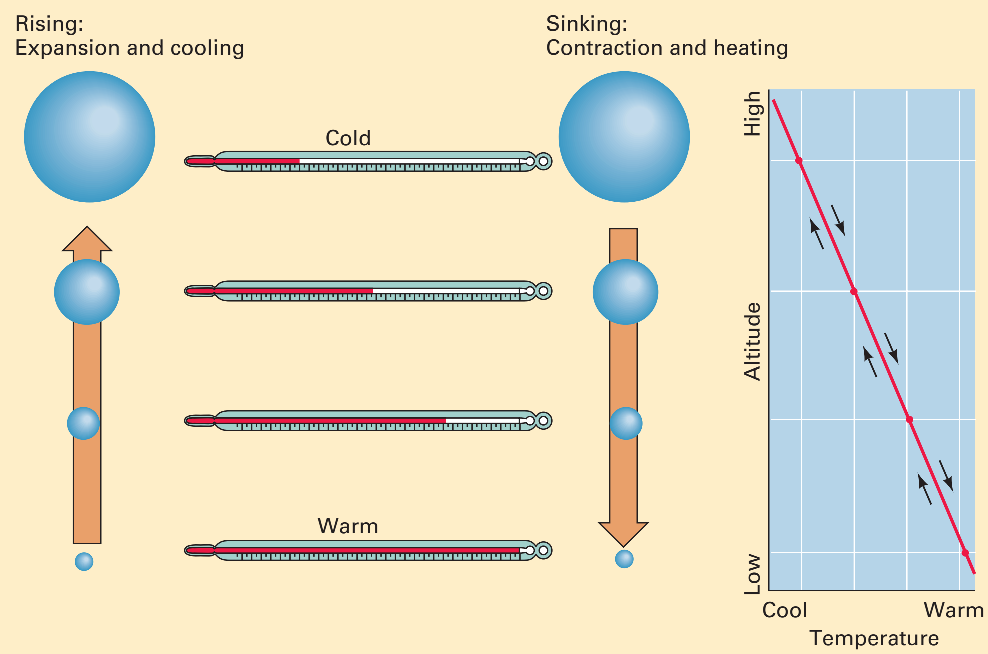
We describe this behavior using the **dry adiabatic lapse rate** for a rising air parcel that has not reached saturation. This rate has a value of about 10°C per 1000 m (5.5°F per 1000 ft) of vertical rise. That is, if a parcel of air is raised 1 km, its temperature will drop by 10°C. Or, in English units, if raised 1000 ft, its temperature will drop by 5.5°F. This is the "dry" rate because there's no condensation.

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).

In the previous chapter we met the *environmental temperature lapse rate*. There's an important difference to note between the environmental temperature lapse rate and the dry adiabatic lapse rate. The temperature lapse rate simply expresses how the temperature of still air varies with altitude. This rate varies 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 rate applies to a mass of air in vertical motion. It is determined by physical laws and not the local atmospheric state.

The adiabatic process is responsible for cloud formation. As we see in the process diagram, once an air parcel reaches saturation, it cools at a different rate, known as the wet adiabatic lapse rate. Unlike the dry adiabatic lapse rate, which remains constant, the **wet adiabatic lapse rate** is variable because it depends on the temperature and pressure of the air and its moisture content. But for most situations we can use a value of 5°C/1000 m (2.7°F/1000 ft). In the process diagram, the wet adiabatic rate is shown as a slightly curving line to indicate that its value increases with altitude.

Wet adiabatic lapse rate Rate at which rising air is cooled by expansion when condensation is occurring; ranges from 4 to 9°C per 1000 m (2.2 to 4.9°F per 1000 ft).



Adiabatic cooling and heating FIGURE 4.6

When air is forced to rise, it expands and its temperature decreases. When air is forced to descend, its temperature increases.

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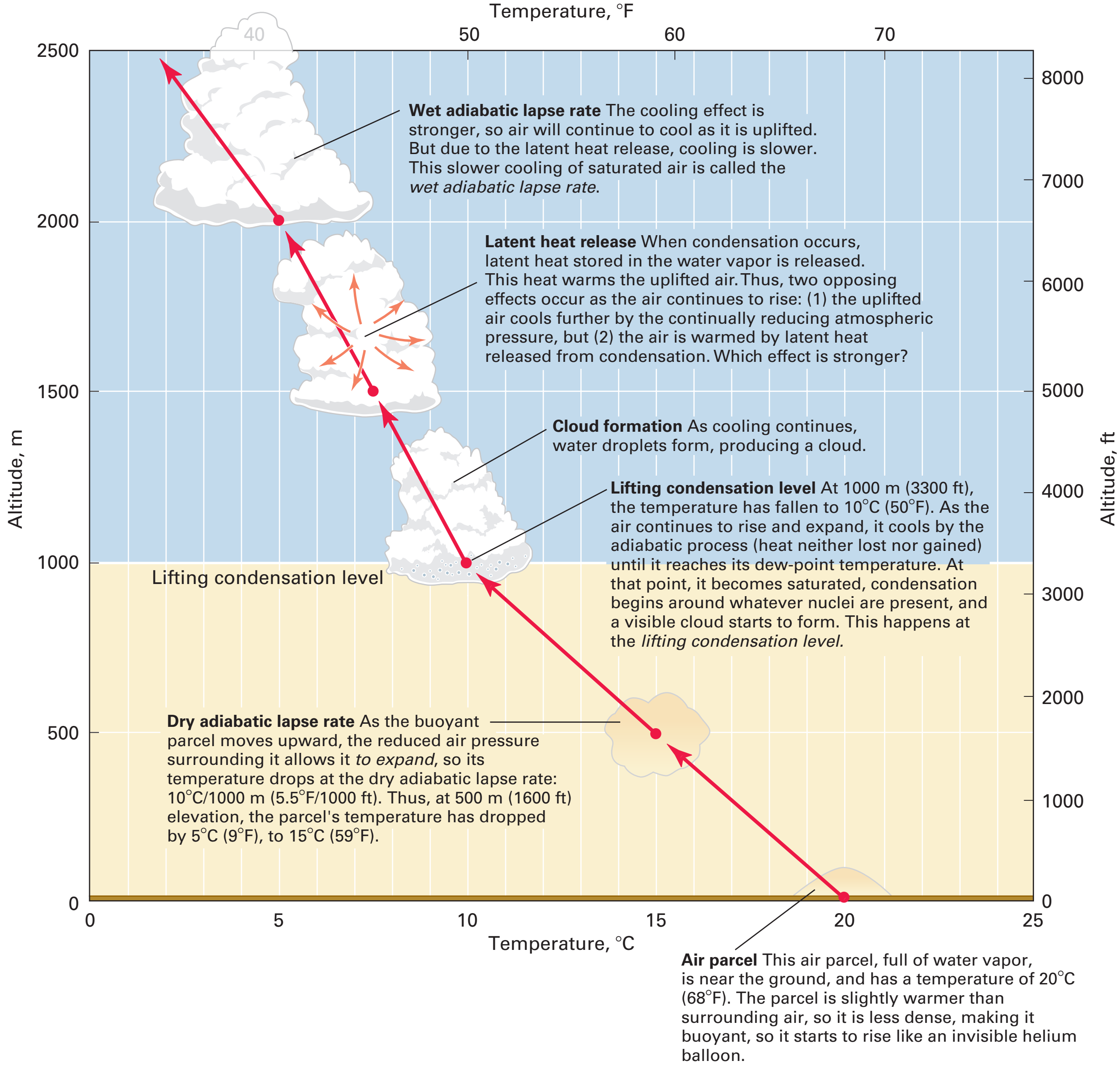
Process Diagram

Cloud formation and the adiabatic process



CONCEPT CHECK **STOP**

What is the adiabatic principle?

How is the adiabatic process involved in cloud formation?

What is the difference between the dry and wet adiabatic lapse rate?

Clouds

LEARNING OBJECTIVES

Explain how condensation nuclei help clouds to form.

Describe how clouds are classified.

Explain what fog is.

Images of Earth from space show that about half of our planet is blanketed in cloud. Clouds play a complicated temperature role—both cooling and warming the Earth and atmosphere. In this chapter, we will look at one of the most familiar roles of clouds—producing precipitation.

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 and 0.002 in.) in diameter. Cloud particles require a tiny center of solid matter to grow around. Such a speck of matter is called a **condensation nucleus**, and would typically have a diameter between 0.1 and 1 μm (0.000004 and 0.00004 in.).

Condensation nucleus A tiny bit of solid matter (aerosol) in the atmosphere on which water vapor condenses to form a tiny water droplet.

The surface of the sea is an important source of condensation nuclei (FIGURE 4.7). Droplets of spray from the crests of the waves are carried upward by turbulent air. When these droplets evaporate, they leave behind a tiny residue of salt suspended in the air. This aerosol strongly attracts water molecules, helping begin 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. 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 grow colder, ice crystals begin to appear.

Ocean aerosols FIGURE 4.7

Breaking or spilling waves in the open ocean, shown here from the deck of a ship, are an important source of aerosols.

The coldest clouds, with temperatures below −40°C (−40°F), occur at altitudes of 6 to 12 km (20,000 to 40,000 ft) and are made up entirely of ice particles.

CLOUD FORMS

Anyone who has looked up at the sky knows that clouds come in many shapes and sizes (FIGURE 4.8). They range from the small, white puffy clouds often seen in summer to the gray layers that produce a good, old-fashioned rainy day. Meteorologists classify clouds into four families, arranged by their height in the sky. They are called: high, middle, and low clouds, and clouds with vertical development.

We group clouds into two major classes—stratiform, or layered clouds, and cumuliform, or globular clouds. *Stratiform clouds* are blanket-like and cover large areas. A common type is stratus, which covers the entire sky.

Cloud gallery FIGURE 4.8

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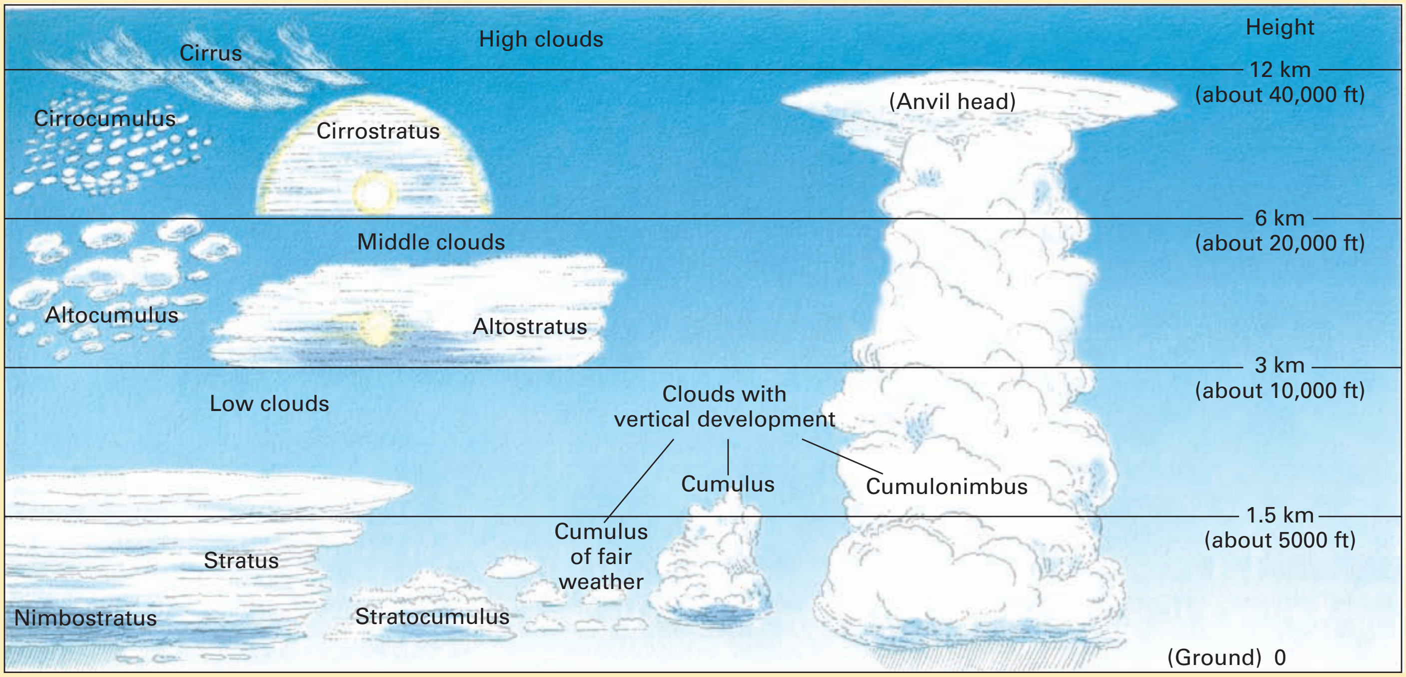
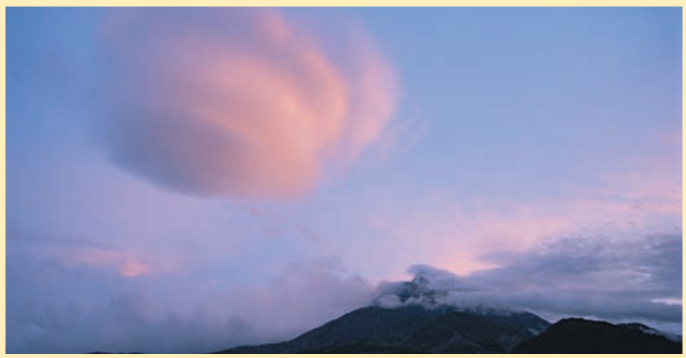
A Cloud families and types Clouds are grouped into families on the basis of height. Individual cloud types are named according to their form.

Classification of clouds according to height and form



B 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.

C Lenticular cloud A lenticular, or lens-shaped, cloud forms as moist air flows up and over a mountain peak or range.



D Cumulus Puffy, fair-weather cumulus clouds fill the sky above a prairie.

E Altocumulus High cumulus clouds, in a pattern sometimes called a *mackerel sky*, as photographed near sunset in Boston.

Dense, thick stratiform clouds can produce large amounts of rain or snow.

Cumuliform clouds are globular masses of cloud that are associated with small to large parcels of rising air. The most common cloud of this type is the cumulus cloud. They can be dense, tall clouds that can produce thunderstorms. This form of cloud is the cumulonimbus. ("Nimbus" is the Latin word for rain cloud, or storm.)

FOG

Fog is simply a cloud layer at or very close to the Earth's surface. However, fog is not formed in quite the same way as clouds in the sky.

One type of fog, known as *radiation fog*, is formed at night when the temperature of the air layer at the ground level falls below the dew point. This kind of fog is associated with a low-level temperature inversion. 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. This *sea fog* is frequently found along the California coast. It forms within a cool marine air layer in direct contact with the colder water of the California current.

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.

CONCEPT CHECK **STOP**

What are condensation nuclei? How do they help clouds form?

How are clouds classified? Name four cloud families, two broad cloud forms, and three specific cloud types.

What is fog?

Precipitation

LEARNING OBJECTIVES

Describe what causes precipitation.

Name the four types of precipitation processes and describe their differences.

Explain the conditions that cause thunderstorms.

Depending on the circumstances, precipitation can be a welcome relief, a minor annoyance, or a life-threatening hazard (FIGURE 4.9). Whether a source of relief or hazard, precipitation provides the fresh water essential for most forms of terrestrial life.

In warm clouds, raindrops form by condensation and grow by collision. The process diagram explains this process.

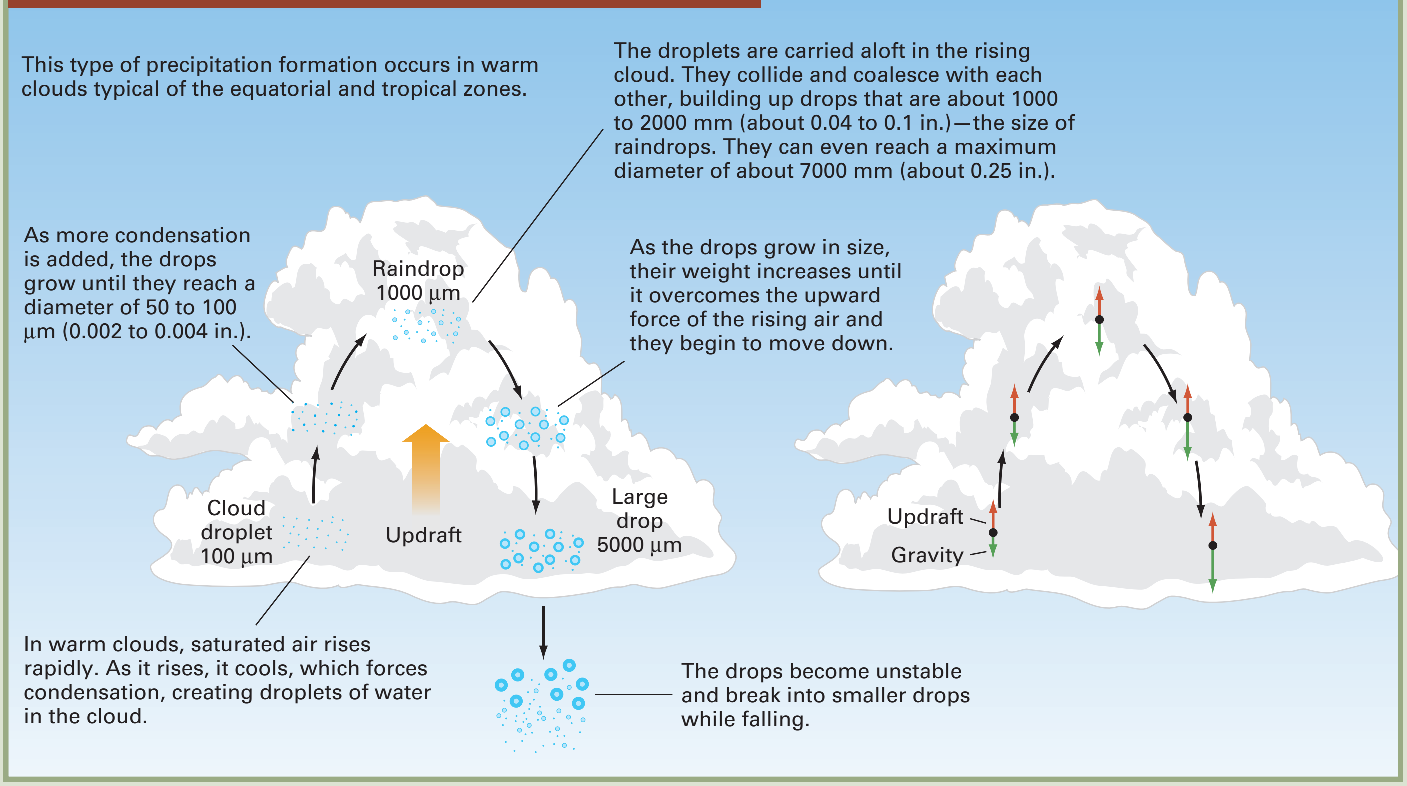
Snow is formed within cool clouds, which are a mixture of ice crystals and supercooled water droplets. The ice crystals take up water vapor and grow by deposition. At the same time the supercooled water droplets lose water vapor by evaporation and shrink. When an ice crystal collides with a droplet of supercooled water, it freezes the droplet. The ice crystals then coalesce to form snow particles, which can become heavy enough to fall from the cloud. Snowflakes formed entirely by deposition can have intricate crystal structures but most particles of snow have endured collisions and coalesce with each other, losing their shape and becoming simple lumps of ice.

Precipitation FIGURE 4.9

Monsoon rains drench refugees crossing a flooded field in Bangladesh.

By the time this precipitation reaches the ground, it may have changed form. When raindrops fall through a cold air layer, they freeze into pellets or grains of ice. When snow falls through a warm layer, it melts and arrives as rain.

Rain formation in warm clouds



Process Diagram

Perhaps you have experienced an *ice storm* (FIGURE 4.10). Ice storms occur when the ground is frozen and the lowest air layer is also below freezing. 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.

Hail is another common type of precipitation. It consists of pea-sized to grapefruit-sized lumps of ice—that is, with a diameter of 5 mm (0.2 in.) or larger. We will discuss how hail is produced in the section on thunderstorms.

We talk about precipitation in terms of the depth that falls during a certain time. So, for example, we use centimeters or inches per hour or per day. A centimeter (inch) of rainfall would cover the ground to a depth of 1 cm (1 in.) if the water did not run off or sink into the soil.

Snowfall is measured by melting a sample column of snow and reducing it to an equivalent in rainfall. In

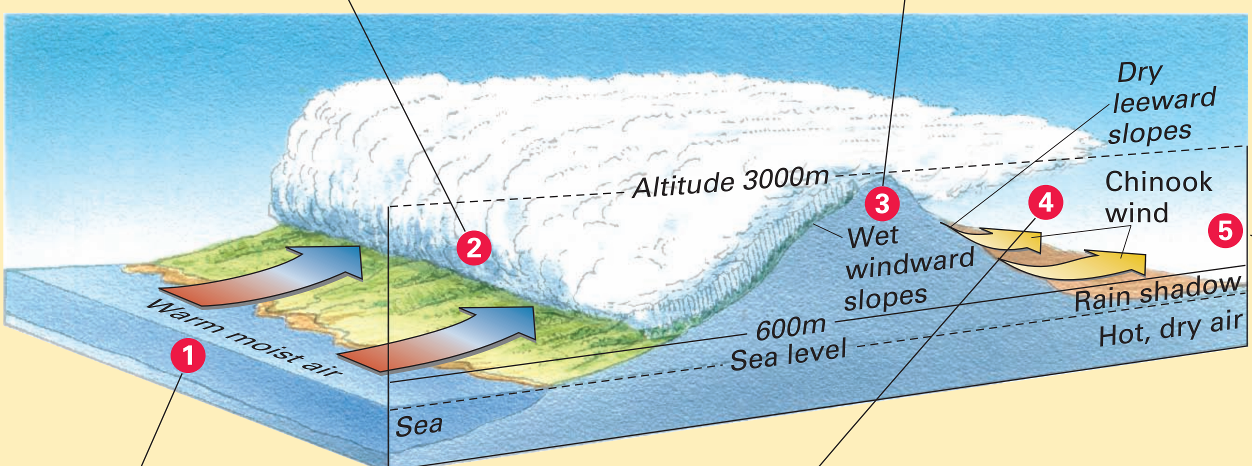
Ice storm FIGURE 4.10

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.

Orographic precipitation FIGURE 4.11

When the air has cooled sufficiently, water droplets begin to condense, and clouds will start to form, marked as point (2). The cloud cools at the wet adiabatic rate, until, eventually, precipitation begins. Precipitation continues to fall, as air moves up the slope.

After passing over the mountain summit, at point (3), the air begins to descend down the leeward slopes of the range. As it descends it is compressed and so, according to the adiabatic principle, it gets warmer. This causes the water droplets and the ice crystals in the cloud to evaporate or sublimate. Eventually the air clears, and it continues to descend, warming at the dry adiabatic rate.



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Air passing over a large ocean surface becomes warm and moist by the time it arrives at the coast, marked by point (1). As the air rises on the windward side of the range, it is cooled by the adiabatic process, and its temperature drops according to the dry adiabatic rate.

At the base of the mountain on the far side, point (4), the air is now warmer—and drier, since much of its moisture has been removed by the precipitation. This creates a rain shadow on the far side of the mountain—a belt of dry climate extending down the leeward slope and beyond. Several of the Earth's great deserts are formed by rain shadows.

this way, we can combine rainfall and snowfall into a single record of precipitation. Ordinarily, a 10-cm (or 10-in.) layer of snow is assumed to be equivalent to 1 cm (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.

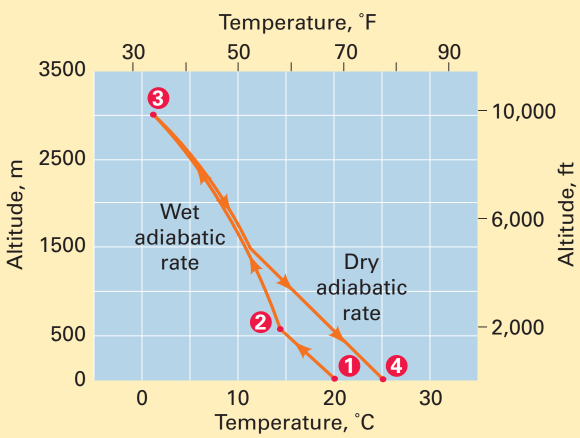
So far, we have seen how air that is moving upward will be chilled by the adiabatic process leading, eventually, to precipitation. But one key piece of the precipitation puzzle has been missing—what causes air to move upward in the first place?

Air can move upward in four ways. In this chapter, we will discuss the first two: *orographic precipitation* and *convectional precipitation*. A third way for air to be forced upward is through the movement of air masses. This type of process usually occurs during cyclones, as we will see in more detail in Chapter 6, and so we call it *cyclonic precipitation*. The fourth way, also covered in Chapter 6, is by *convergence*, in which air currents converge together at a location from different directions. Air "piles up" and is forced upward.

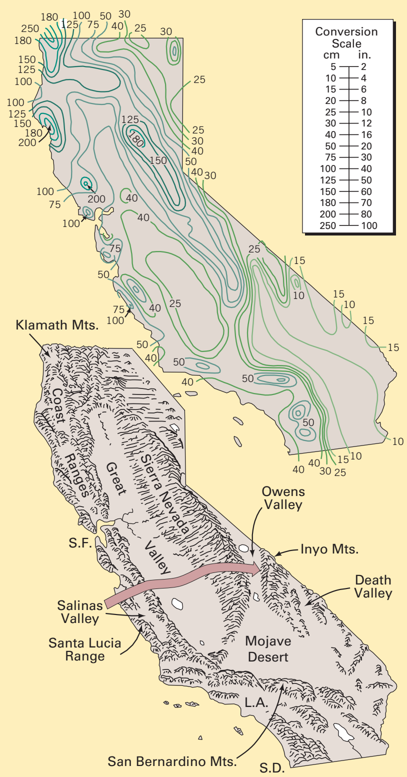
OROGRAPHIC PRECIPITATION

Orographic precipitation occurs when a through-flowing current of moist air is forced to move upward (FIGURE 4.11). The term *orographic* means "related to mountains," and to understand the orographic precipitation process, you can think of what happens to a mass of air moving up and over a mountain range. 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. At the base of the mountain on the far side, the air is warmer and drier. Its moisture has fallen as precipitation on the windward slope, creating the effect of a *rain shadow* on the far side of the mountain—a belt of dry climate that extends down the leeward slope and beyond.

Orographic precipitation
Precipitation induced when moist air is forced over a mountain barrier.



When strong and persistent, the descending flow of hot, dry air is termed a chinook wind. When channeled into valleys on the leeward side, chinook winds can raise local temperatures very rapidly. The dry air has great evaporating ability, and it can make a snow cover rapidly sublimate in winter or a dry brush cover to tinder in summer.



California mountain ranges have a strong effect on precipitation because of the prevailing flow of moist oceanic air from west to east. The upper diagram shows lines of equal precipitation. We can see that centers of high precipitation coincide with the western slopes of mountain ranges, including the coast ranges and Sierra Nevada. The desert regions lie to the east, in their rain shadows.

CONVECTIONAL PRECIPITATION

Convectional precipitation Precipitation induced when warm, moist air is heated at the ground surface, rises, cools, and condenses to form water droplets, raindrops and, eventually, rainfall.

Air can also be forced upward through convection, leading to **convectional precipitation**. 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. Because it is less dense, warm air rises above cold air. This process is convection, and hot-air balloons operate on this principle. In the case of our field, a bubble of air will form over the field, rise, and break free from the surface. FIGURE 4.12 shows this process.

As the bubble of air rises, it is cooled adiabatically, so its temperature decreases as it rises. We also know that the temperature of the surrounding air will decrease with altitude. Nonetheless, as long as the bubble is still warmer than the surrounding air, it will be less dense and so it will continue to rise.

If the bubble remains warmer than the surrounding air and uplift continues, adiabatic cooling chills the bubble below the dew point, and condensation sets in. The rising air column becomes a puffy cumulus cloud. In Figure 4.12, the flat base of the cloud marks the *lifting condensation level*—the level at which condensation begins. The bulging "cauliflower" top of the cloud is the top of the rising warm-air column pushing into higher levels of the atmosphere. Normally, the small cumulus cloud will encounter winds aloft that mix it into the local air. After drifting some distance downwind, the cloud evaporates.

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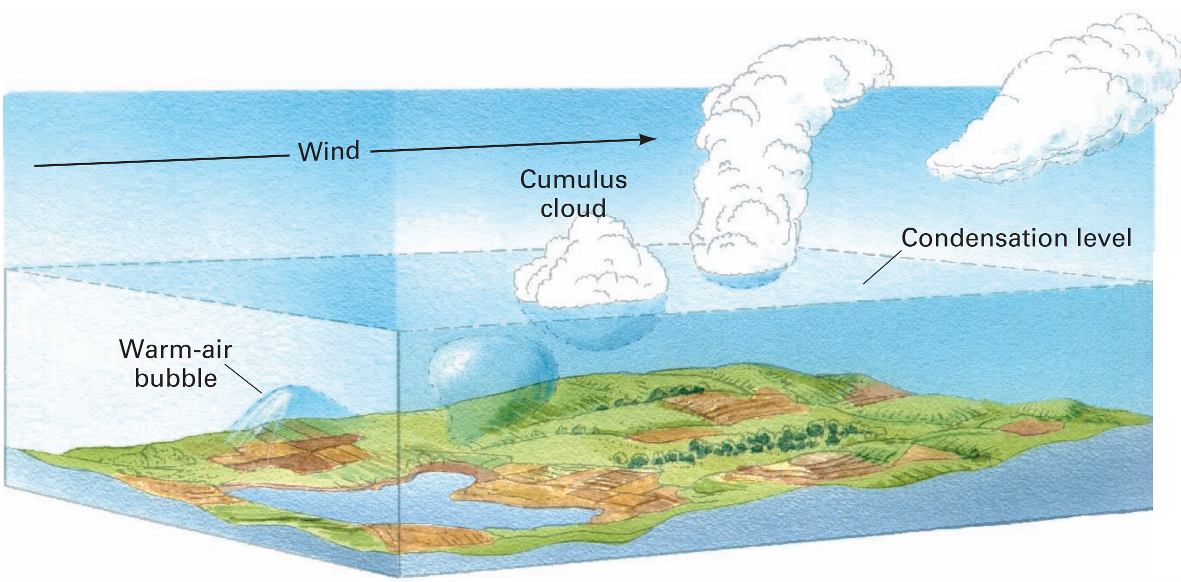
THUNDERSTORMS AND UNSTABLE AIR

Thunderstorm Intense local storm associated with a tall, dense cumulonimbus cloud in which there are very strong updrafts of air.

Thunderstorms are awesome events. Intense rain and violent winds, lightning, and thunder renew our respect for nature's



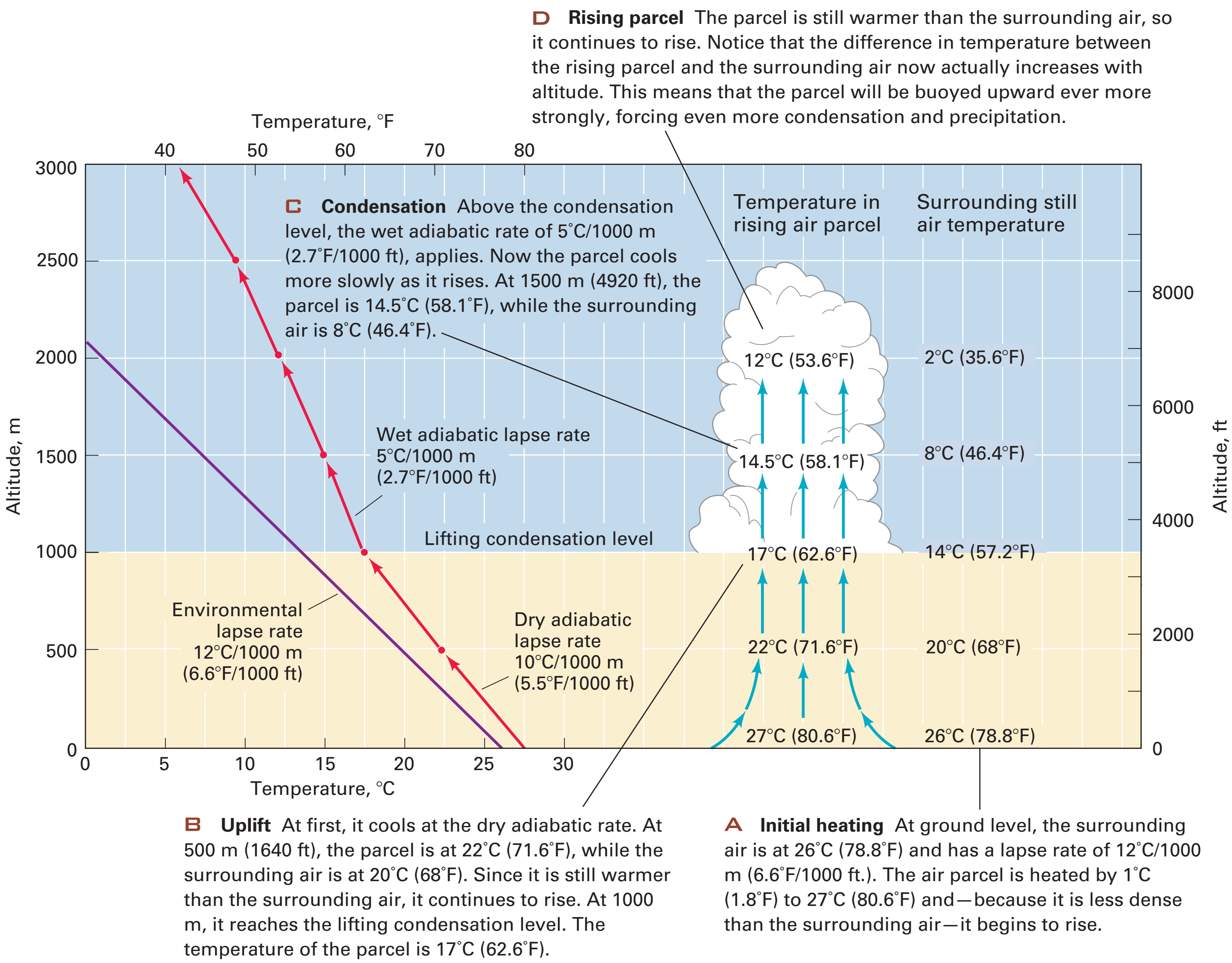
Formation of a cumulus cloud FIGURE 4.12

A bubble of heated air rises above the lifting condensation level to form a cumulus cloud.

power. But what causes thunderstorms? The answer is that when convection continues strongly, air can become unstable, creating dense cumulonimbus clouds or thunderstorms.

Two environmental conditions encourage thunderstorms to develop: (1) air that is very warm and moist, and (2) an environmental temperature lapse rate in which temperature decreases more rapidly with altitude than it does for either the dry or wet adiabatic lapse rates. Air with these characteristics is referred to as unstable. **Figure 4.13** shows how convection in unstable air works.

The key to the convectional precipitation process in unstable air is latent heat. As we saw at the beginning of the chapter, when water vapor condenses into droplets or ice particles, it releases latent heat. This heat keeps a rising parcel of air 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 will weaken. Eventually, uplift stops, since the energy source, latent heat, is gone. The cell dissipates into the surrounding air.



Convection in unstable air Figure 4.13

When the air is unstable, a parcel of air that is heated enough to rise will continue to rise to great heights.

Hot summer air masses in the central and southeastern United States are often unstable. Summer weather patterns sweep warm, humid air from the Gulf of Mexico over the continent. Over a period of days, the intense summer insolation strongly heats the air layer near the ground, producing a steep environmental lapse rate. So, both of the conditions that create unstable air are present, making thunderstorms very common in these regions during the summer.

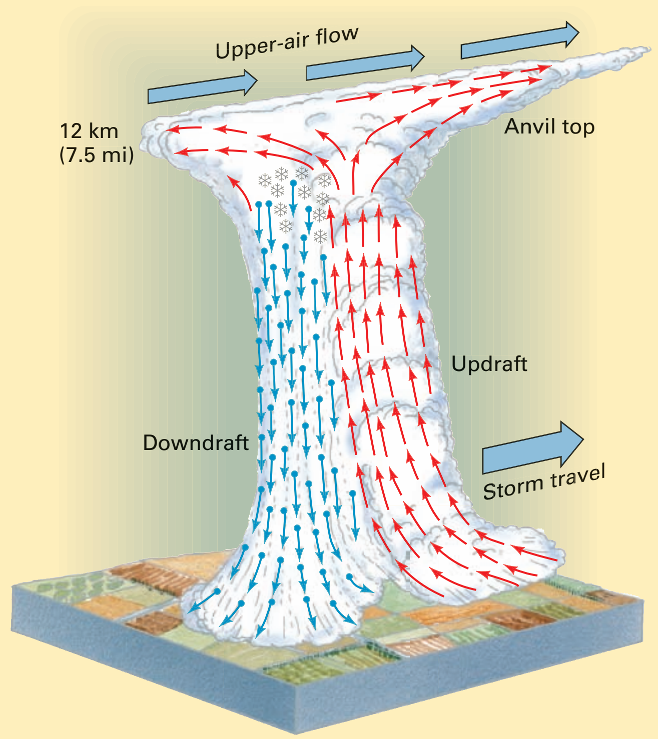
ANATOMY OF A THUNDERSTORM

A single thunderstorm typically consists of several individual convection cells. A single convection cell is shown in FIGURE 4.14A. A succession of bubble-like air parcels rise up within the cell. These bubbles are intensely cooled, according to the adiabatic process, producing precipitation. This precipitation can be water if the clouds are at the lower levels, mixed water and snow at intermediate levels, and snow at high levels where cloud temperatures are coldest.

As the rising air parcels reach high levels, which may be 6 to 12 km (about 20,000 to 40,000 ft) or even higher, the rising rate slows. At such high altitudes the winds are typically strong, dragging the cloud top downwind and giving the thunderstorm cloud its distinctive shape—resembling an old-fashioned blacksmith's anvil (FIGURE 4.14B).

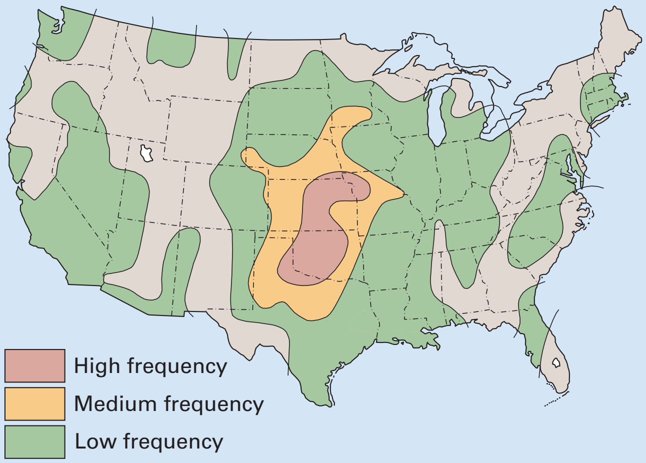
Ice particles falling from the cloud top act as nuclei for freezing and deposition at lower levels. Large ice crystals form and begin to sink rapidly. As they melt,

Thunderstorm FIGURE 4.14



A Anatomy of a thunderstorm cell Successive bubbles of moist condensing air push upward in the cell. Their upward movement creates a corresponding downdraft, expelling rain, hail, and cool air from the storm as it moves forward.

B Anvil top Large thunderstorms often show a top plume of cloud swept downwind by strong winds at high altitudes. This storm, over Lake Tanganyika in Gombe Stream National Park, Tanzania, is moving from right to left.



Frequency of severe hailstorms FIGURE 4.15

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.

they coalesce into large, falling droplets. As these raindrops rapidly fall adjacent to the rising air bubbles, they pull the air downward, feeding a downdraft within the convection cell. This downdraft of cool air emerges from the cloud base laden with precipitation. It approaches the surface and spreads out in all directions. As part of the downdraft moves forward, more warm, moist surface air can rise and enter the updraft portion of the storm. This effect helps perpetuate the storm. The downdraft creates strong local winds.

We are familiar with the heavy rains and powerful wind gusts—sometimes violent enough to topple trees and raise the roofs of weak buildings—that accompany thunderstorms. In addition, thunderstorms can produce hail. Hailstones are formed when layers of ice build up on ice pellets that are suspended in the strong updrafts of the thunderstorm. They can reach diameters of 3 to 5 cm (1.2 to 2.0 in.) or larger. When they become too heavy for the updraft to support, they fall to Earth.

Crop destruction caused by hailstorms can add up to losses of several hundred million dollars. Damage to wheat and corn crops is particularly severe in the Great Plains, running through Nebraska, Kansas, Missouri, Oklahoma, and northern Texas (FIGURE 4.15).

CONCEPT CHECK **STOP**

Name four types of precipitation processes.

What conditions lead to thunderstorms?

Air Quality

Learning Objectives

List substances that act as air pollutants.

Explain where air pollutants come from.

Explain what causes smog.

Describe acid rain, its causes and effects.

Most people living in or near urban areas have experienced air pollution firsthand. Perhaps you've felt your eyes sting or your throat tickle as you drive an urban freeway. Or you've noticed black dust on windowsills or window screens and realized that you are breathing in that dust as well.

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. We've already met aerosols—small bits of matter in the air, so small that they float freely with normal air movements—and gases, in earlier chapters. Particulates are larger, heavier particles that sooner or later fall back to Earth.

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 pollutants are carbon monoxide, sulfur oxides, nitrogen oxide gases, and volatile organic compounds—including evaporated gasoline, dry cleaning fluids, and incompletely combusted fossil fuels—which occur as both gases and aerosols. The remaining pollutants are in the form of lead and particulates. The buildup of these substances in the air can lead to many types of pollution, including acid rain and smog. Urban air pollution reduces visibility and illumination. Specifically, a smog layer can cut illumination by 10 percent in summer and 20 percent in winter. The ozone in smog also absorbs ultraviolet radiation, at times completely preventing it from reaching the ground. Although this reduces the risk of human skin cancer, it may also permit increased viral and bacterial activity at ground level.

The combustion of fossil fuels is the most important source of all of these pollutants in the United States. It accounts for 78 percent of emissions. Gasoline and diesel engine exhausts contribute most of the carbon monoxide, half the volatile organic compounds, and about a third of the nitrogen oxides.

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.

ACID DEPOSITION

Perhaps you've heard about acid rain killing fish and poisoning trees (Figure 4.16). Acid rain is part of the phenomenon of acid deposition. 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.

Effects of acid rain FIGURE 4.16

A Forests Acid fallout from a nearby nickel smelter killed this lush forest in Monchegorsk, Russia, which then burned.

B Buildings Acid rain has eroded and eaten away the face of this stone angel in London, England.

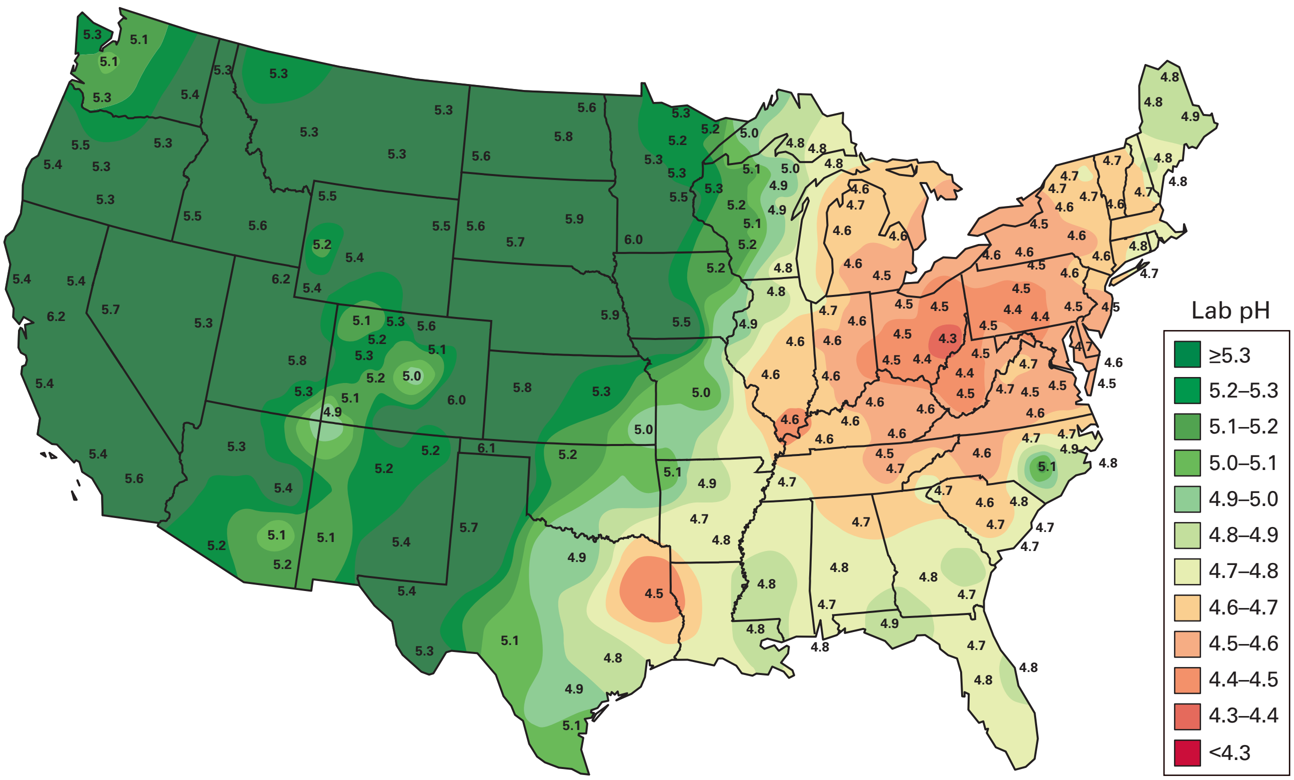
What are the effects of acid rain? Acid deposition in Europe and North America has had a severe impact on some ecosystems (FIGURE 4.17). In Norway, acidification of stream water has virtually eliminated many salmon runs by inhibiting salmon egg development. In 1990, American scientists estimated that 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.

During the 1990s, the United States 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. In these areas, 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.

AIR POLLUTION CONTROL

The United States and Canada have some of the strictest laws in the world limiting air pollution. Strategies have been developed to reduce emissions by trapping and processing pollutants after they are generated. There have also been calls for alternative, nonpolluting technologies—solar, wind, or geothermal power—rather than coal burning to generate electricity.

In any event, we can do much to preserve the quality of the air we breathe by reducing fossil fuel consumption. It will be a considerable challenge to our society and others to preserve and increase global air quality in the face of an expanding human population and increasing human resource consumption.



Acidity of rainwater for the United States in 2005 FIGURE 4.17

Values are pH units, which indicate acidity. The eastern United States, notably Ohio, Pennsylvania, and West Virginia, shows the lowest, most acid values. (National Atmospheric Deposition Program (NRSp-3)/National Trends Network, Illinois State Water Survey.)

What a Geographer Sees

Global Locator

Smog

The term *smog* was coined by combining the words “smoke” and “fog” to describe a considerable density of aerosols and gas pollutants over an urban area. In this photograph of Cairo, the smog obscures vision, but we can see through to the city, and some hazy sunlight can still get through to the people on the ground. In other cases, however, smog can be dense enough to hide aircraft flying overhead from view. It irritates the eyes and throat, and it can corrode structures over long periods of time.

A geographer looking at such a hazy scene could tell you that a dense mixture of aerosols and gaseous pollutants—produced by human activity—is responsible for the blur. Modern urban smog has three main toxic ingredients: nitrogen oxides, volatile organic compounds, and ozone. Nitrogen oxides and volatile organic compounds mostly come from cars and industrial power plants. Ozone forms through a photochemical reaction in the air. In urban smog, ozone can harm plant tissues and eventually kill sensitive plants.

CONCEPT CHECK **STOP**

What is an air pollutant?

Where do air pollutants come from?

What is smog?

What is acid rain? What are its effects?

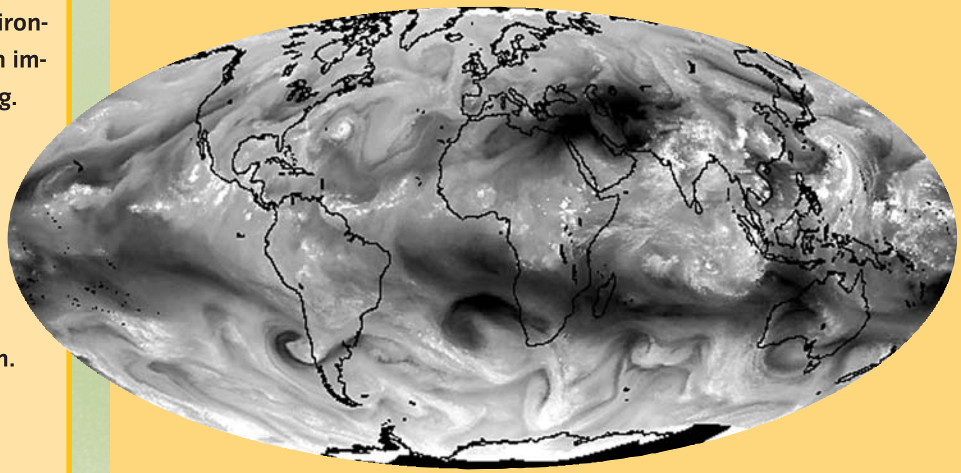
What is happening in this picture ?

Water vapor composite image

The Geostationary Operational Environmental Satellite (GOES) system is an important tool for weather forecasting. The satellites can show the movement of clouds over the surface of the Earth, or, as in this case, track global water vapor.

This is the water vapor image from April 11, 2000. The brightest areas show regions of active precipitation. Dark areas show low water vapor content.

- Are the areas of precipitation and low water vapor what you would expect?
- Cyclones are marked by dry air spiraling inward with moist air. Can you spot any cyclonic systems building up?



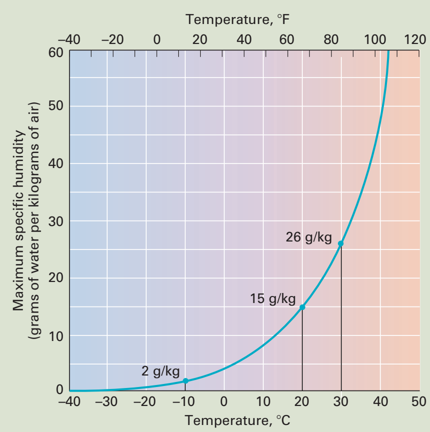
VISUAL SUMMARY

1 Water and the Hydrosphere

1. Water can change state by evaporating, condensing, melting, freezing, and through sublimation and deposition.
2. The hydrosphere is the realm of water in all its forms. The fresh water in the atmosphere and on land in lakes, streams, rivers, and groundwater is only a very small portion of the total water in the hydrosphere.
3. Precipitation is the fall of liquid or solid water from the atmosphere to reach the Earth's land or ocean surface.

2 Humidity

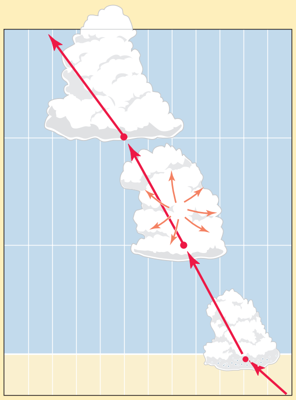
1. Humidity describes the amount of water vapor present in air.
2. Warm air can hold much more water vapor than cold air.
3. Specific humidity measures the mass of water vapor in a mass of air, in grams of water vapor per kilogram of air. Relative humidity measures water vapor in the air as the percentage of the maximum amount of water vapor that can be held at the given air temperature.



4. Condensation occurs at the dew-point temperature.

3 The Adiabatic Process

1. The adiabatic principle states that when a gas is compressed, it warms, and when a gas expands, it cools.
2. When an air parcel moves upward in the atmosphere, it encounters a lower pressure and so expands and cools.
3. The dry adiabatic lapse rate describes the rate of cooling with altitude. When condensation or deposition is occurring, the cooling rate is described as the wet adiabatic lapse rate.



4 Clouds

1. Clouds are composed of droplets of water or crystals of ice that form on condensation nuclei.
2. Clouds typically occur in layers, as stratiform clouds, or in globular masses, as cumuliform clouds. Fog occurs when a cloud forms at ground level.

5 Precipitation

1. Precipitation from clouds occurs as rain, hail, snow, and sleet.
2. There are four types of precipitation processes—orographic, convectional, cyclonic, and convergent.
3. 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.
4. When a surface is heated unequally, an air parcel can 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. This is convectional precipitation.
5. If the air is unstable, thunderstorms can form, generating hail and lightning.

6 Air Quality

1. Air pollution is defined as 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.
2. Smog, a common form of air pollution, contains nitrogen oxides, volatile organic compounds, and ozone. Acid deposition of sulfate and nitrate particles can acidify soils and lakes, causing the death of fish and trees.

KEY TERMS

- **hydrosphere** p. 96
- **precipitation** p. 100
- **humidity** p. 101
- **dew-point temperature** p. 103
- **adiabatic principle** p. 103
- **dry adiabatic lapse rate** p. 104
- **wet adiabatic lapse rate** p. 104
- **condensation nucleus** p. 106
- **orographic precipitation** p. 111
- **convectional precipitation** p. 112
- **thunderstorm** p. 112
- **air pollutant** p. 116

CRITICAL AND CREATIVE THINKING QUESTIONS

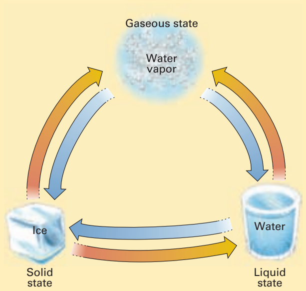
1. What is the hydrosphere? Where, and in what amounts, is water found on our planet? How does water move in the hydrologic, or water, cycle?
2. How is the moisture content of air influenced by air temperature?
3. What happens when a parcel of moist air is chilled? Use the terms *saturation*, *dew point*, and *condensation* in your answer.
4. What is the adiabatic process? Why is it important?
5. Distinguish between dry and wet adiabatic lapse rates. When do they apply for a parcel of air moving upward in the atmosphere? Why is the wet adiabatic lapse rate smaller than the dry adiabatic rate? Why is the wet adiabatic rate variable in amount?
6. How is precipitation formed? Describe the process for warm and cool clouds.
7. Compare and contrast orographic and convectional 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 convectional precipitation occur in an orographic situation? Under what conditions?
8. What is unstable air? Sketch the anatomy of a thunderstorm cell. Show rising bubbles of air, updraft, downdraft, precipitation, and other features.
9. Describe the most common forms of air pollution and the damage that air pollution can cause.

SELF-TEST

1. Of the freshwater reservoirs below, the one with the smallest size is _______________.
   a. atmospheric water b. groundwater
   c. freshwater lakes d. soil water

2. The movement of water among the great global reservoirs constitutes the _______________.
   a. water-factor cycle
   b. hydraulic cycle
   c. hydrologic cycle
   d. evaporation-precipitation cycle

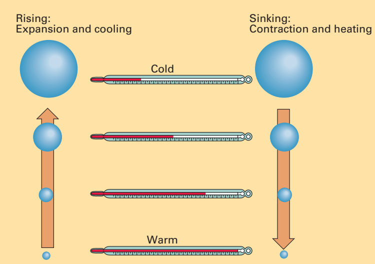
3. The diagram shows the three states of water. Identify and label the six processes through which water changes state. In which of these processes is latent heat absorbed, and in which is it released?



4. Relative humidity _______________.
   a. is the total amount of water vapor present in the air
   b. is responsible for life on Earth
   c. depends upon the volume of water present in the air unrelated to temperature
   d. is the amount of water vapor in the air compared to the amount it could hold

5. The _______________ of the air represents the actual quantity of water vapor held by the air.
   a. relative humidity b. saturation level
   c. specific humidity d. absolute saturation level

6. An air mass is rising and expanding, as shown. How does its temperature change? What term is used to describe temperature changes that arise solely as a result of air expansion or compression?



7. Since rising air cools less rapidly when condensation is occurring as a result of the release of latent heat, the _______________ has a lesser absolute value than the _______________.
   a. dry adiabatic lapse rate; wet adiabatic lapse rate
   b. dry adiabatic lapse rate; environmental adiabatic lapse rate
   c. environmental adiabatic lapse rate; wet adiabatic lapse rate
   d. wet adiabatic lapse rate; dry adiabatic lapse rate

8. What type of cloud is shown in the photograph? Do such clouds form at high, middle, or low level in the sky?

9. _______________ is the type of precipitation that forms as rain freezes during its descent through the atmosphere.
   a. freezing rain b. snow
   c. hail d. sleet

10. _______________ precipitation is a result of air being lifted over a highland area.
   a. convective b. orographic
   c. convergence d. frontal

11. _______________ lifting of air is due to heating.
   a. convective b. orographic
   c. frontal d. adiabatic

12. The two conditions that promote thunderstorm development are _______________.
   a. warm, moist air and a decreasing lapse rate
   b. cool, dry air in collision with a colder air mass
   c. warm, moist air and an environmental lapse rate with an absolute value greater than the wet and dry rates
   d. cold, wet air, and an environmental lapse rate with an absolute value greater than the wet and dry rates

13. Smog has three toxic ingredients of which _______________ are (is) not a member.
   a. nitrogen oxides
   b. hydrocarbons
   c. polycarbonates
   d. ozone

14. A smog layer can cut visibility and illumination by up to _______________ percent in winter.
   a. 5 b. 10 c. 15 d. 20

15. Acid deposition is produced by the release of sulfur dioxide and _______________ into the air.
   a. carbon dioxide b. ozone
   c. nitric oxide d. sulfur perchlorate

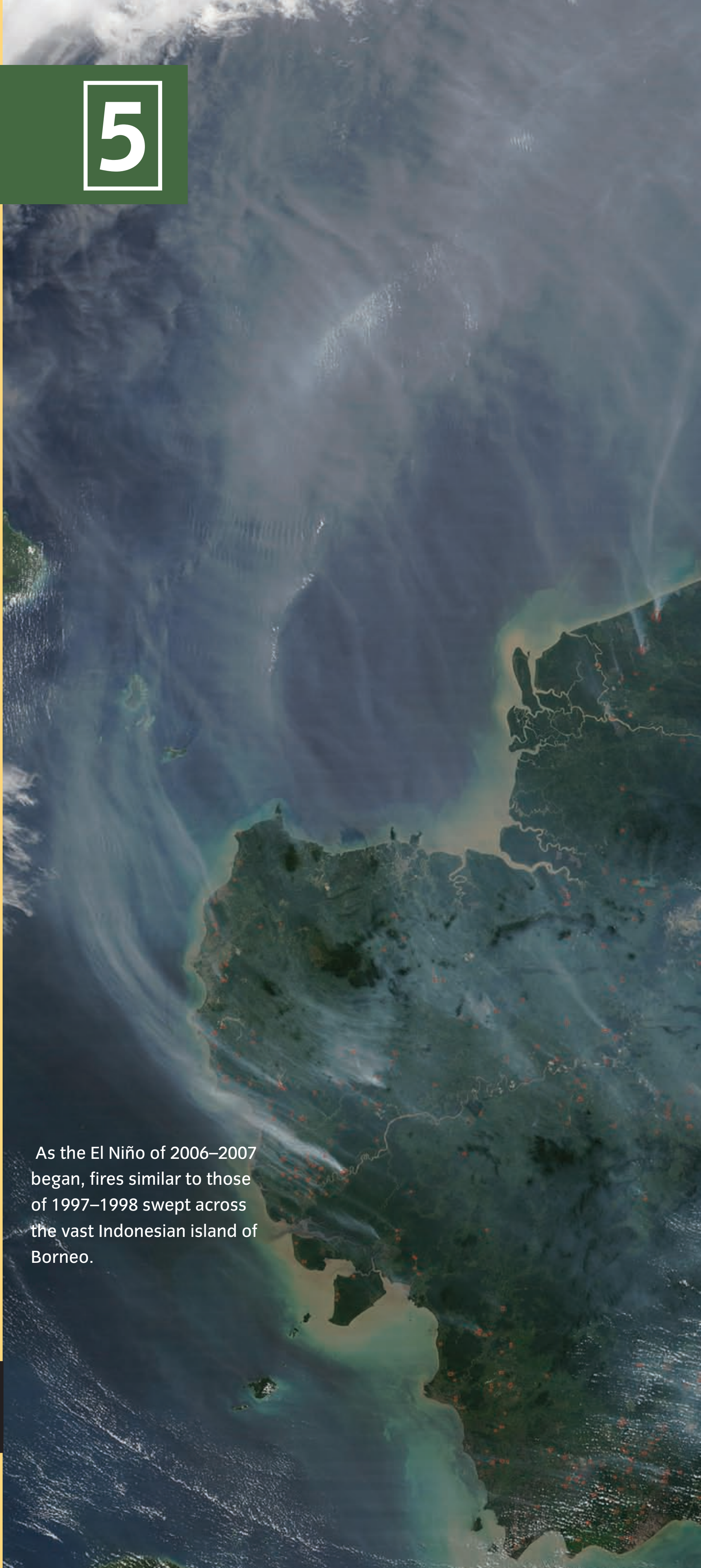
Winds and Global Circulation

5

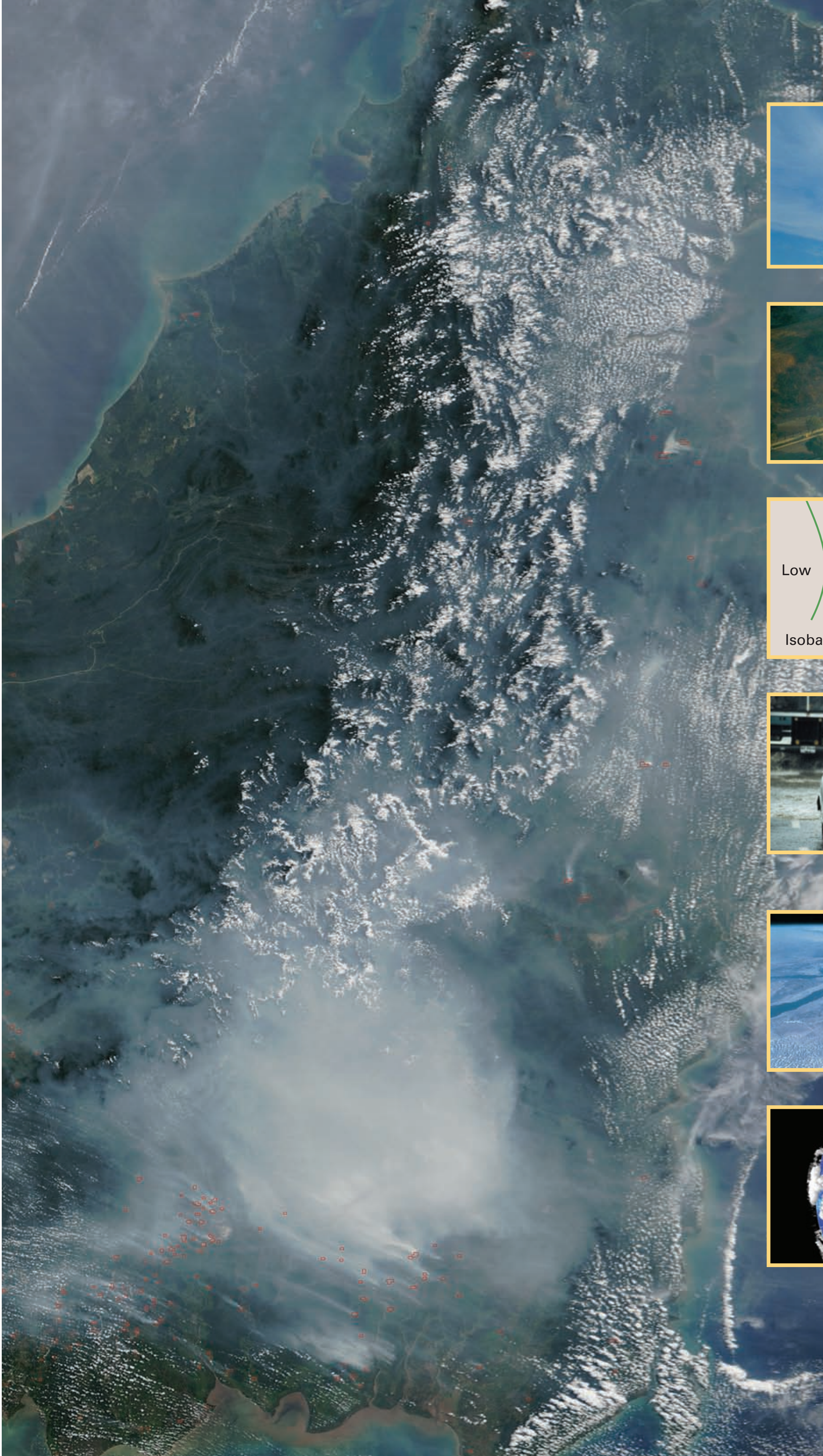
In the last weeks of 1997, extreme weather across the globe killed around 2100 people and left property damage worth $33 billion in its wake. Forest fires raged in Sumatra, Borneo, and Malaysia, while large portions of Australia and the East Indies were plunged into drought. Torrential rains drenched Peruvian and Ecuadorian coast ranges, and ice storms left 4 million people in Quebec and the northeastern United States stranded without power. This was the work of a weather pattern known as El Niño.

El Niño occurs every three to eight years. It was given the Spanish name El Niño (meaning "the little boy," or "Christ Child") by Peruvian fishermen whose anchovy harvests plummeted around Christmas. Under normal conditions strong winds blow westward, "piling up" very warm ocean water in the western Pacific. This water is replaced by cool bottom water along the South American coast, which is filled with nutrients for feeding marine life. But a chain of El Niño events kills these winds, and without the pressure of these winds to hold them back, warm sterile waters surge eastward, lowering the anchovy population.

The El Niño chain is set in motion by a seesawing in pressure across the equatorial zone. We don't know exactly what causes this phenomenon, but it is a striking example of our planet's dynamic circulation patterns of wind and water.



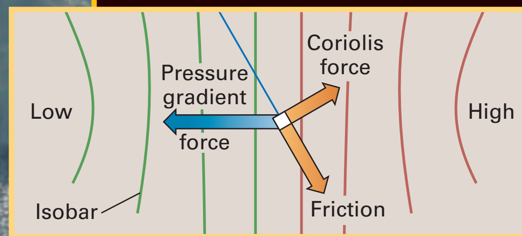
As the El Niño of 2006–2007 began, fires similar to those of 1997–1998 swept across the vast Indonesian island of Borneo.



CHAPTER OUTLINE

■ **Atmospheric Pressure p. 126**

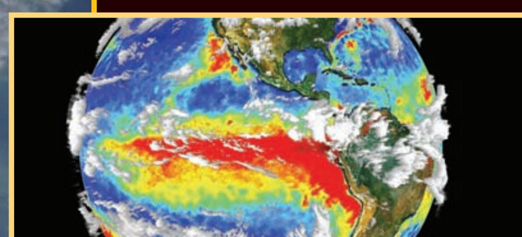
■ **Local Wind Patterns p. 129**



■ **Cyclones and Anticyclones p. 132**

■ **Global Wind and Pressure Patterns p. 134**

■ **Winds Aloft p. 139**



■ **Ocean Currents p. 144**

Atmospheric Pressure

LEARNING OBJECTIVES

Define atmospheric pressure.

Explain how a barometer works.

We live at the bottom of a vast ocean of air—the Earth's *atmosphere* (FIGURE 5.1). 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 $lb/in.^2$).

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.

Atmospheric pressure Pressure exerted by the atmosphere because of the force of gravity acting upon the overlying column of air.

Barometer Instrument that measures atmospheric pressure.

Ocean of air FIGURE 5.1

The Earth's terrestrial inhabitants live at the bottom of an ocean of air. This buoyant weather balloon, known as a radiosonde, will carry instruments upward that radio back temperature and pressure at levels aloft. Sable Island, Nova Scotia.

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 5.2).

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 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 5.3). Changes in pressure at higher elevations can have more serious effects on the human body. In the moun-

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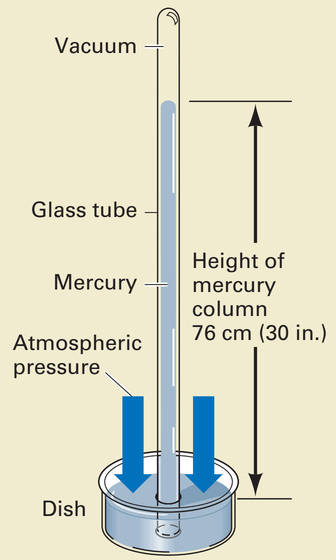
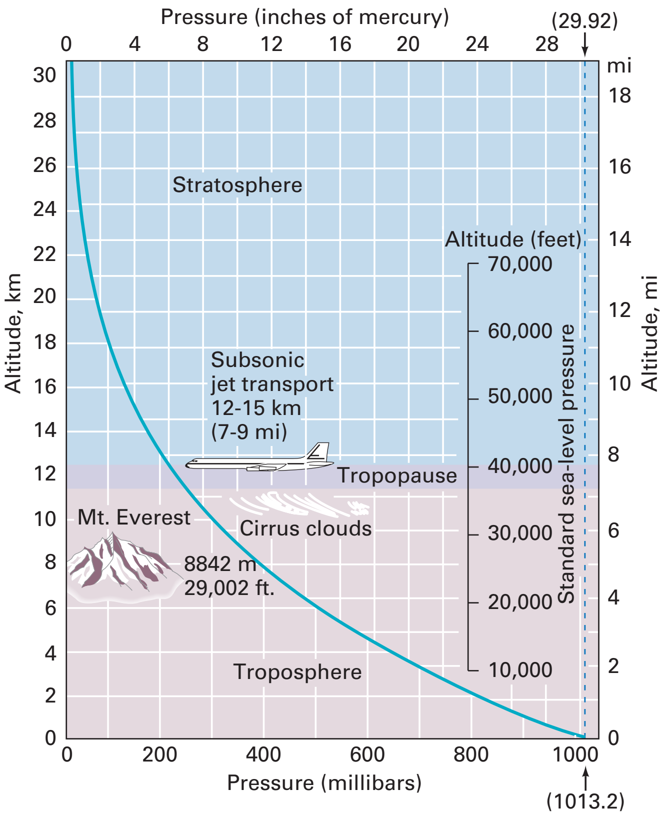


Mercury barometer FIGURE 5.2

Atmospheric pressure pushes the mercury upward into the tube, balancing the pressure exerted by the weight of the mercury column. As atmospheric pressure changes, the level of mercury in the tube rises and falls.



Atmospheric pressure and altitude FIGURE 5.3

Atmospheric pressure decreases rapidly with altitude near the Earth's surface but much more slowly at higher altitudes.

Climbers on Everest FIGURE 5.4

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.

tains or at high altitudes, with decreased air pressure, less oxygen moves into lung tissues, producing fatigue and shortness of breath (FIGURE 5.4). These symptoms, sometimes accompanied by headache, nosebleed, or nausea, are known as mountain sickness. They are likely to occur at altitudes of 3000 m (about 10,000 ft) or higher.

CONCEPT CHECK STOP

What causes atmospheric pressure?

How does a mercury barometer work?

How does atmospheric pressure change with altitude?

What effect can this have on mountain climbers?

Local Wind Patterns

LEARNING OBJECTIVES

Describe how pressure gradients drive wind.

Discuss local wind systems.

Explain convection loops.

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 5.5).

Combination cup anemometer and wind vane FIGURE 5.5

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 instrument leading to the meter, which is located indoors.

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 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 5.6).

Isobars Lines on a map drawn through all points having the same atmospheric pressure.

Pressure gradient Change of atmospheric pressure measured along a line at right angles to the isobars.

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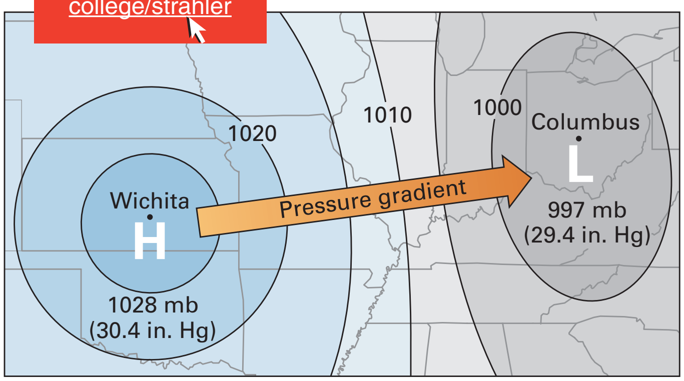


Isobars and a pressure gradient FIGURE 5.6

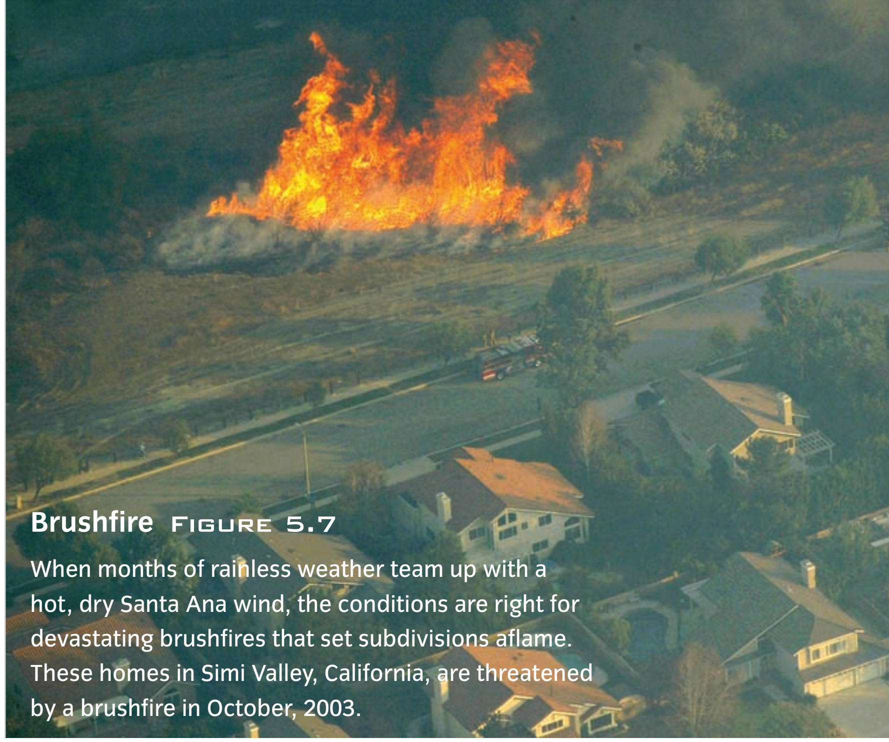
This figure shows a pressure gradient. Because atmospheric pressure is higher at Wichita than at Columbus, the pressure gradient will push air toward Columbus, producing wind. A greater pressure difference between the two locations would produce a greater force and a stronger wind.

> **Convection loop** Circuit of moving fluid, such as air or water, created by unequal heating of the fluid.

How do pressure gradients come about? Pressure gradients develop because of unequal heating in the atmosphere. We can see how by examining the development of **convection loops** in the process diagram.

LOCAL WINDS

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 5.7). In October 2003, fires driven by Santa Ana winds destroyed over 3000 homes and killed more



Brushfire FIGURE 5.7

When months of rainless weather team up with a hot, dry Santa Ana wind, the conditions are right for devastating brushfires that set subdivisions aflame. These homes in Simi Valley, California, are threatened by a brushfire in October, 2003.

Process Diagram

Convection loops

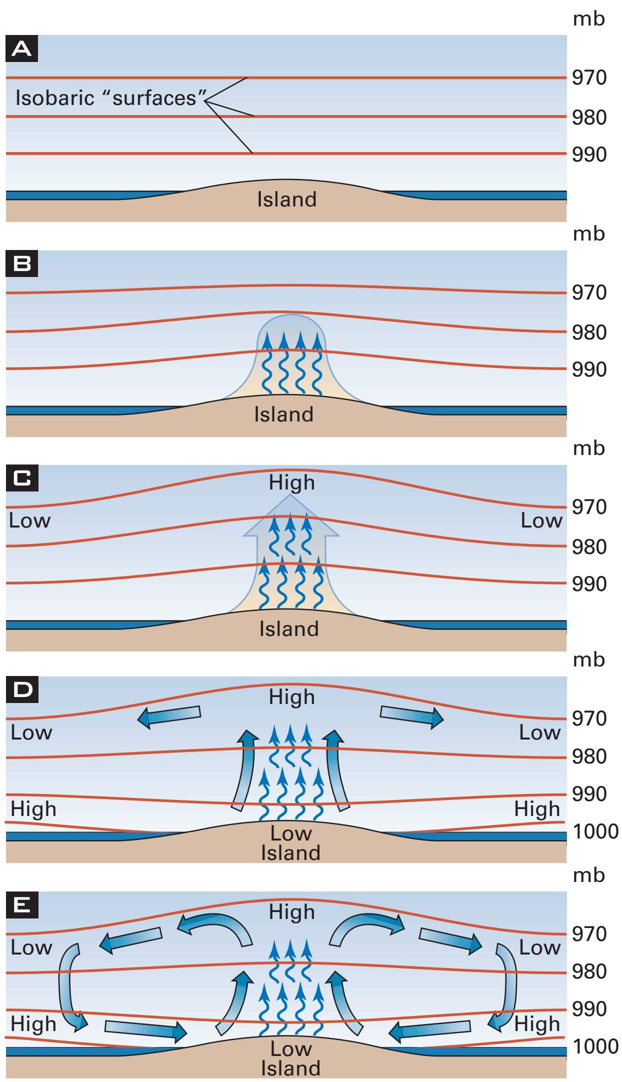
Uniform atmosphere (heated equally) Imagine a uniform atmosphere above a ground surface. The isobaric levels (or "surfaces") are parallel with the ground surface. (*Isobar* = equal pressure)

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 in 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.

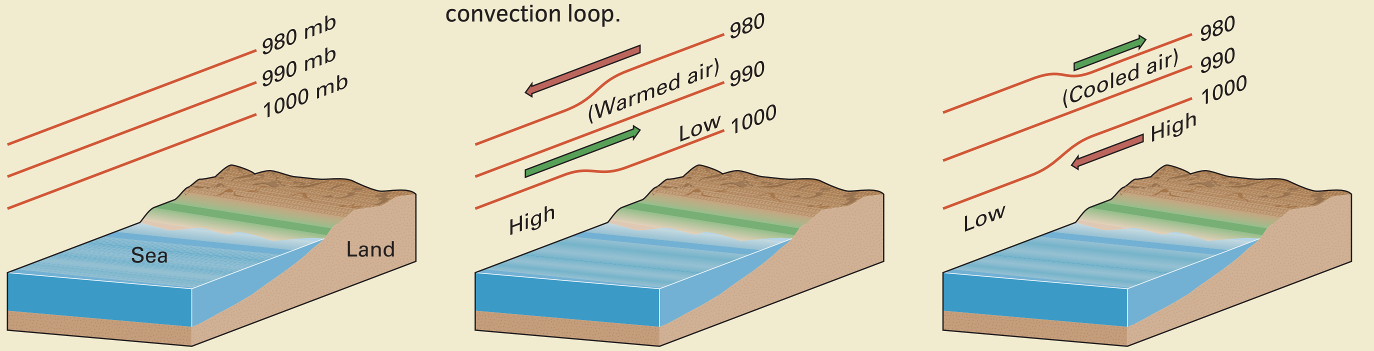
Convection loops The new pressure gradient at the surface moves air from the ocean surfaces toward the island, while air moving in the opposite direction at upper levels completes the two loops.



Early in the day, winds are often calm.

During the day, the land warms the air above it. This warm air moves oceanward aloft, while surface winds bring cool marine air landward at the surface, creating the convection loop.

At night, radiation cooling over land creates a reversed convection loop, developing a land breeze.



Early morning—calm

Afternoon—sea breeze

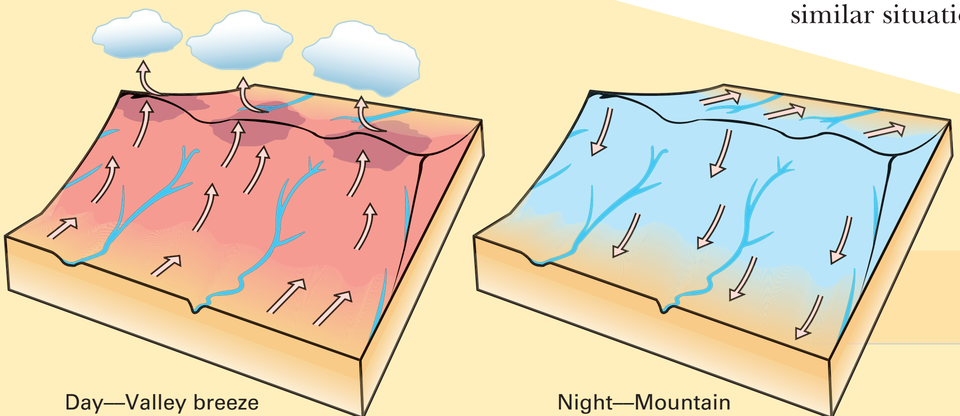
Night—land breeze

Sea and land breezes FIGURE 5.8

Since land surfaces heat and cool more rapidly than water, temperature contrasts often develop along the coastline.

than a dozen people in a huge crescent of wildfire that extended over 250,000 acres from Ventura County to the Mexican border. The Santa Ana is an example of a *local wind* system—generated by local effects. Other local winds include the chinook, a warm and dry wind.

Sea and *land breezes* are simple examples of how uneven heating and cooling of the air can set up convection loops that create local winds (FIGURE 5.8). A similar situation creates *mountain* and *valley winds* (FIGURE 5.9).



Day—Valley breeze

Night—Mountain breeze

Valley and mountain breezes FIGURE 5.9

During the day, mountain hill slopes are heated intensely by the Sun, making the air expand and rise, creating a valley breeze. An air current moves up valleys from the plains below—upward over rising mountain slopes, toward the summits.

At night, the hill slopes are chilled by radiation, setting up a reversed convection loop. The cooler, denser hill slope air moves valleyward, down the hill slopes, to the plain below.

CONCEPT CHECK STOP

What is a pressure gradient?

How do pressure gradients drive local wind patterns?

Explain how convection loops develop.

Give two examples of local winds.

Cyclones and Anticyclones

LEARNING OBJECTIVES

Explain the Coriolis effect.

Discuss cyclones and anticyclones.

Explain Hadley cells and how they affect wind patterns.

THE CORIOLIS EFFECT

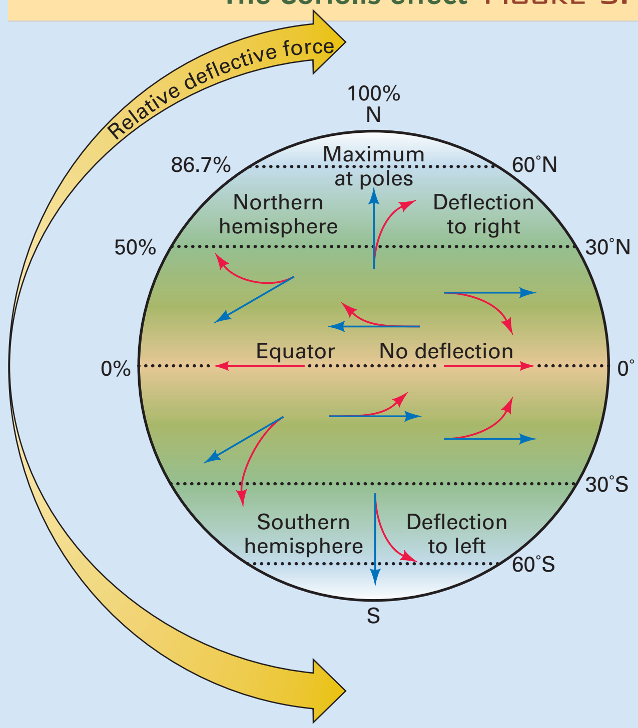
We've seen that the pressure gradient force moves air from high pressure to low pressure. For sea and land breezes, which are local in nature, this pushes wind in about the same direction as the pressure gradient. But on global scales, the direction of air motion is more complicated. The difference is caused by the Earth's rotation, through the **Coriolis effect** (FIGURE 5.10A).

Coriolis effect Effect of the Earth's rotation that acts like a force to deflect a moving object on the Earth's surface to the right in the northern hemisphere and to the left in the southern hemisphere.

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 (FIGURE 5.10B). In the southern hemisphere, objects move as if pulled to the left. This apparent deflection doesn't depend on direction of motion—it occurs whether the object is moving toward the north, south, east, or west.

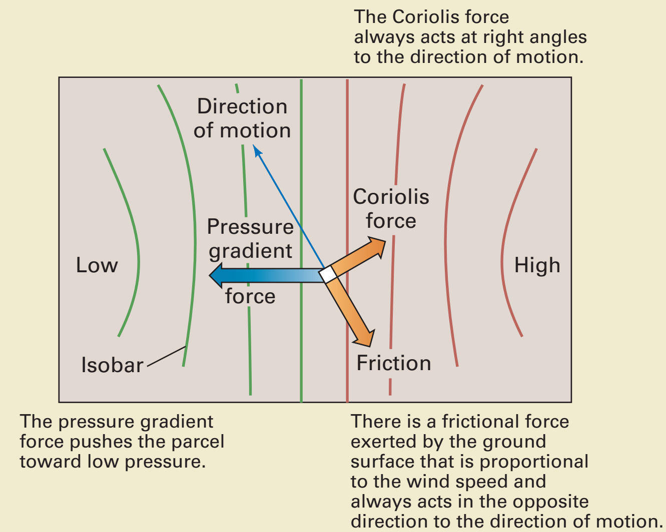
Geographers are usually concerned with analyzing the motions of air masses or ocean currents from the viewpoint of an Earth observer on the geographic grid, not from the viewpoint of space. So, as a shortcut, we

The Coriolis effect FIGURE 5.10



A 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.

B 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.



Balance of forces on a parcel of surface air
FIGURE 5.11

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.

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 5.11).

CYCLONES AND ANTICYCLONES

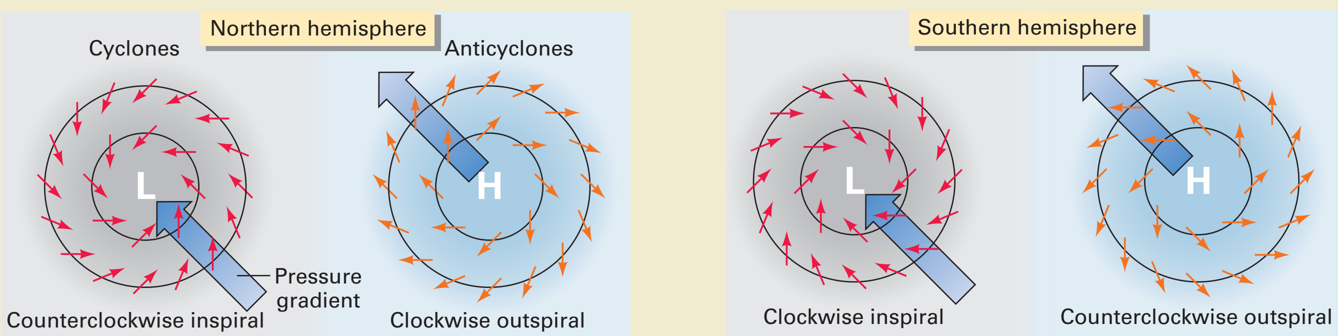
Cyclone Center of low atmospheric pressure.

Anticyclone Center of high atmospheric pressure.

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 5.12). This inward spiraling motion is called *convergence*. In high-pressure centers, known as **anticyclones**, air spirals downward and outward. This outward spiraling motion is called *divergence*.

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 FIGURE 5.12



A 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.

B In the southern hemisphere, the cyclonic spiral will be clockwise because the Coriolis force acts to the left. For anticyclones, the situation is reversed.

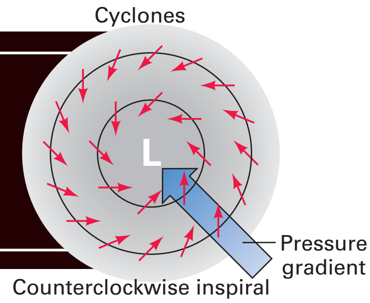
Cyclones and anticyclones can be a thousand kilometers (about 600 mi) across, or more. A fair weather system—an anticyclone—may stretch from the Rockies to the Appalachians. Cyclones and anticyclones can remain more or less stationary, or they can move, sometimes rapidly, to create weather disturbances.

CONCEPT CHECK STOP

What causes the Coriolis effect?

How does the Coriolis force deflect the paths of moving objects?

What are cyclones and anticyclones? How do they develop?



Global Wind and Pressure Patterns

LEARNING OBJECTIVES

Define Hadley cells and explain how they affect wind patterns.

Discuss the intertropical convergence zone (ITCZ) and the subtropical high-pressure belts.

Describe monsoon circulation.

Explain the differences between pressure patterns in the northern and southern hemispheres.

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 5.13**). **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 convection loops. Air rises over the equator and is drawn poleward by the pressure gradient. But as the air moves poleward, the Coriolis force turns it westward, so it eventually descends at about a 30° latitude, completing the convection loop. This is a Hadley cell.

Hadley cell Low-latitude atmospheric circulation cell with rising air over the equatorial trough and sinking air over the subtropical high-pressure belts.

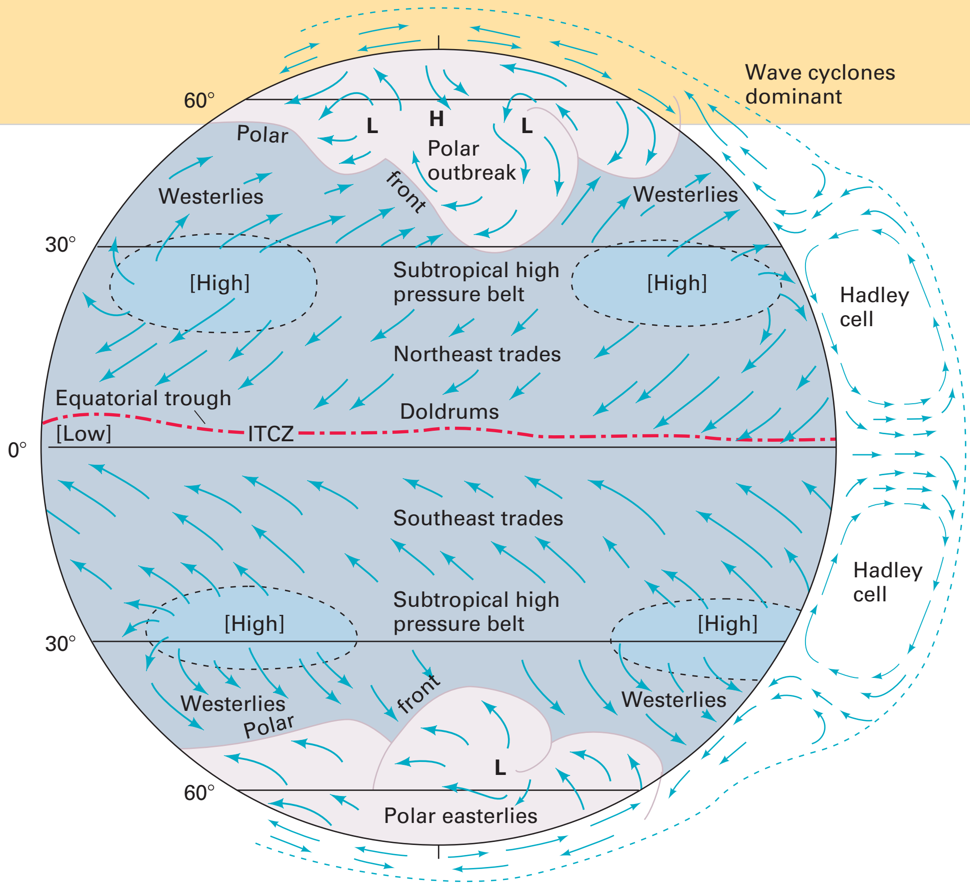
The rising air at the equator produces a zone of surface low pressure known as the *equatorial trough*. Air in both hemispheres moves toward this equatorial trough. There it converges and rises as part of the Hadley circulation. The narrow zone where the air converges is called the **intertropical convergence zone (ITCZ)**. Because the air is largely moving upward, surface winds are light and variable. This region is known as the *doldrums*.

Intertropical convergence zone (ITCZ) Zone of convergence of air masses along the equatorial trough.

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.

Subtropical high-pressure belts Belts of persistent high atmospheric pressure centered at about lat. 30° N and S.

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



Global surface winds on an ideal Earth

FIGURE 5.13

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.

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 move into the region, heading eastward and equatorward along a border known as the **polar front**. This results in highly variable pressures and winds.

> **Polar front**
> Front lying between cold polar air masses and warm tropical air masses.

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.

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 to the mercy of colder winds and air masses from the north and west.

ITCZ AND THE MONSOON CIRCULATION

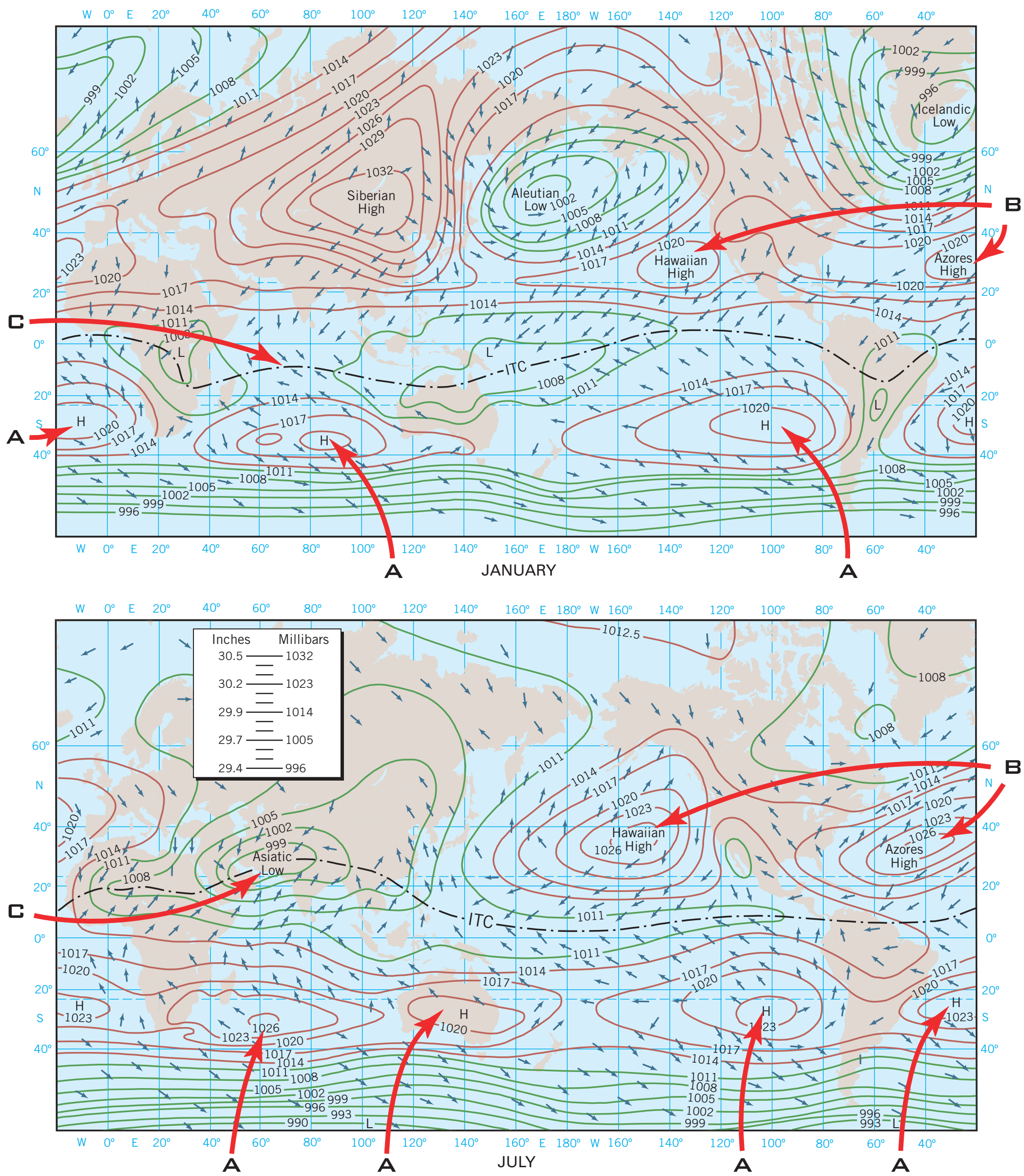
We've seen that insolation is most intense when the Sun is directly overhead, and the latitude at which the Sun is directly overhead changes with the seasons. Since this heating drives the Hadley cell circulation, the ITCZ and subtropical high-pressure belts also shift with the seasons (FIGURE 5.14). We have already noted this shift for the Hawaiian and Azores Highs, which intensify and move northward as July approaches.

The ITCZ also shifts with the seasons. The shift is moderate in the western hemisphere, with the ITCZ moving a few degrees north from January to July over the oceans. In South America, the ITCZ lies across the Amazon in January and swings northward by about 20°. There is also a huge shift of about 40° of latitude in Asia that you can see by comparing the two Mercator maps of Figure 5.14c.

Why does such a large shift occur? In January, an intense high-pressure system, the Siberian high, is found over Asia. Winter temperatures in northern Asia are very cold, so this high pressure is to be expected. In

Atmospheric pressure maps—Mercator Figure 5.14

These global maps show average sea-level pressures and winds for daily observations in either January or July. Average barometric pressure is 1013 mb (29.2 in. Hg). Values greater than this are "high" and are shown in red, while lower values are "low" and are shown in green. Pressure units are millibars reduced to sea level.



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!

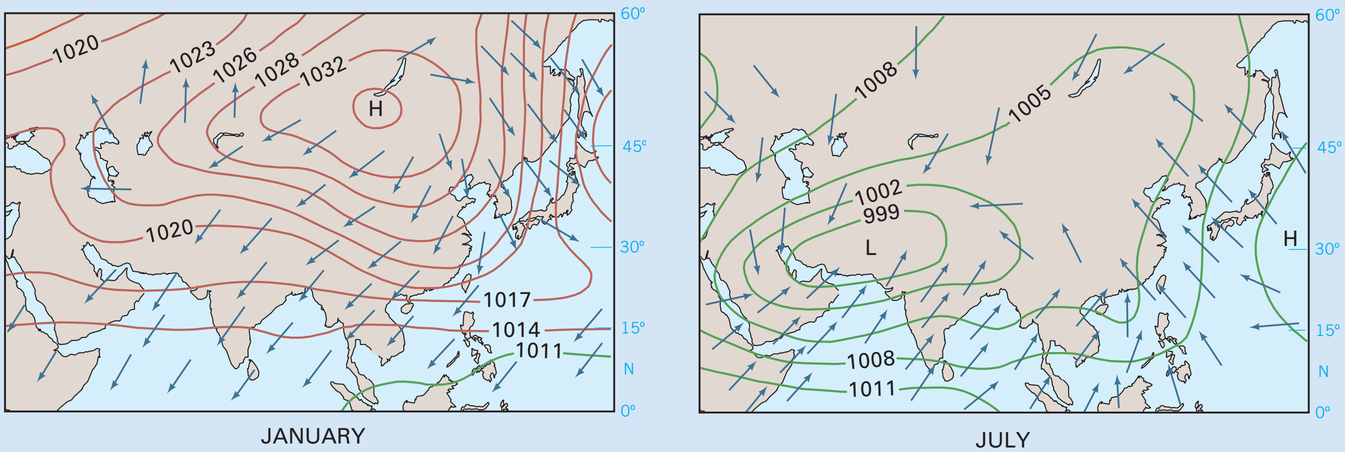
July, this high-pressure center has disappeared, replaced by a low centered over the Middle Eastern desert region. The Asiatic low is produced by the intense summer heating of the landscape.

The movement of the ITCZ and the change in the pressure pattern with the seasons create a reversing wind pattern in Asia known as the *monsoon* (**Figure 5.15**). 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, warm, humid air from the Indian Ocean and the southwestern Pacific moves northward and northwestward into Asia.

In North America during summer, warm, moist air from the Gulf of Mexico tends to move northward across the central and eastern United States. In winter, the air flow across North America generally reverses, and dry, continental air from Canada moves south and eastward.

Asian monsoon **Figure 5.15**

A Monsoon rains Heavy monsoon rains turn streets into canals in Delhi, India.



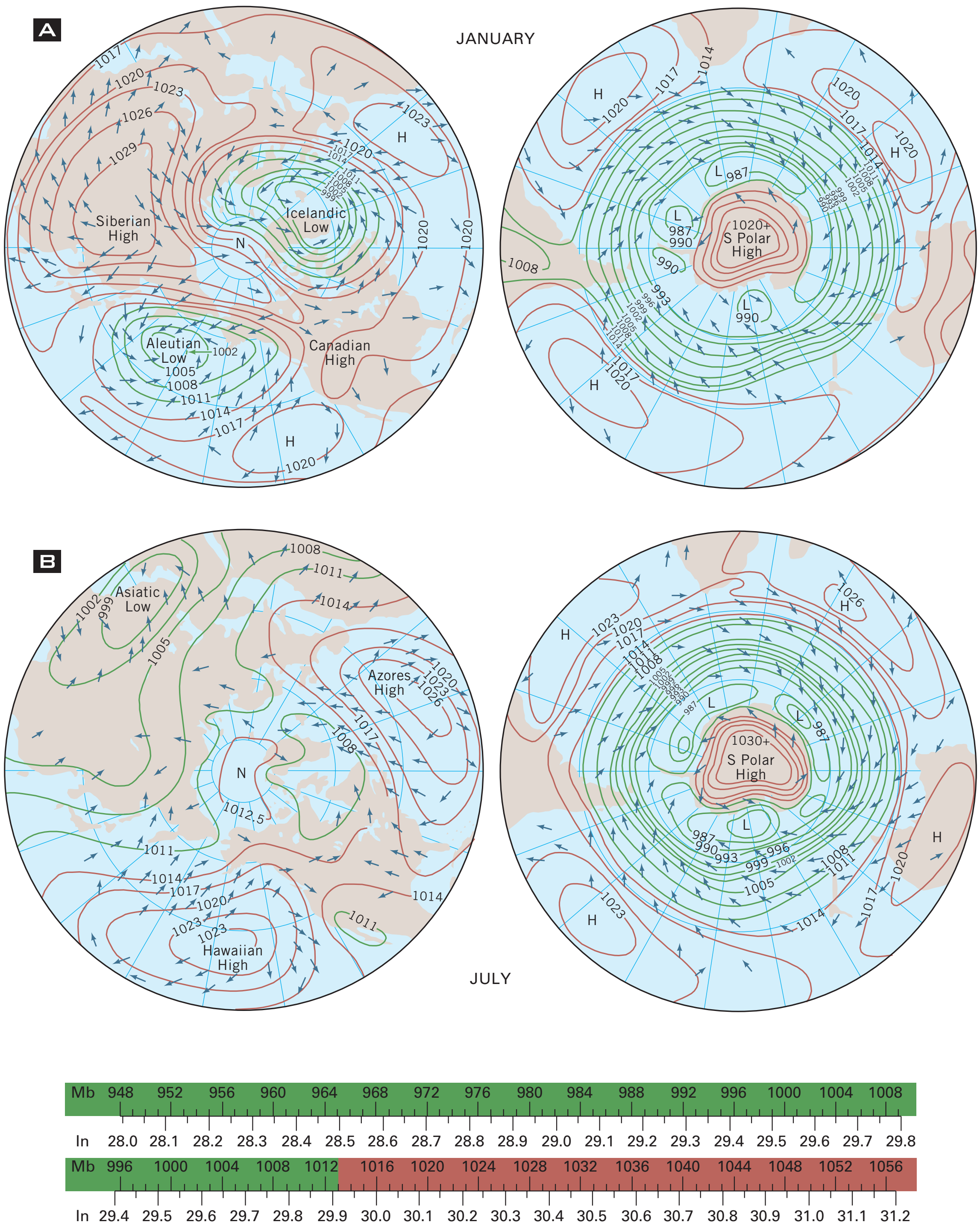
B Monsoon wind patterns The Asiatic monsoon winds alternate in direction from January to July, responding to reversals of barometric pressure over the large continent.

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 5.16).

Atmospheric pressure maps—Polar FIGURE 5.16

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.



A January In 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.

B July In 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.

Continents are colder in winter and warmer in summer than oceans at the same latitude. We know that cold air is associated with surface high pressure and warm air with surface low pressure. So, continents have high pressure in winter and low pressure in summer.

The higher latitudes of the southern hemisphere have a polar continent surrounded by a large ocean. There is a permanent anticyclone—the South Polar high—centered over Antarctica because the continent is covered by ice and is always cold. Easterly winds spiral outward from the high-pressure center. Surrounding the high is a band of deep low pressure, with strong, inward-spiraling westerly winds. 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."

CONCEPT CHECK STOP

How do Hadley cells develop?

What is the ITCZ?

What are subtropical high-pressure belts?

Winds Aloft

LEARNING OBJECTIVES

Explain how pressure gradients develop at upper levels.

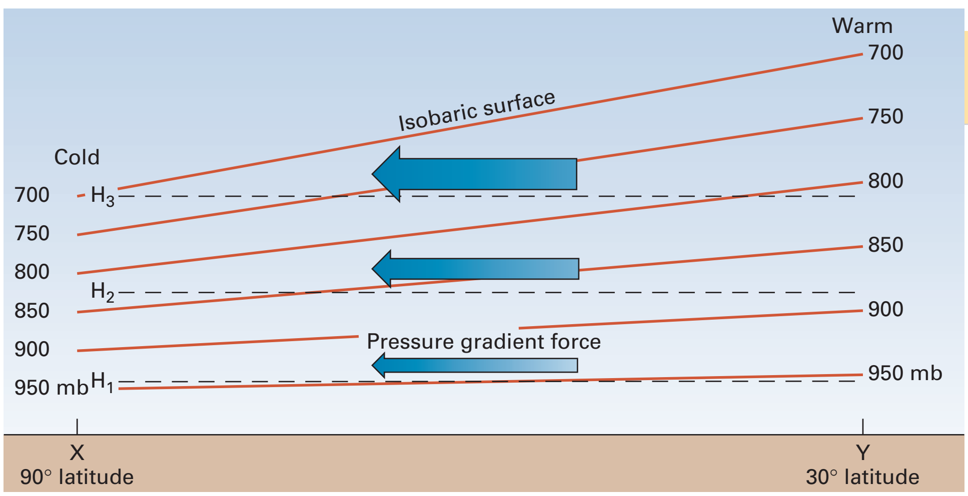
Discuss the geostrophic wind.

Show how Rossby waves develop and grow.

Define jet streams.

We've looked at air flows 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 poles to the equator. This gives rise to a pressure gradient (FIGURE 5.17).



Upper-air pressure gradient
FIGURE 5.17

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.

THE GEOSTROPHIC WIND

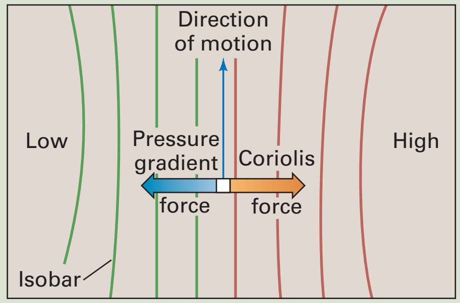
How does a pressure gradient force pushing poleward produce wind, and what will the wind direction be? Any wind motion is subject to the Coriolis force, which turns it to the right in the northern hemisphere and to the left in the southern hemisphere. So, poleward air motion is toward the east, creating 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.

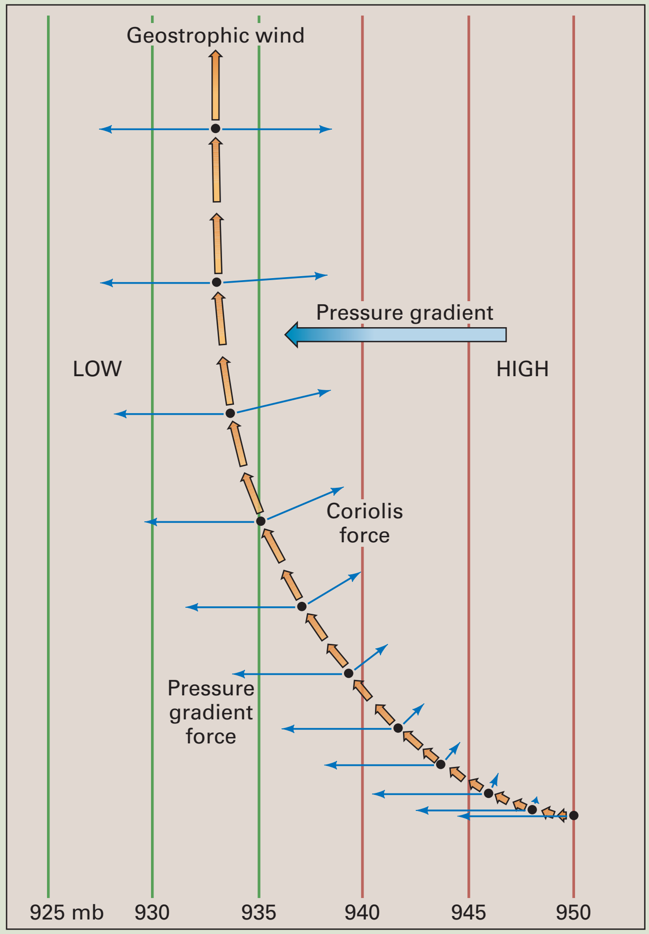
Imagine a parcel of air, as shown in FIGURE 5.18. The air parcel begins to move poleward in response to the pressure gradient force. As it accelerates, the Coriolis force pulls it increasingly toward the right. As its velocity increases, the parcel turns increasingly rightward until the Coriolis force 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 air flow 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.

Geostrophic wind Wind at high levels above the Earth's surface blowing parallel with a system of straight, parallel isobars.

Geostrophic wind FIGURE 5.18



A At upper levels in the atmosphere, a parcel of air is subjected to a pressure gradient force and a Coriolis force.



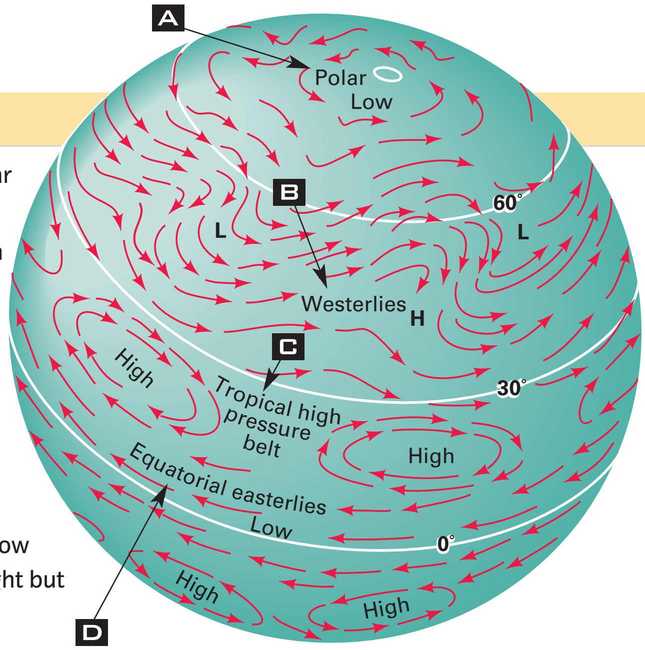
B The parcel of air moves in response to a pressure gradient. At the same time it is turned progressively sideward until the pressure gradient force and Coriolis force balance, producing the geostrophic wind.

GLOBAL CIRCULATION AT UPPER LEVELS

FIGURE 5.19 sketches the general air-flow pattern at higher levels in the troposphere. It has four major features—weak equatorial easterlies, tropical high-pressure belts, upper-air westerlies, and a polar low. We've seen that the general temperature gradient from the tropics to the poles creates a pressure gradient force that 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.

Global upper-level winds FIGURE 5.19



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*.

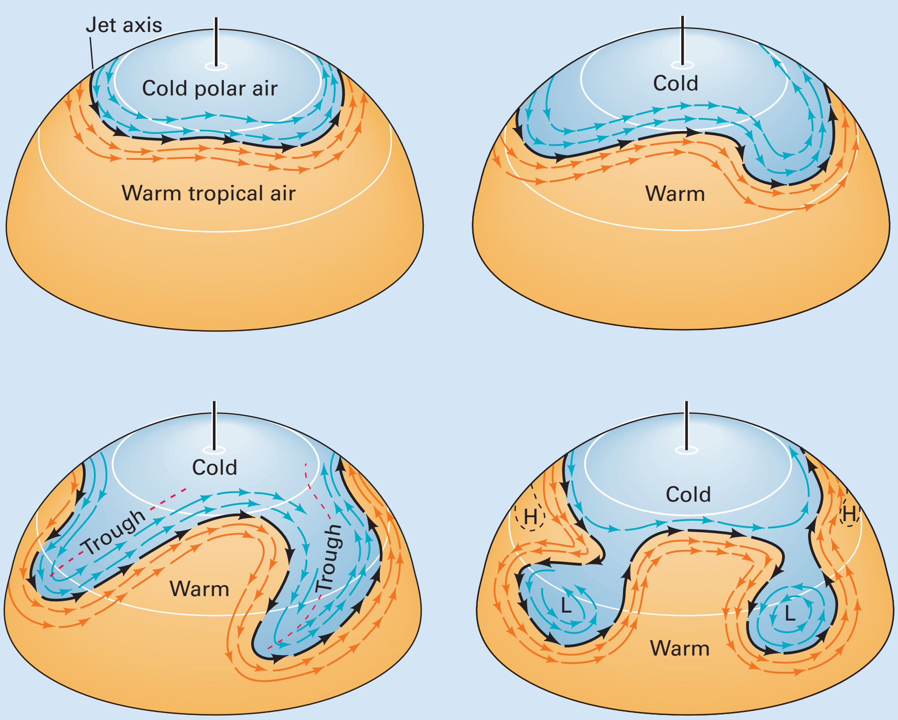
ROSSBY WAVES, JET STREAMS, AND THE POLAR FRONT

Rossby waves
Horizontal undulations in the flow path of the upper-westerlies; also known as upper-air waves.

When the upper-air westerlies undulate from their smooth westerly flow, they frequently create **Rossby waves**. The waves arise in the zone where cold polar air meets warm tropical air, called the *polar front*. About three to seven Rossby waves arise here. FIGURE 5.20 describes their formation cycle. Rossby waves are the reason weather in the midlatitudes is often so variable, because they cause pools of warm, moist air and

Rossby waves FIGURE 5.20

Rossby waves form in the westerlies of the northern hemisphere, marking the boundary between cold polar air and warm tropical air.



A The flow of air along the front will be fairly smooth for several days or weeks, but then it will begin to undulate.

B As the undulation becomes stronger, Rossby waves begin to form. Warm air pushes poleward, while cold air is brought to the south.

C The waves become stronger and more developed. A tongue of cold air is brought to the south as warm air is carried northward.

D Eventually, the tongue is pinched off leaving a pool of cold air at a latitude far south of its original location. The waves form cyclones of cold air, which can persist for some days or a week.

> **Jet streams**
> High-speed air flow in narrow bands within the upper-air westerlies and along certain other global latitude zones at high levels.

cold, dry air to alternately invade midlatitude land masses.

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.

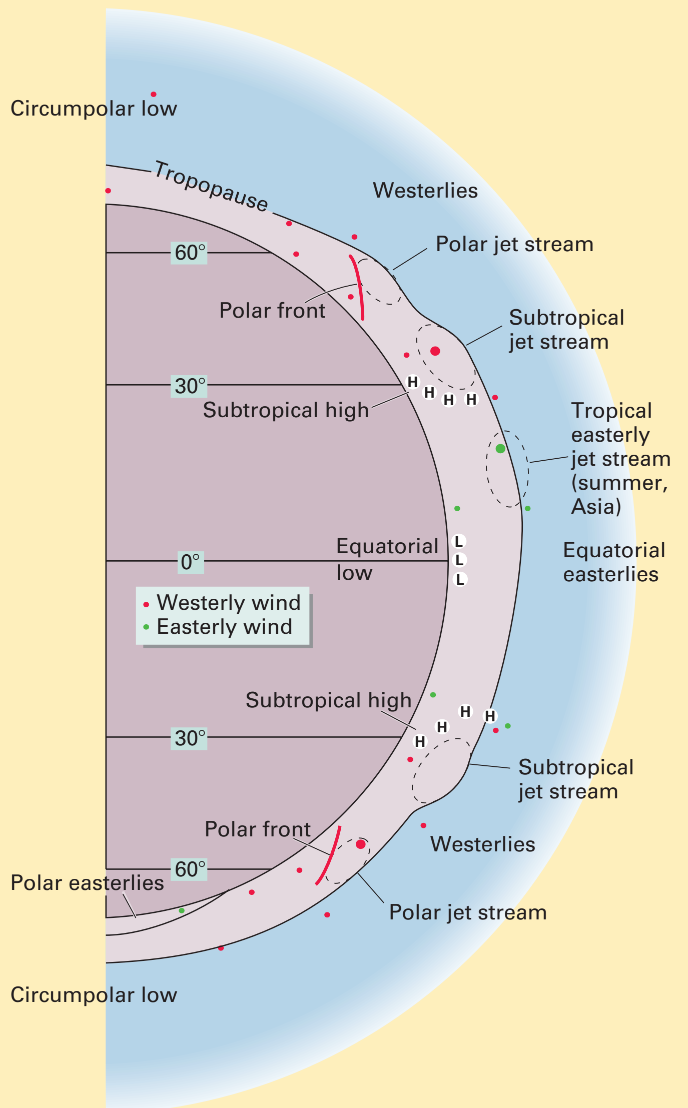
There are three kinds of jet streams. Two are westerly streams, and the third is a weaker jet with easterly winds that develops in Asia as part of the summer monsoon circulation. These are shown in FIGURE 5.21A. The most poleward type of jet stream is located along the polar front. It is called the *polar-front jet stream* (or simply the "polar jet") (FIGURE 5.21B).

The polar jet is generally located between 35° and 65° latitude in both hemispheres. It follows the edges of Rossby waves at the boundary between cold polar air and warm subtropical air. 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).

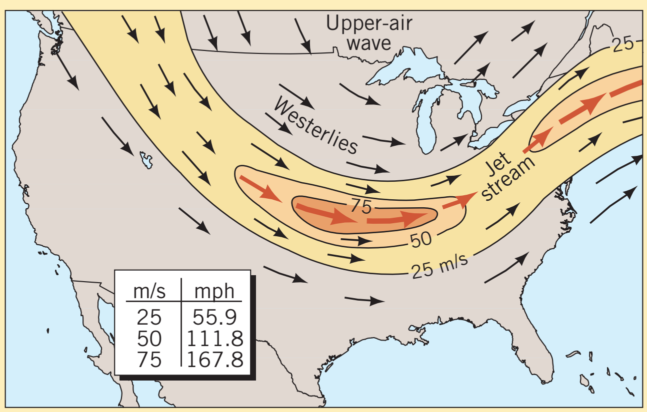
The subtropical jet stream occurs at the tropopause, just above subtropical high-pressure cells in the northern and southern hemispheres. There, westerly wind speeds can reach 100 to 110 m/s (about 215 to 240 mph), associated with the increase in velocity that occurs as an air parcel moves poleward from 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.

Jet streams FIGURE 5.21



A Upper-level circulation cross section A schematic diagram of wind directions and jet streams along an average meridian from pole to pole. The four polar and subtropical jets are westerly in direction, in contrast to the single tropical easterly jet.



B Polar jet stream The polar jet stream is shown on this map by lines of equal wind speed.

What a Geographer Sees

Jet stream clouds

The white areas (A) are wind-blown sandsheets, while the medium tones are weathered rock materials that have not been carried as far by wind or water from their origin. Ranges of hills and low mountains (B) appear darker due to a sparse vegetation cover. The overall blue tint is produced by atmospheric scattering, which is more intense in the blue region of the spectrum.

In this space photo, the astronauts aimed their camera to take in the Nile River Valley and the Red Sea. At the left you can see the tip of the Sinai Peninsula. They also captured a beautiful band of cirrus clouds, at about 25° N lat. A geographer would identify this as a band of jet stream clouds that occur 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).

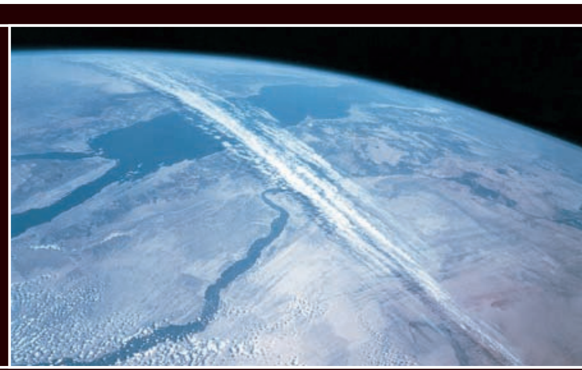
CONCEPT CHECK STOP

What is the geostrophic wind?

Where do Rossby waves develop?

Why are Rossby waves important?

What are jet streams?



Ocean Currents

Learning Objectives

Describe ocean currents and why they occur.

Explain the general features of global surface current patterns.

Explain El Niño and La Niña ocean current changes in the Pacific.

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 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.

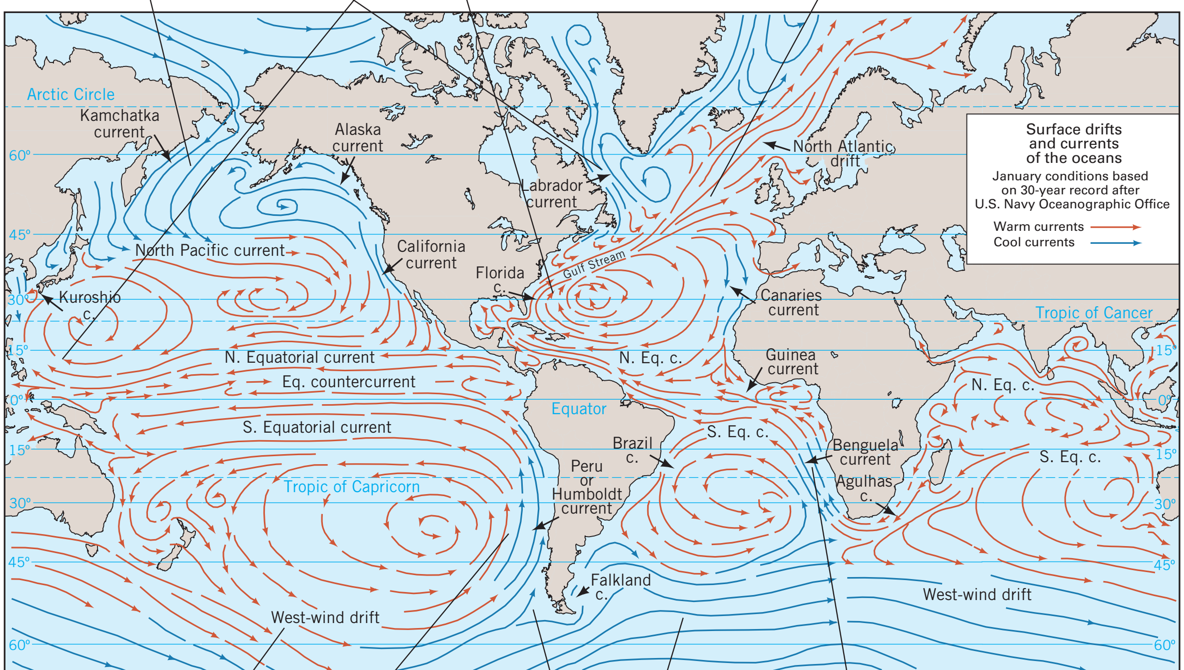
January ocean currents FIGURE 5.22

Surface drifts and currents of the oceans in January.

Cold currents flow equatorward. 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.

Ocean current Persistent, dominantly horizontal flow of water.

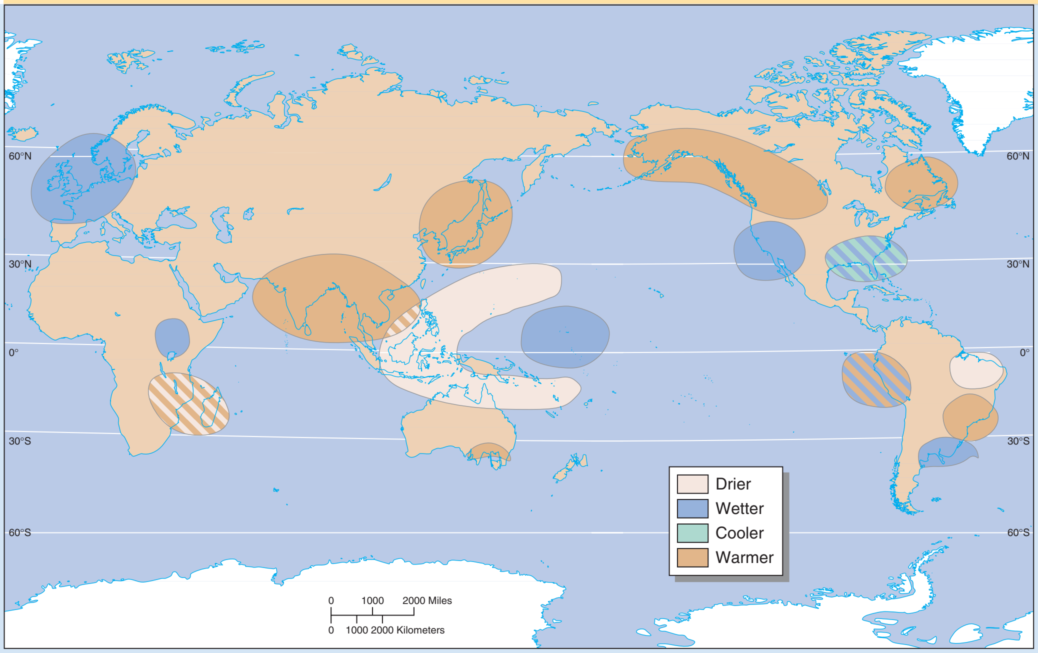
An **ocean current** is any persistent, dominantly horizontal flow of ocean water. Current systems exchange heat between low and high latitudes and are essential in sustaining the global energy balance. Surface currents are driven by prevailing winds, while deep currents are powered by changes in temperature 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. FIGURE 5.22 presents a world map of surface ocean currents for the month of January.

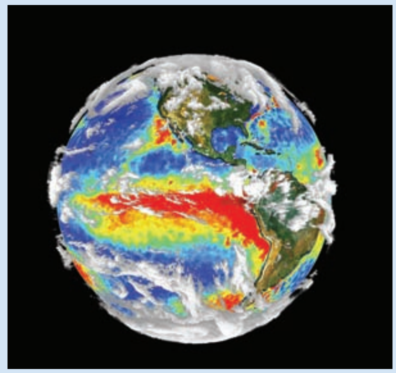
CURRENT PATTERNS

A dramatic phenomenon of ocean-surface currents is *El Niño*, which we met in the chapter opener. During an El Niño event, Pacific surface currents shift into a characteristic pattern. Pacific upwelling along the Peruvian coast ceases, trade winds weaken, and a weak equatorial eastward current develops. Precipitation patterns change across the globe, bringing floods to some regions and droughts to others. 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 5.23 shows sea-surface temperature observed during the El Niño Southern Oscillation, or ENSO.

El Niño-ENSO FIGURE 5.23



A 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.



B ENSO-driven warmer waters off western South America.

CONCEPT CHECK STOP

HOW are pressure differences created in ocean water?

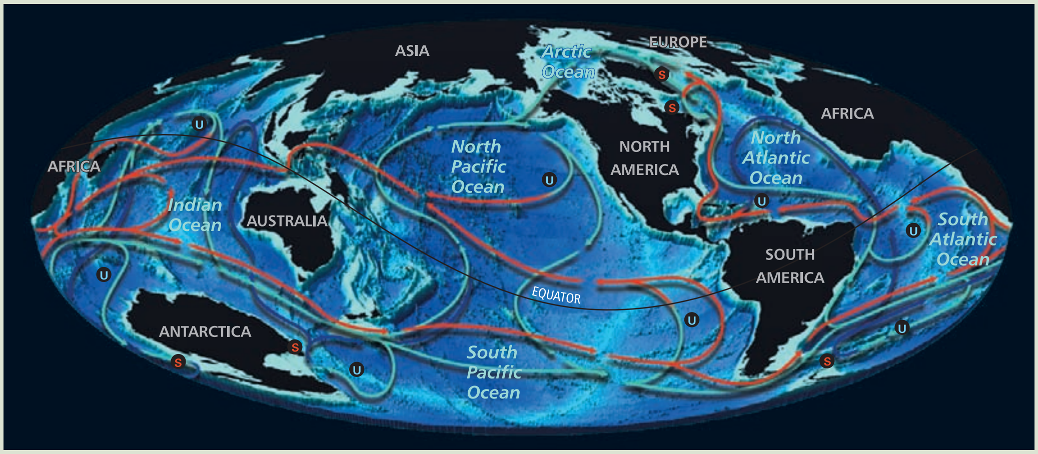
HOW do El Niño and La Niña conditions affect Peruvian coastal upwelling and trade winds?

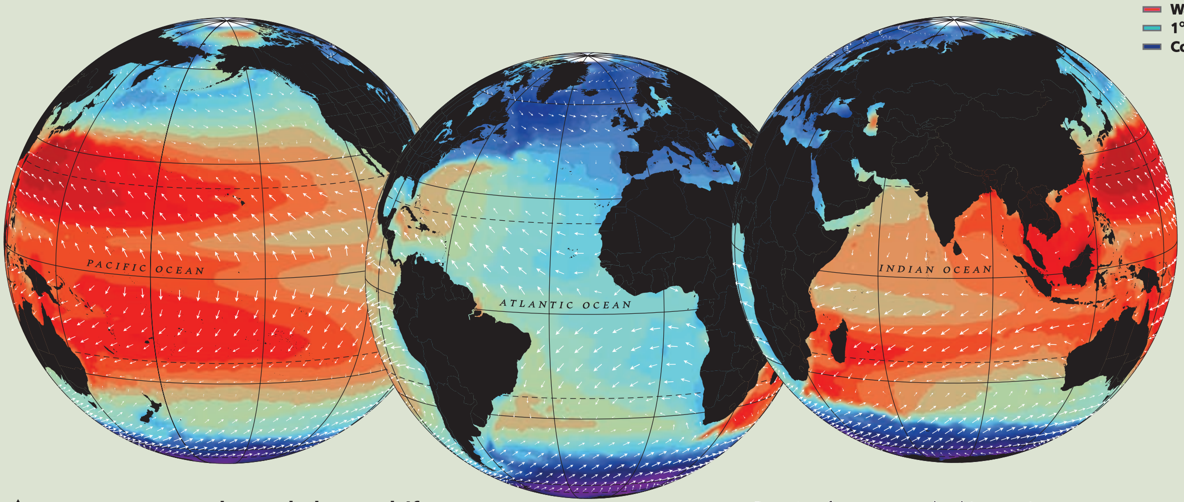
OCEAN CURRENTS

The atmosphere and oceans exchange heat, fresh water, momentum, and gases. While the atmosphere changes rapidly, the world ocean changes more slowly because of its vast bulk. On land, we feel the fast and slow changes of the atmosphere–ocean system as weather and climate.

▶ Ocean circulation

Ocean circulation is the large-scale movement of oceanic waters. Warm surface waters in the tropics generally move poleward, losing heat on route. They sink at higher latitudes, flow equatorward, and eventually upwell to the surface to complete the circuit. Ocean circulation also carries waters across different basins, redistributing heat geographically.



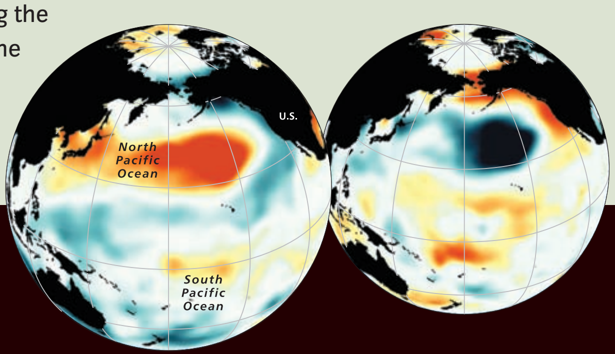


▲ Ocean topography and Ekman drift

The speed and direction of ocean currents can be computed from small variations in the height of the sea surface. These satellite-derived images depict a ten-year average of the shape of the changing ocean surface. The undulations range over a few meters in height, and flow occurs along the color contours. The white arrows show ocean velocity caused exclusively by the effect of wind on the top layer of the ocean, which is called the Ekman Drift.

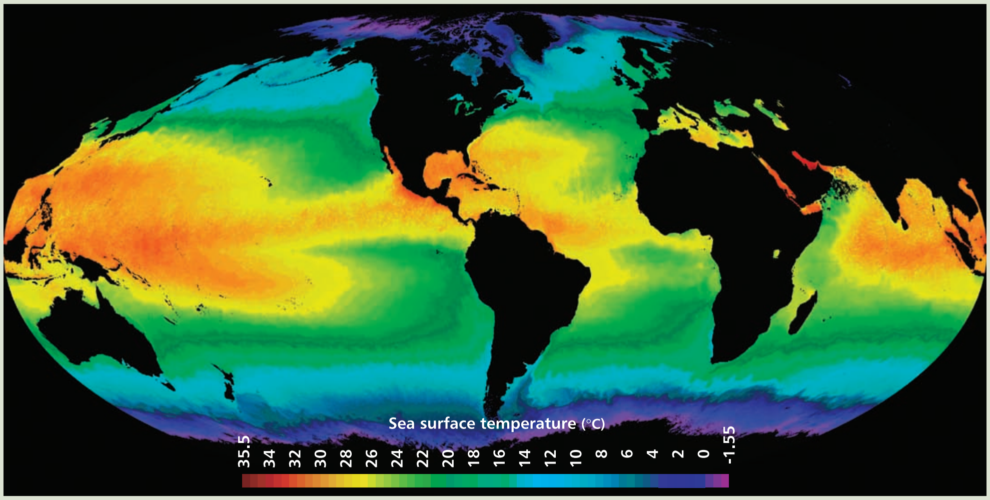
▶ Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) is a long-lived climate pattern of Pacific Ocean temperatures. The extreme warm or cool phases can last for as long as two decades. Ocean temperatures suggest a reversal to cool PDO conditions in 1998.



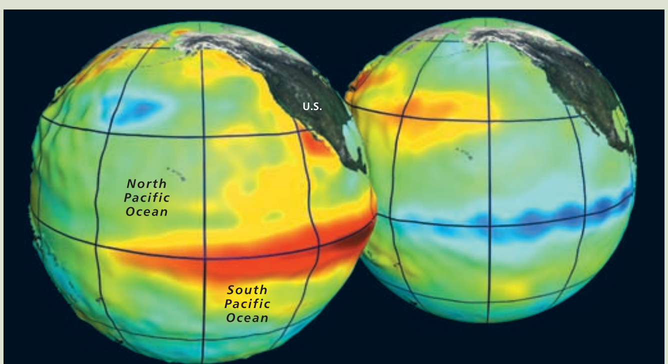
SEA SURFACE TEMPERATURE

Because the heat-holding capacity of water is so high, sea surface temperature has an important effect on both weather and climate. Slow changes in ocean-atmosphere systems, such as El Niño, the North Atlantic Oscillation, and the Pacific Decadal Oscillation, can be felt in climate cycles over many years.

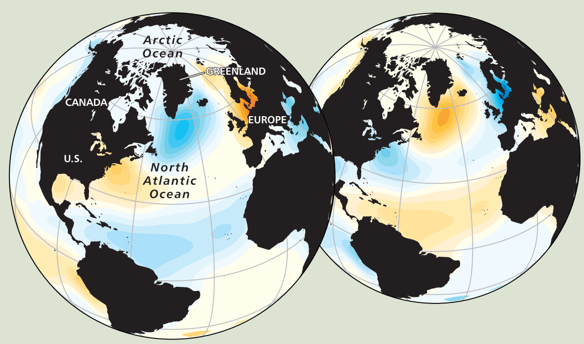


◀ **Sea-surface temperature** While ocean temperatures are generally warm near the equator and cold at high latitudes, winds and currents distort this simple picture. Thus, the western equatorial Pacific is warmer than the eastern half, and warm equatorial currents move poleward in the form of major ocean currents such as the Gulf Stream.

▼ **El Niño–La Niña** El Niño is the appearance of warm water in the eastern equatorial Pacific (left) near Christmas time. El Niño is often followed by La Niña, characterized by cold ocean temperatures across the equatorial Pacific. These local ocean properties are connected to global changes in atmospheric patterns.

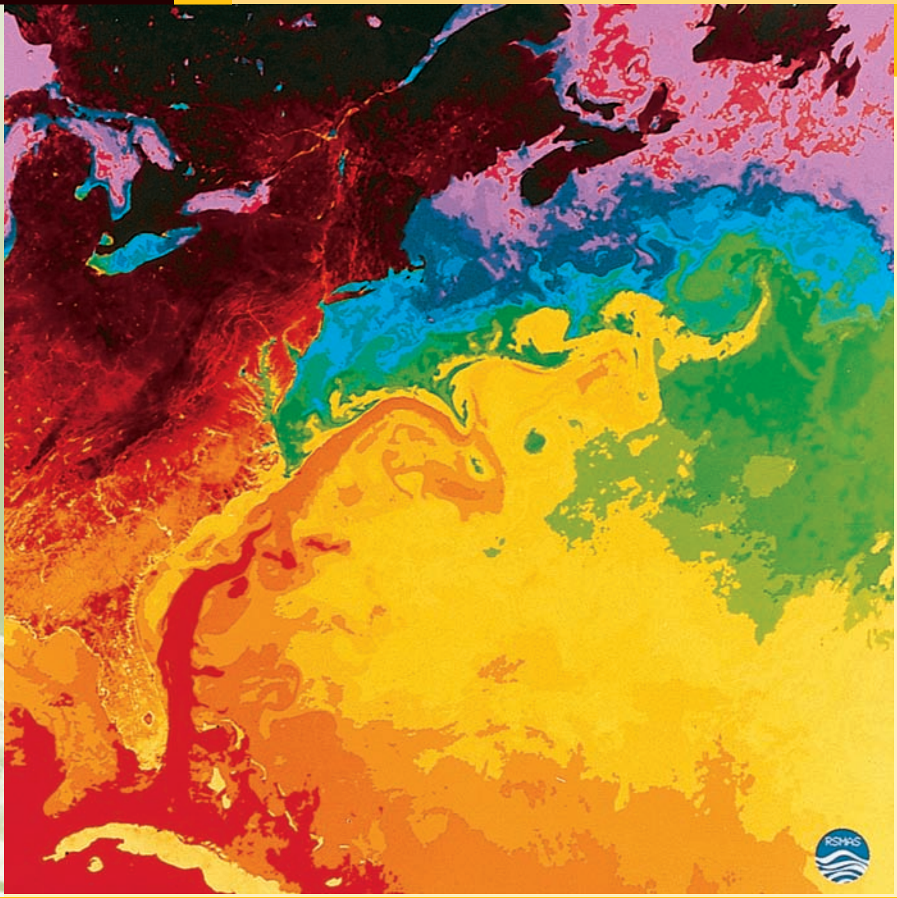


▼ **North Atlantic Oscillation** The weather of northern Europe has dramatic swings every 5–10 years in connection with the North Atlantic Oscillation. When the air pressure over Portugal becomes larger than that over Iceland, the westerly wind in the Atlantic becomes stronger and brings warm and wet marine air to northern Europe for a mild winter. The opposite brings a colder and drier winter. The extreme warm or cool phases can last for as long as two decades. Ocean temperatures suggest a reversal to cool PDO conditions in 1998.



What is happening in this picture?

- This striking image, acquired by a NASA satellite, shows land- and sea-surface temperature for a week in April. The eastern coast of North America is on the left, with the Atlantic Ocean on the right. The color scale ranges from deep red (hot) to violet (cold). The Gulf Stream, bringing warm waters northward, stands out as a tongue of red and yellow, extending from the Caribbean along the coasts of Florida and the Carolinas. Can you pick out the tip of the Labrador current, bringing cold water southward?
- Looking at the land, note the purple colors of the northern Great Lakes. What might this indicate?



VISUAL SUMMARY

1 Atmospheric Pressure

1. The term *atmospheric pressure* describes the weight of air pressing on a unit of surface area. Atmospheric pressure is measured using a barometer.
2. Atmospheric pressure decreases rapidly as altitude increases.

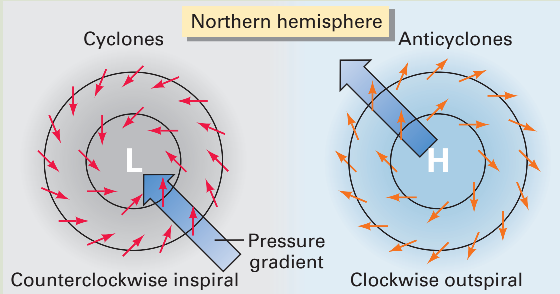
2 Local Wind Patterns

1. Air motion is produced by pressure gradients. Local winds are generated by local pressure gradients.
2. Pressure gradients form when air is unevenly heated, creating convection loops.
3. Sea and land breezes are examples of convection loops formed from unequal heating and cooling of land and water surfaces. Mountain and valley winds, Santa Ana, and chinooks are other examples of local winds.

3 Cyclones and Anticyclones

1. The Earth's rotation creates the Coriolis effect.

2. The Coriolis force deflects wind motion, making air spiral around cyclones (centers of low pressure and convergence) and anticyclones (centers of high pressure and divergence).



4 Global Wind and Pressure Patterns

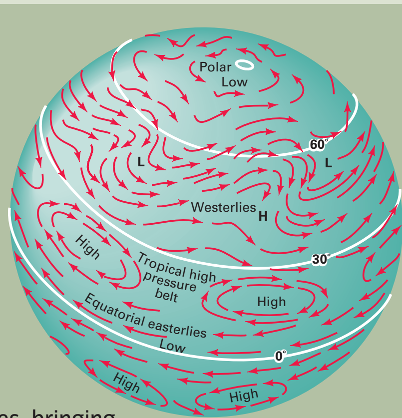
1. Hadley cells develop because the equatorial and tropical regions are heated more intensely than the higher latitudes.

2. These loops drive 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.

5 Winds Aloft

1. Winds in the atmosphere are dominated by a global pressure gradient force between the tropics and pole in each hemisphere.

2. The global pressure gradient force and the Coriolis force generate strong westerly geostrophic winds in the upper air.

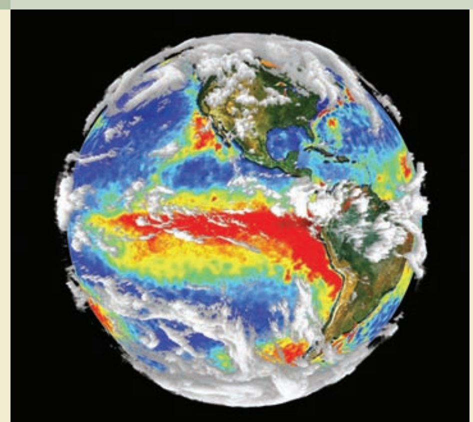


3. Rossby waves develop in the upper-air westerlies, bringing cold, polar air equatorward and warmer air poleward. The polar-front and subtropical jet streams are concentrated westerly wind streams with high wind speeds.

6 Ocean Currents

1. 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.

2. El Niño events occur on a three- to eight-year cycle when an unusual flow of warm water in the equatorial Pacific moves eastward to the coasts of Central and South America, suppressing the normal northward flow of the Humboldt Current. Upwelling along the Peruvian coast is greatly reduced.



KEY TERMS

- **atmospheric pressure** p. 126
- **barometer** p. 126
- **isobars** p. 129
- **pressure gradient** p. 129
- **convection loop** p. 130
- **Coriolis effect** p. 132
- **cyclone** p. 133
- **anticyclone** p. 133
- **Hadley cell** p. 134
- **intertropical convergence zone (ITCZ)** p. 134
- **subtropical high-pressure belts** p. 134
- **polar front** p. 135
- **geostrophic wind** p. 140
- **Rossby waves** p. 141
- **jet streams** p. 142
- **ocean current** p. 145

CRITICAL AND CREATIVE THINKING QUESTIONS

1. What is 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? How does atmospheric pressure change with altitude?

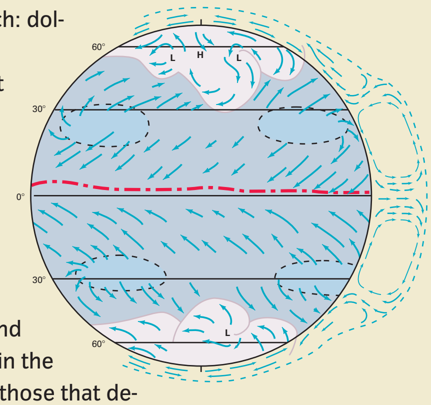
2. Describe a simple convective wind system. In your answer, explain how air motion arises.

3. How do land and sea breezes form? How do they illustrate the concepts of pressure gradient and convection loop?

4. Define cyclone and anticyclone. What type of weather is associated with each and why? Draw four spiral patterns showing outward and inward flow in clockwise and counterclockwise directions. Explain why different diagrams are needed for the northern and southern hemispheres.

5. What is the Asian monsoon? What are its features in summer and winter? How is the ITCZ involved? How is the monsoon circulation related to seasonal high- and low-pressure centers in Asia?

6. On the ideal Earth illustration to the right (without seasons or ocean-continent features) sketch the 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.



7. Compare the winter and summer patterns of high and low pressure that develop in the northern hemisphere with those that develop in the southern hemisphere.

8. 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?

9. What is the general pattern of ocean-surface current circulation? How is it related to global wind patterns?

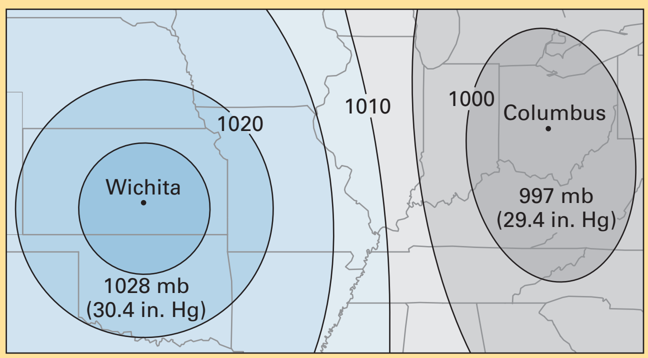
SELF-TEST

1. A barometer is an instrument used to measure _______________.
   a. air pressure
   b. hydraulic pressure
   c. tectonic pressure at earthquake fault zones
   d. glacial compression under ice sheets

2. As an individual moves higher in elevation, the _______________.
   a. easier it is to breathe because the air is cleaner
   b. easier it is to breathe because the air is thinner
   c. harder it is to breathe because the air molecules are closer together
   d. harder it is to breathe because the air is thinner

3. The boiling point of water lowers as one goes higher in elevation because _______________.
   a. water is less dense at higher elevations
   b. air is denser at higher elevations
   c. air pressure is less at higher elevations
   d. upward water pressure is much greater

4. The map shows isobars over Wichita and Columbus. Label the high- and low-pressure centers and draw an arrow showing the direction of the pressure gradient.

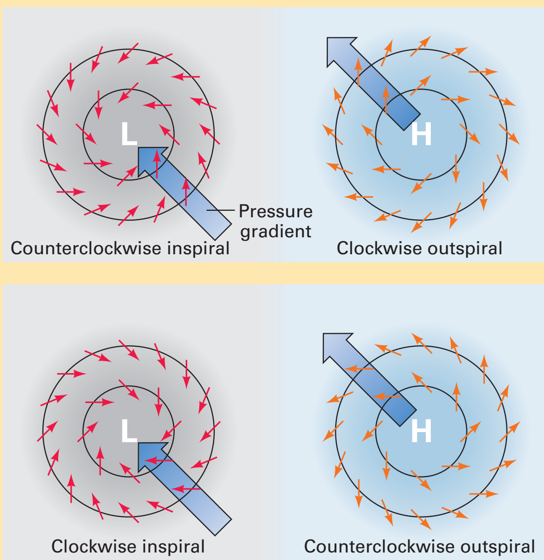


5. A land breeze generally occurs _______________.
   a. at night, when the land cools below the surface temperature of the sea
   b. when strong winds blow in from the sea over the land
   c. only during certain restricted seasons
   d. during the day when the land heats above the surface temperature of the sea

6. A parcel of air at the surface is subjected to three forces and the balance among the pressure gradient, Coriolis, and ______________ forces determines the direction of motion of the parcel of air.
   a. gravitational
   b. frictional
   c. centrifugal
   d. divergent

7. The Coriolis effect is ______________.
   a. a result of the Earth's rotation from east to west
   b. a result of the Earth's rotation from the west to the east and causes objects to curve to the right in the northern hemisphere
   c. a result of the Earth's rotation from the west to the east and causes objects to curve to the left in the northern hemisphere
   d. unrelated to other physical phenomena on the Earth

8. The diagram shows the motion of air in cyclones and anticyclones. Identify which figures represent: (a) a northern hemisphere anticyclone, (b) a southern hemisphere anticyclone, (c) a northern hemisphere cyclone, and (d) a southern hemisphere cyclone.



9. Cloudy and rainy weather is often associated with the inward and upward convergence of air within ______________.
   a. anticyclones
   b. cold fronts
   c. warm fronts
   d. cyclones

10. In the Hadley cell convection loop, air rises at the ITCZ and descends in the ______________.
   a. polar high-pressure cells
   b. subpolar low-pressure cells
   c. subtropical high-pressure cells
   d. polar low-pressure cells

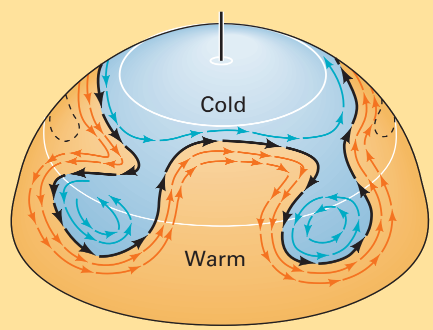
11. The movement of the ITCZ and the change in the pressure pattern with the seasons create a reversing wind pattern in Asia known as the ______________, where cool-dry air flow from the northeast dominates during the low-Sun season and warm-moist air flow from the southwest dominates during the high-Sun season.
   a. northeast trades
   b. southeast trades
   c. monsoon
   d. westerlies

12. At upper levels in the atmosphere, as a parcel of air moves in response to a pressure gradient, it is turned progressively sideward until the gradient and Coriolis forces balance to produce the ______________.
   a. geostrophic wind
   b. tropospheric wind
   c. upper-air westerlies
   d. equatorial easterlies

13. Jet streams are ______________.

   a. narrow zones at a high altitude in which wind streams reach great speeds over the speed of sound
   b. narrow zones at a high altitude in which wind streams sometimes reach speeds of over 150 miles per hour
   c. rivers of wind that only exist along the equator and travel at fairly high velocities
   d. well known for shredding aircraft when they inadvertently enter them

14. The diagram shows the formation of Rossby waves in the upper atmosphere. Label (a) the jet axis, (b) the regions of high pressure, (c) the regions of low pressure, and (d) the newly formed cyclones.



15. El Niño is the name given to the warm phase of an effect associated with the reversal of ______________.
   a. ocean currents in the northern hemisphere
   b. ocean currents in the southern ocean
   c. wind flow patterns along the ITCZ
   d. ocean currents in the southern Pacific Ocean.

Weather Systems

6

"Around 4 a.m. all hell broke loose. I have experienced severe storms with winds in excess of 75 m.p.h., but these gusts were blowing at well over 140 m.p.h. By now only an occasional thud—some building collapsing or losing a roof—would punctuate the noise. Windows from the surrounding buildings imploded, scattering glass everywhere. I looked down at my arm and saw blood, not knowing when I'd been cut. . . .

"My senses were on red alert . . . Everything I see, hear, feel—even taste—goes by so quickly that my mind simply slows it all down to preserve rational thought. The alternative is sheer panic.

"The infamous 'hurricane wail' people talk about is in many ways unreal—'the scream of the devil,' Steve and I agreed. The piercing sound alone is wicked enough, but mixed with breaking glass and crashing debris, it rattled me inside. I will never forget that sound. . . . For more than five hours Andrew pounded the garage and the rest of South Florida with everything it had. As the building shook and the storm raged all around, I felt as though I was inside a tornado and riding an earthquake at the same time."*

Those were the words of veteran storm-chaser Warren Faidley, who decided to ride out the storm as Hurricane Andrew lashed the coast of South Florida on August 23, 1992, with his friends Steve and Mike. Since then we have seen the devastation wrought by hurricanes such as Katrina, with damage at over $100 billion. Such events remind us that we are still at the mercy of the weather.

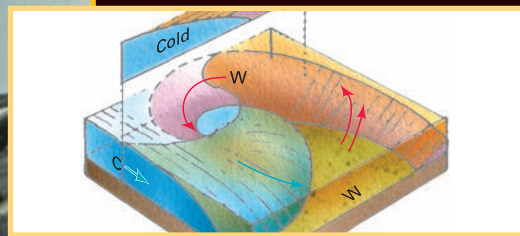
*From *Weatherwise*, vol. 45, no. 6, Copyright © Warren Faidley. Used by permission.

NATIONAL GEOGRAPHIC

Homestead, Florida after Hurricane Andrew.

CHAPTER OUTLINE

■ **Air Masses p. 154**



■ **Traveling Cyclones and Anticyclones p. 159**

■ **Tropical and Equatorial Weather Systems p. 166**

■ **Cloud Cover, Precipitation, and Global Warming p. 174**

Air Masses

LEARNING OBJECTIVES

Define air mass.

Explain how air masses are classified.

Describe cold, warm, and occluded fronts.

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 temperature lapse* rate, and surface-specific humidity. Air masses can be searing hot, icy cold, or any temperature in between. Moisture content can also vary wildly between different air masses.

Air mass
Extensive body of air in which temperature and moisture characteristics are fairly uniform over a large area.

Air masses pick up their temperature and moisture characteristics in *source regions*, where the air moves slowly or stagnates. FIGURE 6.1 gives an example of how air masses can acquire different features over different parts of the globe.

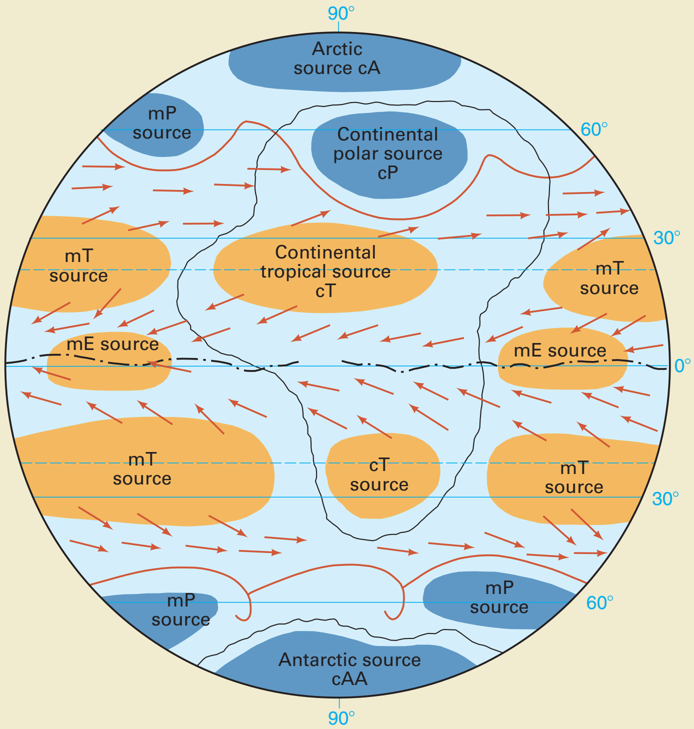
Pressure gradients and upper-level wind patterns drive air masses from one region to another. When an air mass moves to a new area, its properties will change because it is influenced by the new surface environment. For example, the air mass may lose heat or take up water vapor.

We classify air masses by their latitude and by their source regions. Their latitudinal position is important because it determines the surface temperature and the environmental temperature lapse rate of the air mass. The nature of the underlying surface—continent or ocean—usually determines the moisture content. These latitudinal classifications are shown in FIGURE 6.2.

Combining the two types of labels described in FIGURE 6.2 produces a list of six important types of air masses: maritime equatorial (mE), maritime tropical (mT), continental tropical (cT), maritime polar

Source regions
FIGURE 6.1

An air mass with warm temperatures and a high water vapor content develops over warm equatorial oceans. Aldabra Island group, Seychelles.



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

We also use two subdivisions to specify the type of underlying surface:

Air Mass	Symbol	Source region
Maritime	m	Oceans
Continental	c	Continents

Global air masses and source regions FIGURE 6.2

www.wiley.com/college/strahler

In the center of the figure we have 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.

(mP), continental arctic (cA), and continental antarctic (cAA). Air mass temperature can range from −46°C (−51°F) for cA air masses to 27°C (81°F) for mE. Specific humidity of an air mass can range from 0.1 g/kg for the cA air mass to as much as 19 g/kg for the mE air mass. In other words, maritime equatorial air can hold about 200 times as much moisture as continental arctic air.

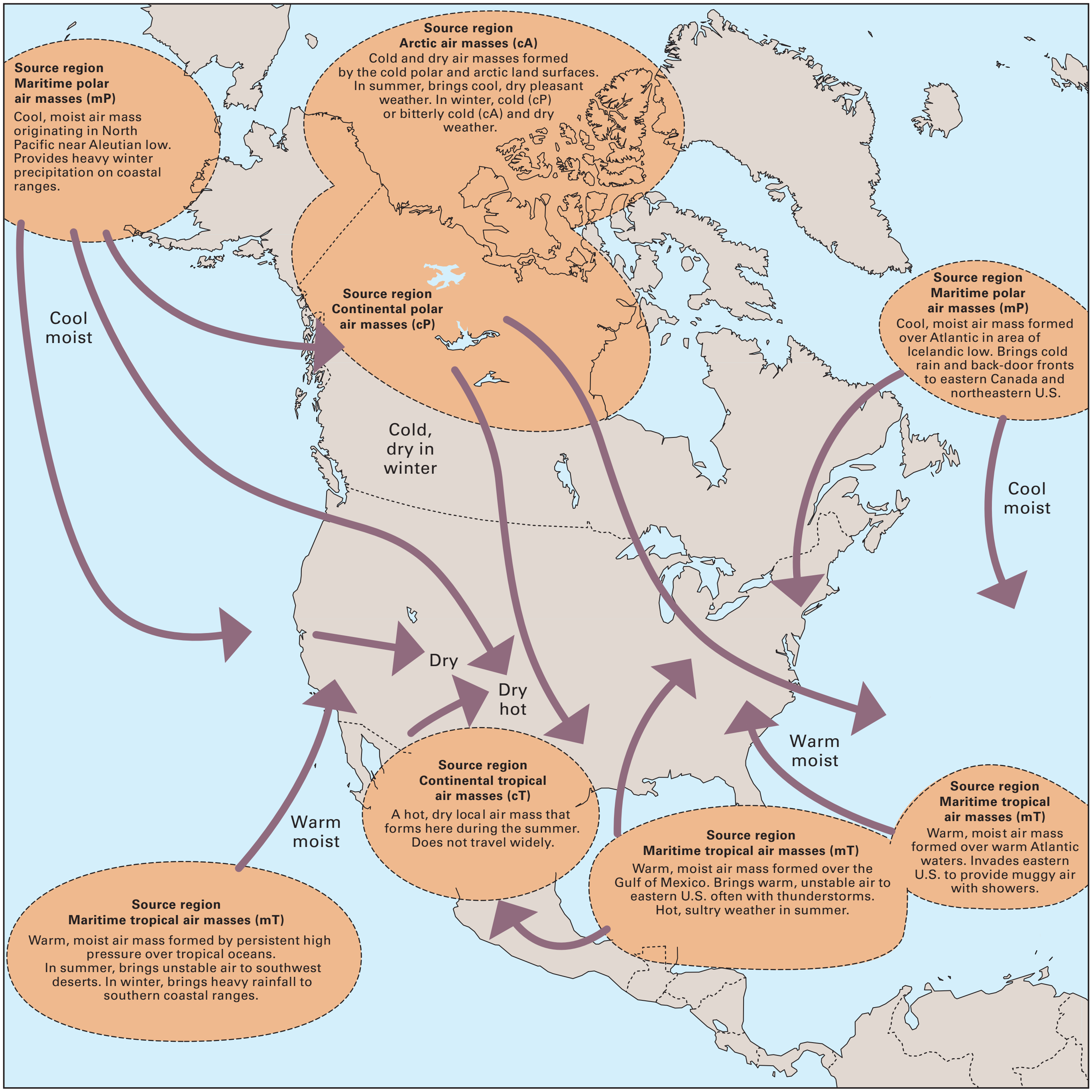
The maritime tropical air mass (mT) and maritime equatorial air mass (mE) originate over warm oceans in the tropical and equatorial zones. They are quite similar in temperature and water vapor content. With their high values of specific humidity, both can produce heavy precipitation. The continental tropical air mass (cT) has its source region over subtropical deserts of the continents. Although this air mass may have a substantial water vapor content, it tends to be stable and has low relative humidity when heated strongly during the daytime.

The maritime polar air mass (mP) originates over midlatitude oceans. It holds less water vapor than the maritime tropical air mass, so the mP air mass yields only moderate precipitation. Much of this precipitation is *orographic* and occurs over mountain ranges on the western coasts of continents. The continental polar air mass (cP) originates over North America and Eurasia in the subarctic zone. It has low specific humidity and is very cold in winter. Last is the continental arctic (and continental antarctic) air mass type (cA, cAA), which is extremely cold and holds almost no water vapor.

FIGURE 6.3 shows the air masses that form near North America and their source regions. These air masses have a strong influence on North American weather.

COLD, WARM, AND OCCLUDED FRONTS

There is usually a sharply defined boundary, or **front**, between a given air mass and its neighboring air masses.



North American air mass source regions and trajectories FIGURE 6.3

Air masses acquire temperature and moisture characteristics in their source regions, then move across the continent.

Front Surface of contact between two unlike air masses.

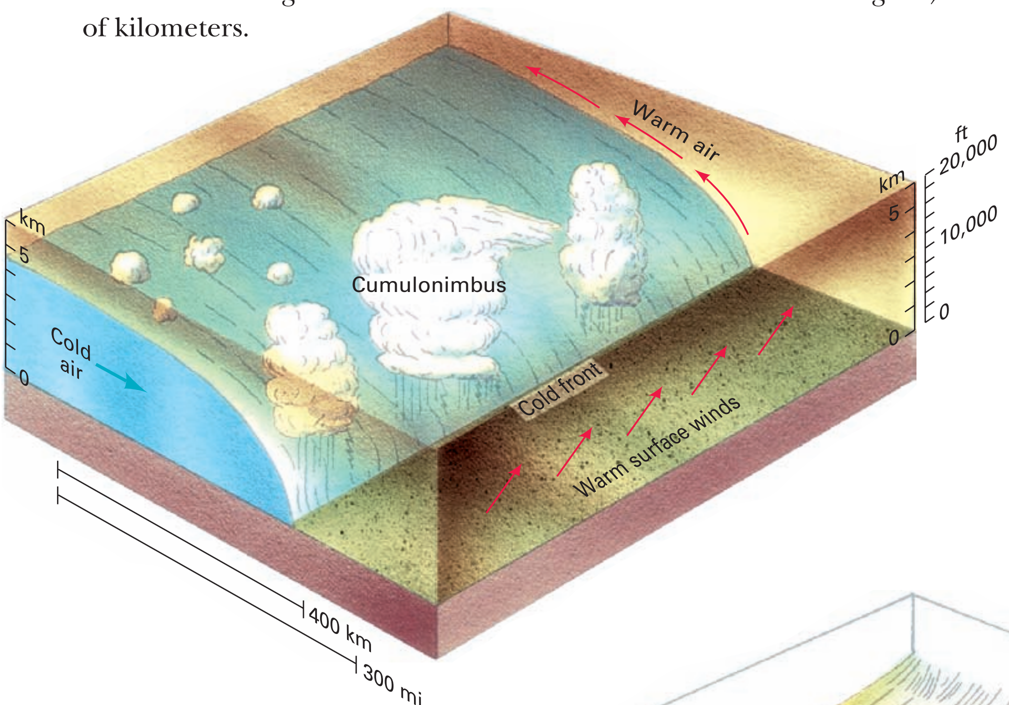
Cold front Moving weather front along which a cold air mass moves underneath a warm air mass, lifting the warm air mass.

A front serves as the leading edge of an air mass, like a bumper on a car.

FIGURE 6.4 shows the structure of a **cold front**. A cold air mass invades a zone occupied by a warm air mass. Because the colder air mass is denser 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. If the warm air is unstable, severe thunderstorms may develop. A cold front often forms a long line of massive *cumulus*—or globular—clouds stretching for tens of kilometers.

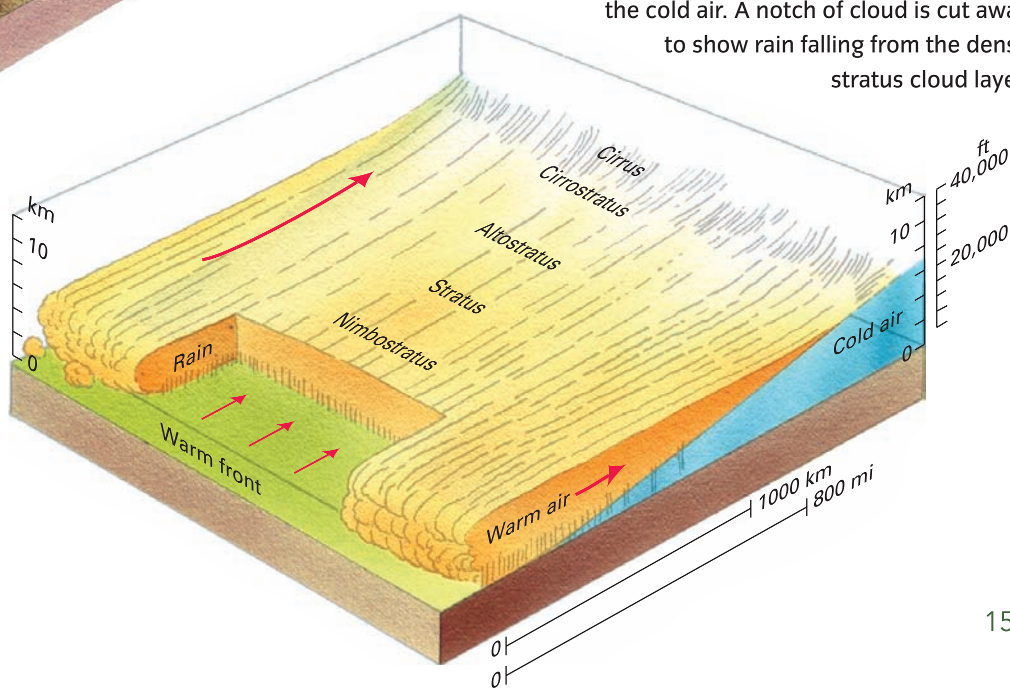
Warm front Moving weather front along which a warm air mass slides over a cold air mass, producing stratiform clouds and precipitation.

FIGURE 6.5 diagrams a **warm front** in which warm air moves into a region of colder air. Here, again, the cold air 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 creates *stratus*—large, dense, blanket-like clouds that often produce precipitation. 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 (not shown in the figure).



Cold front FIGURE 6.4

In a cold front, a cold air mass lifts a warm air mass aloft. The upward motion sets off a line of thunderstorms. The frontal boundary is actually much less steep than is shown in this schematic drawing.



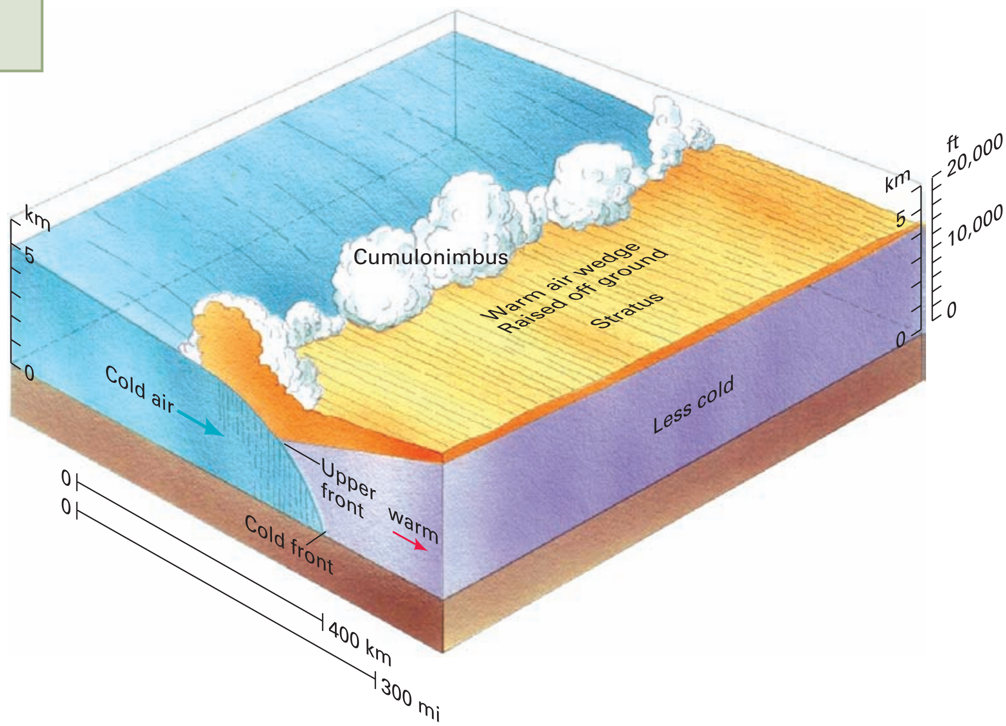
Warm front FIGURE 6.5

In a warm front, warm air advances toward cold air and rides up and over the cold air. A notch of cloud is cut away to show rain falling from the dense stratus cloud layer.

Cold fronts normally move along the ground faster than warm fronts. So, when both types are in the same neighborhood, a cold front can overtake a warm front. The result is an **occluded front**, as shown in FIGURE 6.6. ("Occluded" means closed or shut off.) The colder air of the fast-moving cold front remains next to the ground, forcing both the warm air and the less cold air ahead to rise over it. The warm air mass is lifted completely free of the ground.

Occluded front
Weather front along which a moving cold front overtakes a warm front, forcing the warm air mass aloft.

There is a fourth type of front 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.



Occluded front FIGURE 6.6

In an occluded front, a warm front is overtaken by a cold 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.

CONCEPT CHECK STOP

What is an air mass?

How do air masses acquire their characteristics?

What is a front? Name four types of fronts.

Traveling Cyclones and Anticyclones

LEARNING OBJECTIVES

Explain the weather changes associated with traveling cyclones and anticyclones.

Explain how wave cyclones form.

Describe tornadoes.

Cyclonic storm Intense weather disturbance within a moving cyclone generating strong winds, cloudiness, and precipitation.

Air masses are set in motion by wind systems—typically, cyclones and anticyclones that involve masses of air moving in a spiral. As we saw in Chapter 5, air spirals inward and converges in a cyclone, while air spirals outward and diverges in an anticyclone. Most types of cyclones and anticyclones are large features that move slowly across the Earth's surface, bringing changes in the weather as they move. These are referred to as *traveling cyclones* and *traveling anticyclones.*

In a cyclone, the air cools adiabatically as it rises and converges. If the air is moist, this can cause condensation or deposition, leading to *cyclonic precipitation.* Many cyclones are weak and pass overhead with little more than a period of cloud cover and light precipitation. But when pressure gradients are steep and the inspiraling motion is strong, intense winds and heavy rain or snow can accompany the cyclone. In this case, we call the disturbance a **cyclonic storm** (FIGURE 6.7).

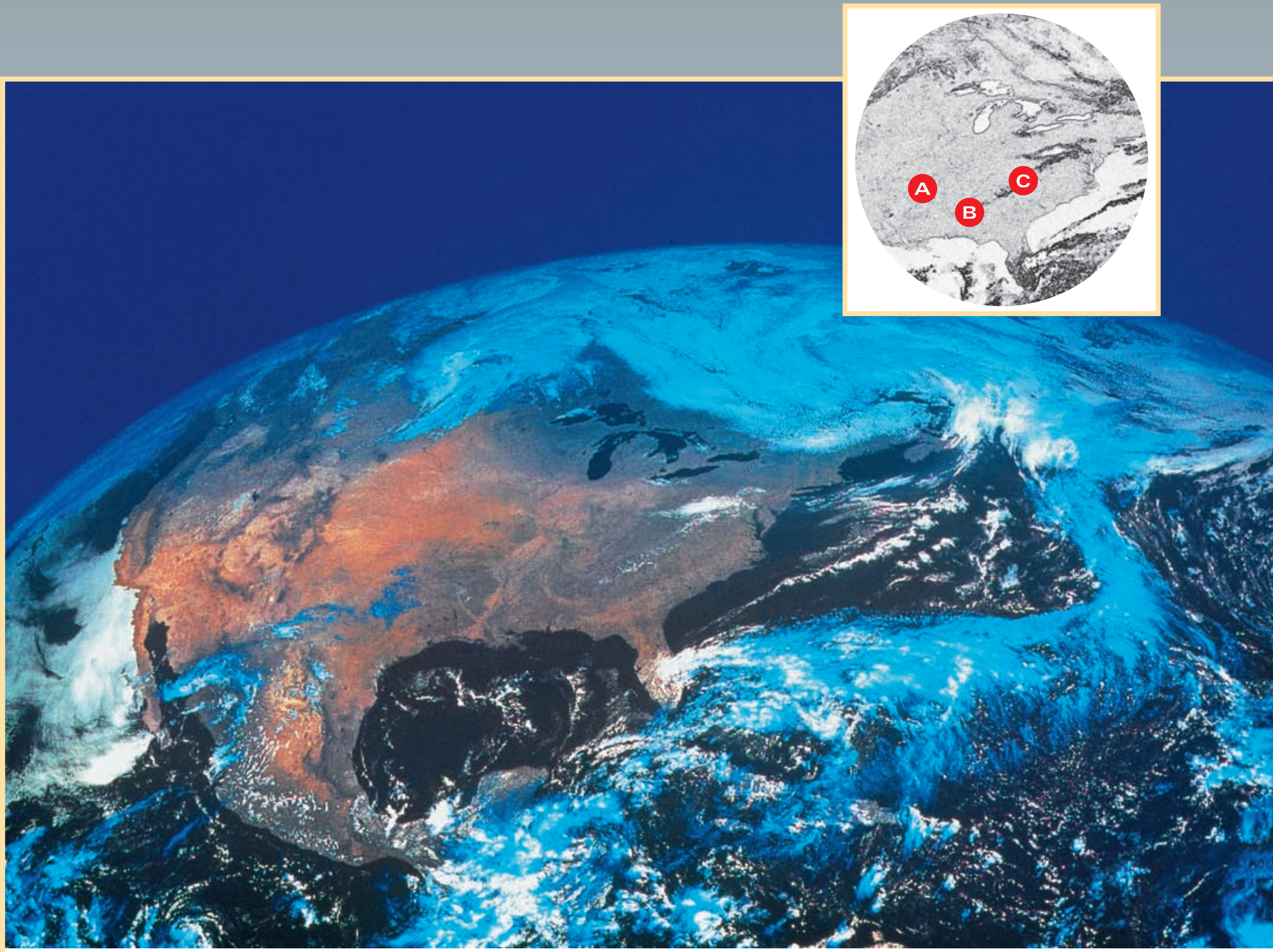
There are three types of traveling cyclones. First is the wave cyclone of midlatitude, Arctic, and Antarctic zones. Wave cyclones range from weak disturbances to powerful storms. Second is the tropical cyclone of tropical and subtropical zones. Tropical cyclones range from mild disturbances to highly 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 it is related to strong convectional activity.

In an anticyclone, the air is warmed adiabatically as it descends and diverges, so condensation does not occur. Skies are fair, 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.* 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. Geostationary satellites image anticyclones around the globe.

Nor'easter FIGURE 6.7

Intense wave cyclones can be powerful storms. Shown here is wave damage from a type of wave cyclone called a "northeaster" or "nor'easter," which struck Saco, Maine, in April, 2007. The nor'easter forms off the Atlantic coast and heads north along the eastern seaboard, bringing strong winds from the northeast, along with high tides and high surf.

What a Geographer Sees



This geostationary satellite image shows a large anticyclone centered over eastern North America. Anticyclones typically bring fair weather, and you can see that skies in this area are cloudless.

There is a boundary between clear sky and clouds running across the Gulf of Mexico and the Florida Peninsula. A geographer would identify that line as the leading edge of a cool, dry air mass. Farther inland you can also see some puffy clouds lying over the Appalachians at C. These are orographic cumulus clouds. At A, there is a light red pattern around the Mississippi River. This is fertile agricultural land on the river's floodplain. At B, you can see a curving reddish arc spanning the states of Mississippi and Alabama. This is also a fertile area of black, rich soil.

WAVE CYCLONES

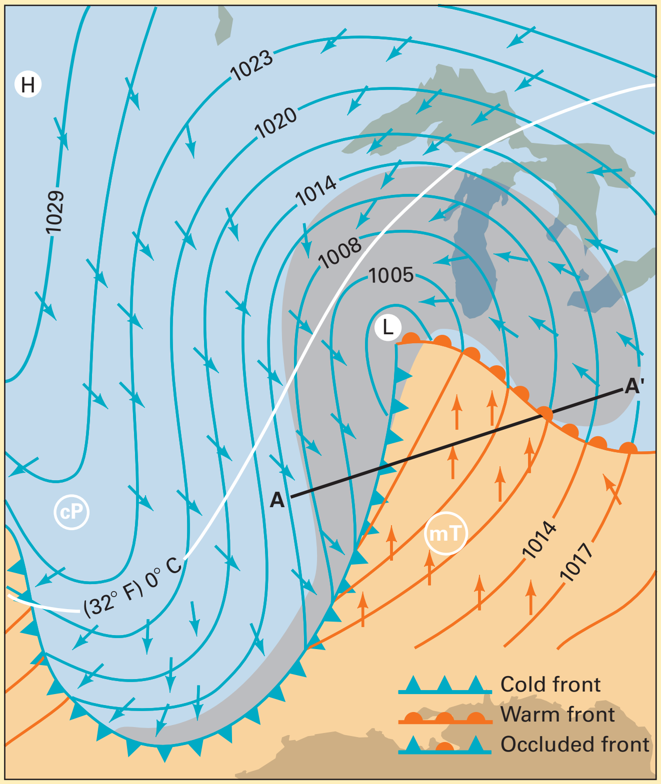
The **wave cyclone** is the dominant weather system in middle and high latitudes. It is a large inspiral of air that repeatedly forms, intensifies, and dissolves along the polar front. Wave cyclones can form when two large anticyclones come into contact on the polar front. One anticyclone contains a cold, dry polar air mass, and the other a warm, moist maritime air mass. The air flow converges from opposite directions on the two sides of the front, setting up an unstable situation. A *low-pressure trough* is created between the two high-pressure cells. This is where the wave cyclone begins to form. The process diagram shows the life history of a wave cyclone, explaining how a wave cyclone forms, grows, and eventually dissolves.

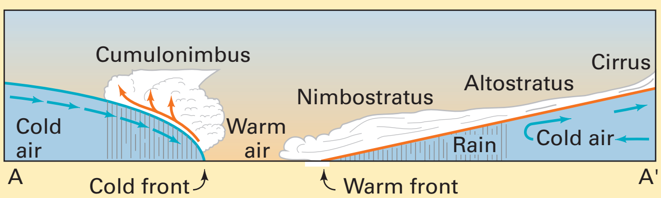
Wave cyclone
Traveling cyclone of the midlatitudes involving interaction of cold and warm air masses along sharply defined fronts.

WEATHER CHANGES WITHIN A WAVE CYCLONE

How does weather change as a wave cyclone passes through a region? **FIGURE 6.8** shows the 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 structure of the storm by looking at the isobars, labeled in millibars.

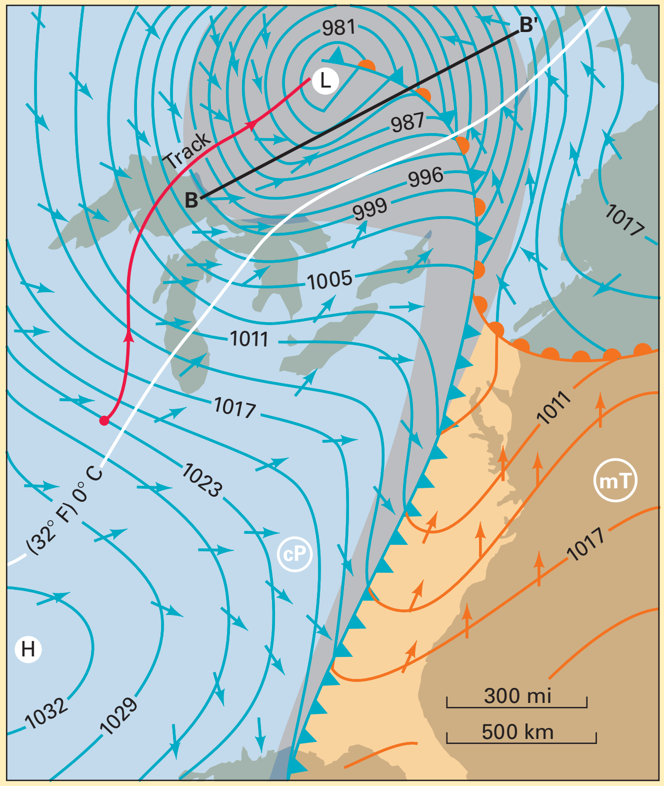
▼ **Open stage.** The isobars show that the cyclone is a low-pressure center with inspiraling winds. The cold front is pushing south and east, supported by a flow of cold, dry continental polar air from the northwest filling in behind it. Note that the wind direction changes abruptly as the cold front passes. There is also a sharp drop in temperature behind the cold front as cP air fills in. The warm front is moving north and somewhat east, with warm, moist maritime tropical air following. The precipitation pattern includes a broad zone near the warm front and the central area of the cyclone. A thin band of precipitation extends down the length of the cold front. Generally, there is cloudiness over much of the cyclone.

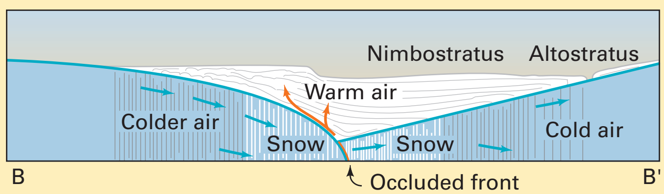




▲ **Cross section of open stage.** A cross section along the line A–A', shows how the fronts and clouds are related. There is a broad layer of stratus clouds along the warm front, which take the form of a wedge with a thin leading edge of cirrus. Westward, this wedge thickens to altostratus, then to 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 their 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 has moved rapidly northeastward, its track 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. 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 in to 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.





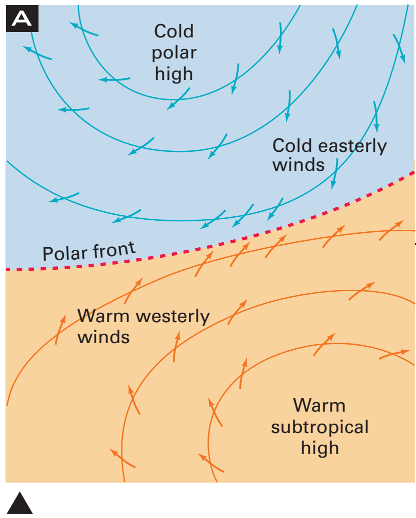
▲ **Cross section of occluded stage.** A cross section shows conditions along the line B–B', cutting through the occluded part of the storm. Notice that the warm air mass is lifted well off the ground and yields heavy precipitation.

Simplified surface weather maps and cross sections through a wave cyclone FIGURE 6.8

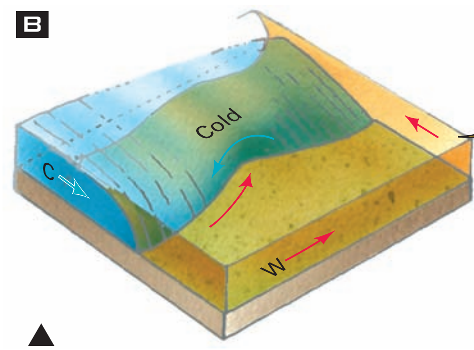
Process Diagram

Life history of a wave cyclone (“low”)

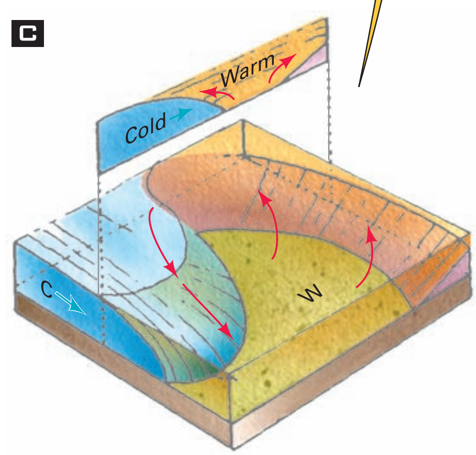
Wave cyclones are large features, spanning 1000 km (about 600 mi) or more. These are the “lows” that meteorologists show on weather maps. They typically last 3 to 6 days. In the Northern Hemisphere, a cyclone normally moves eastward as it develops, propelled by prevailing westerly winds aloft. Figures (a)–(e) show key stages in the life of a cyclone.

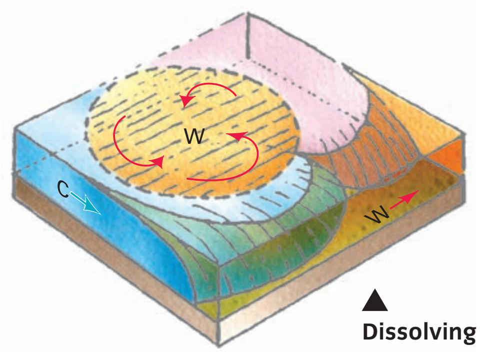


Ripe conditions for a wave cyclone Along the polar front, two very different air masses are in contact, poised to clash. One air mass is dense, cold polar air, and the other is warm, humid subtropical air.

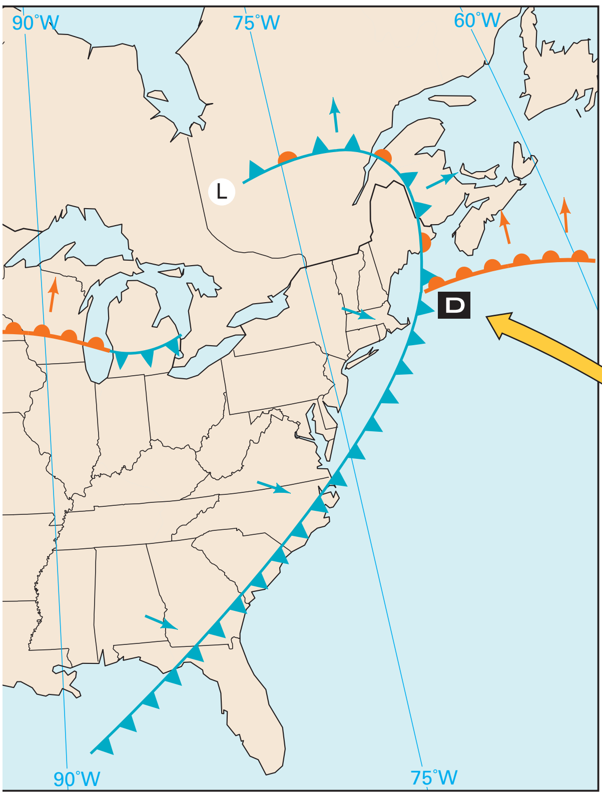


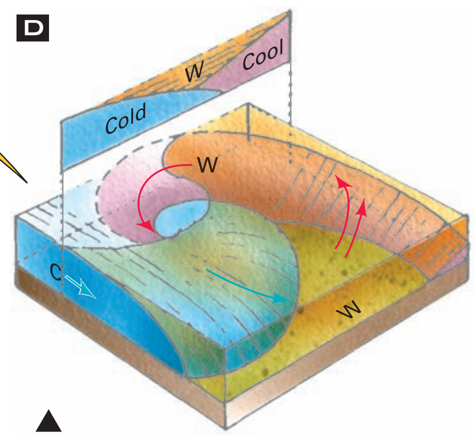
Early stage An undulation or wave motion begins at a point along the polar front. Cold air is turned in a southerly direction and warm air in a northerly direction, so that each advances on the other. This creates two fronts (a cold front and a warm front), and as they begin to move, precipitation starts.





▲
Dissolving stage Eventually, the polar front is reestablished, but a pool of warm, moist air remains aloft. As its moisture content reduces, precipitation dies out, and the clouds gradually dissolve. Soon another wave cyclone will begin at step (a).





▲
Occluded stage The faster-moving cold front overtakes the warm front, lifting the warm, moist air mass at the center completely off the ground. Since the warm air is shut off from the ground, this is called an *occluded* front (*occluded* means "shut off"). This further intensifies precipitation.

◀
Open stage The wave along the cold and warm fronts deepens and intensifies. Cold air actively pushes southward along the cold front, and warm air actively moves northeastward along the warm front. Precipitation zones along the two fronts are now strongly developed. The zone along the warm front is wider than the zone along the cold front.

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THE TORNADO

A **tornado** is a small but intense cyclonic vortex in which air spirals at tremendous speed (FIGURE 6.9). It is associated with thunderstorms spawned by fronts in midlatitudes. Tornadoes can also occur inside tropical cyclones (hurricanes), which we will discuss later.

Tornado Small, very intense wind vortex with extremely low air pressure in the center, formed below a dense cumulonimbus cloud in proximity to a cold front.

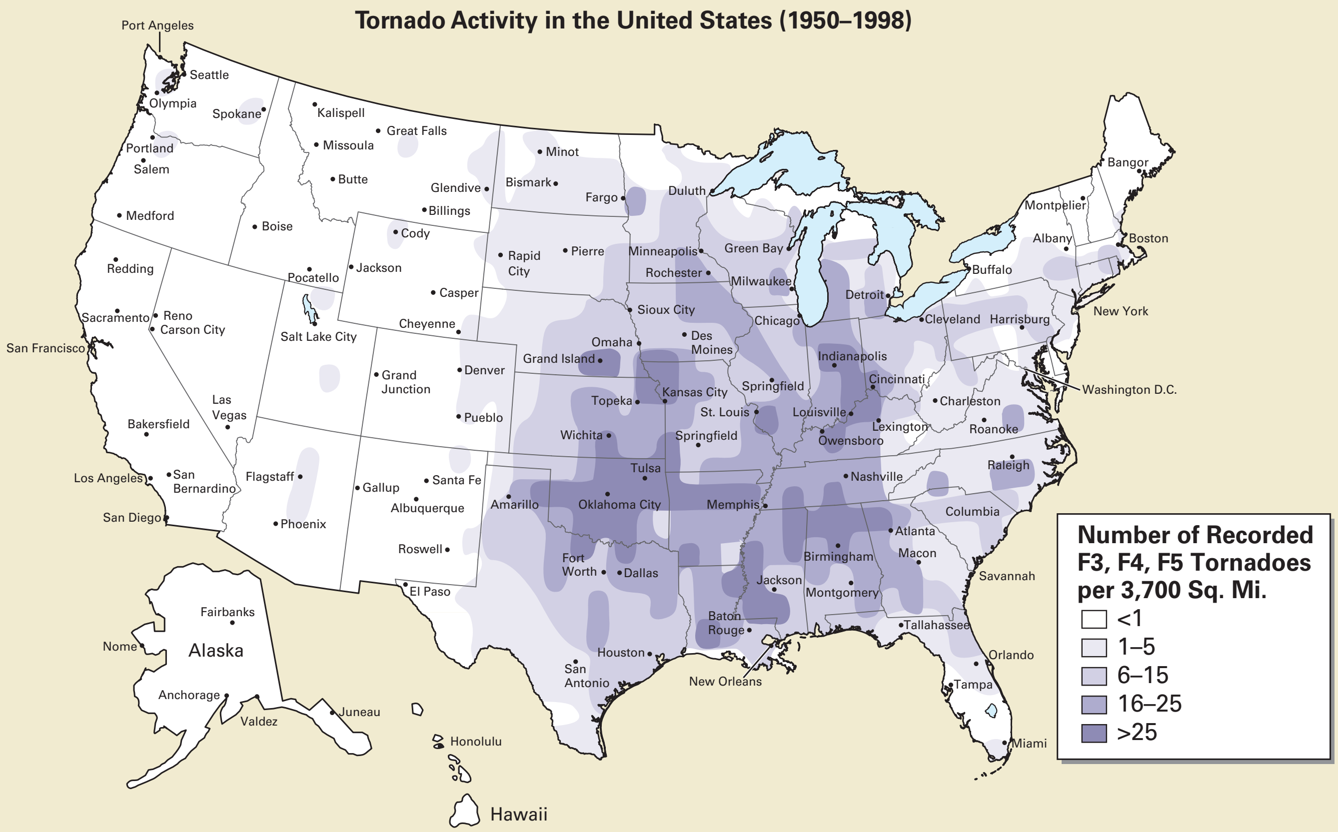
The tornado appears as a dark funnel cloud hanging from the base of a dense storm cloud. At its lower end, the funnel may be 100 to 450 m (about 300 to 1500 ft) in diameter. The funnel appears dark because of condensing moisture, dust, and debris swept up by the wind. As the tornado moves across the countryside, the funnel writhes and twists.

Tornadoes occur as parts of cumulonimbus clouds traveling in advance of a cold front. The conditions are most favorable for tornadoes when a cold front of maritime polar air lifts warm, moist maritime tropical air—most commonly in spring and summer. Tornadoes are most frequent and violent in the United States (FIGURE 6.10). They also occur in Australia in substantial numbers and are occasionally reported from other midlatitude locations.

Wind speeds in a tornado run as high as 100 m/s (about 225 mi/hr), exceeding known speeds of any other storm. Only the strongest buildings constructed of concrete and steel can withstand these violent winds. The National Weather Service maintains a tornado forecasting and warning system. Whenever weather conditions favor tornado development, they alert the danger area and activate systems for observing and reporting any tornado.

Tornado FIGURE 6.9

This massive tornado destroyed the town of Manchester, South Dakota, a few minutes before this 2003 photo was taken by photographer Carsten Peter.



Frequency of occurrence of strong tornadoes in the contiguous United States FIGURE 6.10

The data shown in this map span a period from 1950 to 1998. Only strong tornadoes are counted (F3 or above on the Fujita tornado scale). Most tornadoes occur in the central and southeastern states and are rare over mountainous and forested regions. They are almost unknown west of the Rocky Mountains and are relatively less frequent on the eastern seaboard.

CONCEPT CHECK STOP

What weather patterns accompany traveling cyclones and traveling anticyclones?

What is a wave cyclone? How does it develop?

What is a tornado?

Tropical and Equatorial Weather Systems

LEARNING OBJECTIVES

Define easterly waves and polar outbreaks.

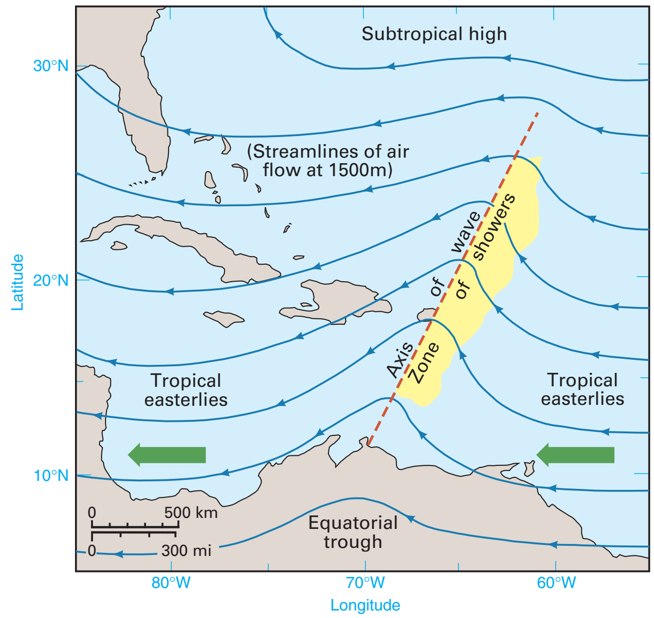
Describe tropical cyclones and their impact.

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 air mass movement is slow and gradual. Air masses are warm and moist, and different air masses tend to have similar characteristics to each other, so there aren't such clearly defined fronts. And without these fronts, there are no large, intense wave cyclones. On the other hand, the high moisture content leads to intense convectional activity in low-latitude maritime air masses. Because these air masses are very moist, only slight convergence and uplifting are needed to trigger precipitation.

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 (trades). These waves occur in latitudes 5° to 30° N and S over oceans, but not over the equator itself (FIGURE 6.11).

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.

Polar outbreaks are another distinctive feature of low-latitude weather. They occur when powerful tongues of cold polar air from the midlatitudes occasionally penetrate into very low latitudes. These tongues are known as polar outbreaks. The leading edge of a polar outbreak is a cold front with squalls, which is followed by unusually cool, clear weather with strong, steady winds. The polar outbreak is best developed in the Americas. A severe polar outbreak may bring subfreezing temperatures to areas of subtropical climate, seriously damaging agricultural crops such as citrus fruits or coffee.

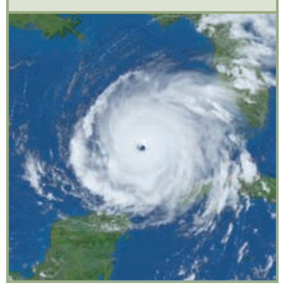


An easterly wave passing over the West Indies
FIGURE 6.11

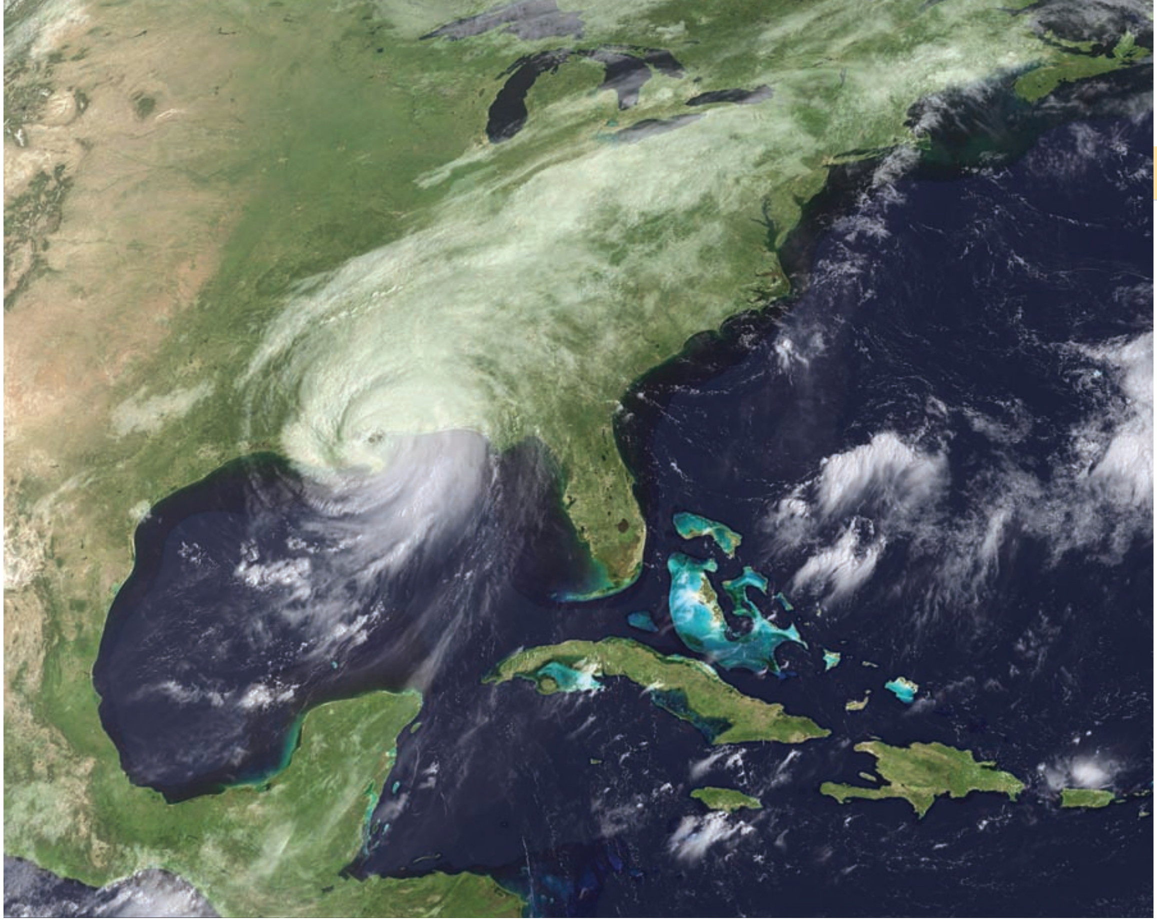
There is a zone of weak low pressure at the surface, under the axis of the wave. The wave travels westward at a rate of about 100 km per day. Surface air flow converges on the eastern, or rear, side of the wave axis. This convergence causes the moist air to be lifted, producing scattered showers and thunderstorms.

TROPICAL CYCLONES

Tropical cyclone
Intense traveling cyclone of tropical and subtropical latitudes, accompanied by high winds and heavy rainfall.



The **tropical cyclone** is the most powerful and destructive type of cyclonic storm (FIGURE 6.12). 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 develops over oceans in 8° to 15° N and S latitudes but not closer to the equator. We do not know the exact formation mechanism, but typically the tropical cyclone originates as an easterly wave or weak low, which then intensifies and grows into a



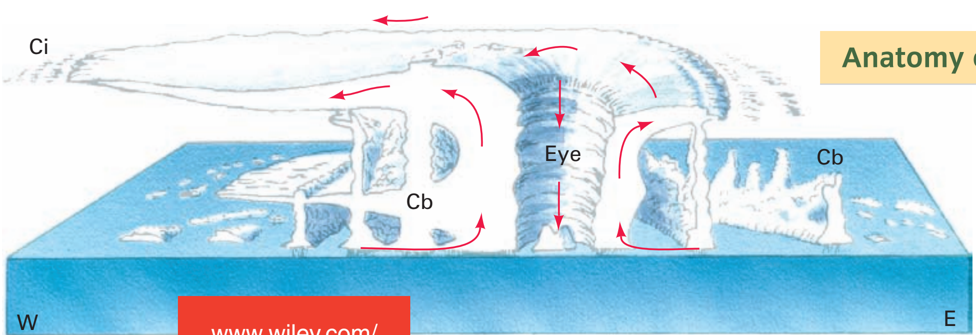
Hurricane Katrina FIGURE 6.12

NASA's MODIS satellite imager acquired this view of Hurricane Katrina on August 28, 2005, as it struck Louisiana.

deep, circular low. High sea-surface temperatures, over 27°C (81°F), are required for tropical cyclones to form. Once formed, the storm moves westward through the trade-wind belt, often intensifying as it travels. It can then curve northwest, north, and northeast, 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 can attest.

An intense tropical cyclone is an almost circular storm center of extremely low pressure. 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 to 500 km (about 100 to 300 mi). Wind speeds can range from 30 to 50 m/s (about 65 to 135 mi/hr) and sometimes much higher. Barometric pressure in the storm center commonly falls to 950 mb (28.1 in. Hg) or lower.

A characteristic feature of a well-developed tropical cyclone is its central eye, in which clear skies and calm winds prevail (FIGURE 6.13). The eye is a cloud-free vortex produced by the intense spiraling of the storm. In the eye, air descends from high altitudes and is adiabatically warmed. As the eye passes over a site, calm prevails, and the sky clears. 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 are highest along the cloud wall of the eye.



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Anatomy of a cyclone FIGURE 6.13

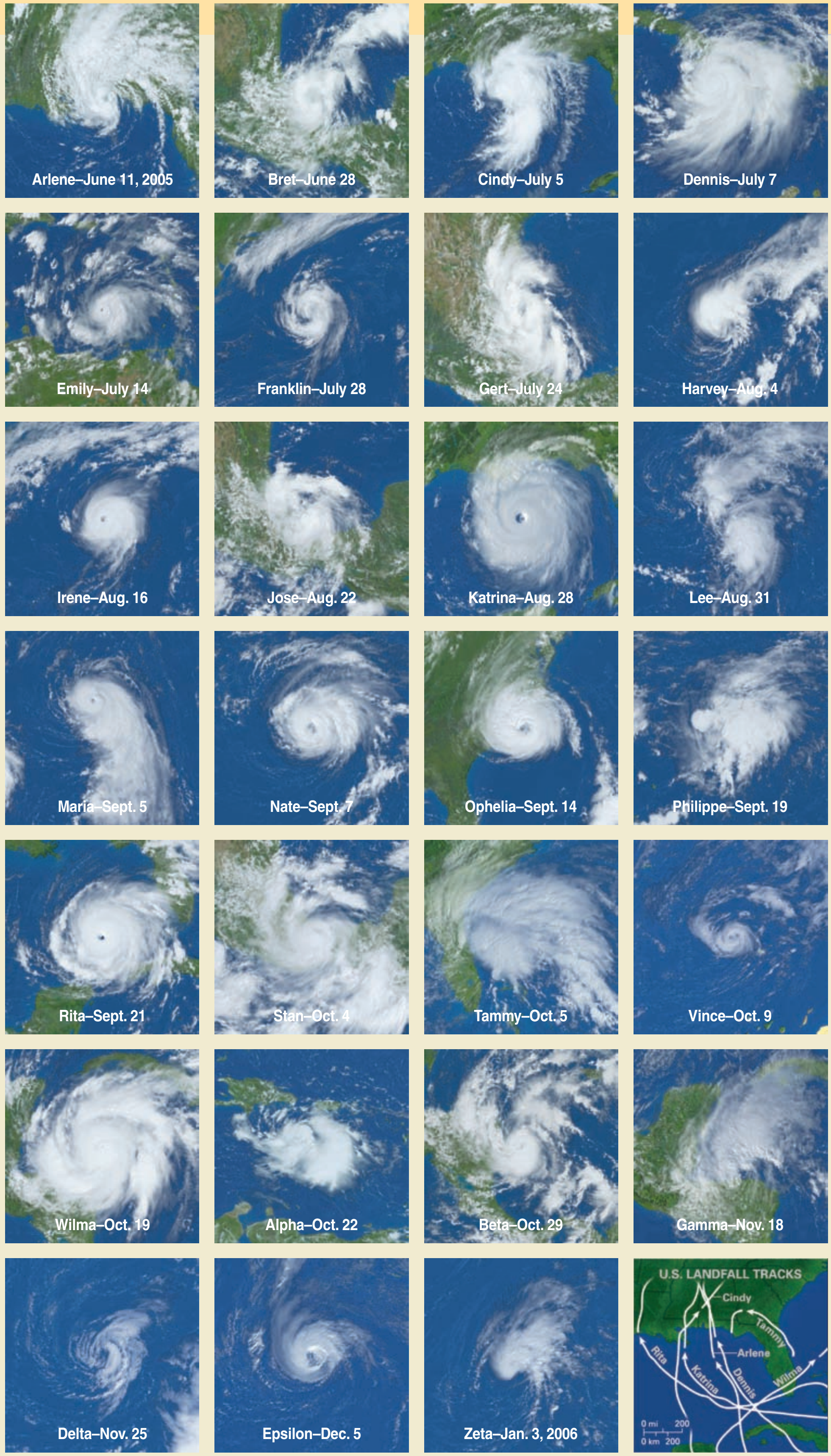
In this schematic diagram, cumulonimbus (Cb) clouds in concentric rings rise through dense stratiform clouds. Cirrus clouds (Ci) fringe out ahead of the storm. The width of the diagram represents about 100 km (about 600 mi).

Tropical cyclones always form over oceans. 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. 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. In the Indian Ocean, cyclones originate both north and south of the equator, moving north and east 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.

Tropical cyclones occur only during certain seasons. For hurricanes of the North Atlantic, the season runs from May 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.

We now use satellite images to track cyclones. They are often easy to identify by their distinctive pattern of inspiraling bands of clouds and a clear central eye. **Figure 6.14** provides a gallery of Atlantic hurricanes of 2005.

For convenience, tropical cyclones are given names as they are tracked by weather forecasters. Male and female names are alternated in an alphabetical sequence renewed



Hurricanes of 2005 FIGURE 6.14

The year 2005 was the most active year on record for Atlantic hurricanes. Shown here are the 27 named storms that occurred during the official season of June 1 to November 30. A twenty-eighth storm, Zeta, was observed during December and into January of 2006. 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 mi/hr).

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.

IMPACTS OF TROPICAL CYCLONES

Tropical cyclones can be tremendously destructive. Islands and coasts feel the full force of the high winds and flooding as tropical cyclones move onshore. Since the atmospheric pressure at the center of the cyclone is so low, sea level rises toward the center of the storm. High winds create a damaging surf and push water toward the coast, raising sea level even higher. Waves attack the shore at points far inland of the normal tidal range.

Storm surge Rapid rise of coastal water level accompanying the onshore arrival of a tropical cyclone.

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**, that carries ocean water and surf far inland (FIGURE 6.15). At Galveston, Texas, in 1900, a sudden storm surge generated by a severe hurricane flooded the low coastal city and drowned about 6000 people—the largest death toll in a natural disaster yet experienced within the United States.

Tropical cyclones also produce a large amount of rainfall. Although this rainfall is a valuable water resource, it can also produce freshwater flooding, raising rivers and streams out of their banks. On steep slopes, soil saturation and high winds can topple trees and produce disastrous earthflows and landslides (FIGURE 6.16).

Stranded vessel FIGURE 6.15

Hurricane Andrew's storm surge and high winds stranded this large motor vessel far from its berth in Homestead, Florida (1992).

Earthflow FIGURE 6.16

This entire neighborhood in Tegucigalpa, Honduras, slumped downhill (moving from left to right) during Hurricane Mitch (1998). Torrential rains saturated the soil, allowing gravity to take effect.

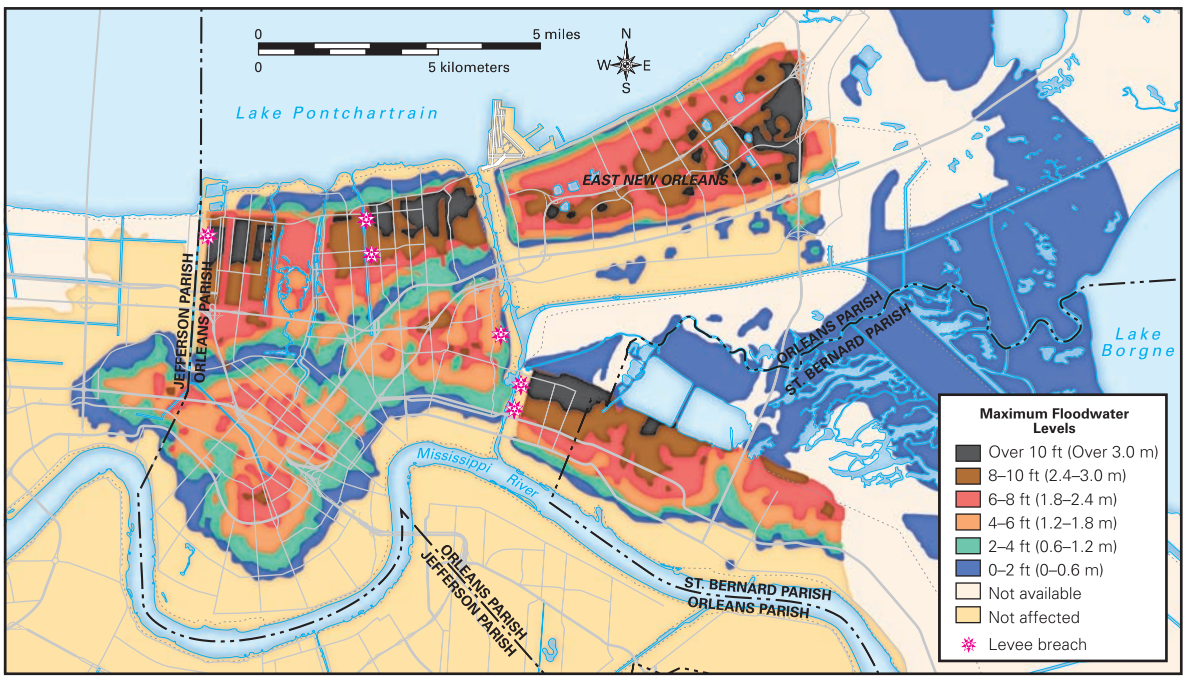
Tropical cyclone activity varies from year to year and decade to decade. Tropical cyclone intensity is ranked from category 1 (weak) to 5 (devastating) on the Saffir-Simpson scale. In the Atlantic Basin, 13 strong hurricanes of category 3 or higher struck the eastern United States or the Florida Peninsula from 1947 to 1969, while only one hurricane struck the same region in the period 1970–1987. Although a number of strong storms, including category 4 or 5 hurricanes Gilbert (1988), Hugo (1989), and Andrew (1992) occurred in 1988–1992, Atlantic hurricane activity remained depressed until 1994.

However, in 1995 a new phase of Atlantic hurricane activity began. Since 1995, sea-surface temperatures in the northern Atlantic during August–October have averaged about 0.5°C (about 1°F) warmer than during 1970–1994, providing more latent heat to fuel the cyclones. High-level easterly winds, which can shear the tops off growing storms, weakened on average by about 2 m/s (about 4 mi/hr) during the same period.

The result has been the present period of hurricane activity, unequaled in the historic record. By 2005, the average number of named storms had increased to 13 per year, as compared to 8.6 during 1970–1994. The number of hurricanes had increased from 5 to 7.7 per year, with 3.6 major hurricanes as compared to 1.5 in prior years. In 2005 alone, there were 27 named storms, with a record 4 storms reaching category 5. The most recent climatological studies suggest that this enhanced hurricane activity is linked to slowly changing cyclical patterns of ocean currents and will persist for another 15–20 years.

South Florida is particularly at the mercy of Atlantic hurricanes. In 1992, Hurricane Andrew struck the east coast of Florida near Miami. It was the second most damaging storm to occur in the United States, claiming 26 lives and more than $35 billion in property damage, measured in today's dollars. The chapter opener documents one observer's account of riding out Hurricane Andrew in a concrete and steel parking garage. In 2004, four major hurricanes affected 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.

In 2005, Hurricane Katrina laid waste to the city of New Orleans and much of the Louisiana and Missis-



Flooding in New Orleans FIGURE 6.17

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.

sippi Gulf coasts. Originating southeast of the Bahamas, the hurricane first crossed the South Florida Peninsula as a category 1 storm and then moved into the Gulf of Mexico, where it intensified to a category 5 storm. After the storm weakened somewhat as it approached the Gulf coast, its eye came ashore at Grand Isle, Louisiana, with sustained winds of 56 m/s (125 mi/hr) early on August 29.

New Orleans is a city that is particularly vulnerable to hurricane flooding. The city was built largely on the floodplain of the Mississippi River, and most of its land area has slowly sunk below sea level as underlying river sediments have compacted through time. Levees protect the city from Mississippi River floods, as well as from ocean waters along the saline Lakes Borgne on the east and Ponchartrain on the north, which are connected to the Gulf. Rainwater falling into the sunken basin is pumped up and out of the city by discharge into canals that lead to Lake Ponchartrain. Several canals and shipping channels also connect the river with the lakes and the Gulf.

Katrina's first assault was mounted from the east, as a storm surge swept westward from Lake Borgne, overtopping and eroding levees and flooding east New Orleans and St. Barnard Parish (FIGURE 6.17). Penetrating deep into the city along the Intracoastal Waterway, the surge overtopped and breached floodwalls and levees along the main canal connecting the Mississippi with Lake Ponchartrain. To the north, water levels rose in Lake Ponchartrain, overtopping 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. Over the next two days, the water level rose until it equalized with the level of Lake Ponchartrain. Eighty percent of the city was covered with water at depths of up to 6 m (20 ft).

The result was devastation unparalleled in American disaster history (FIGURE 6.18). 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 at 8 m (25 ft) penetrating from 10 to 20 km (6–12 mi) inland. And, adding insult to injury, much of New Orleans was reflooded three weeks later by Hurricane Rita, a category 3 storm that made landfall on September 24 at the Louisiana–Texas border.

Hurricane Katrina floods New Orleans
FIGURE 6.18

In the aftermath of Hurricane Katrina, many neighborhoods in New Orleans lay in ruins. The red object in the foreground is a barge. This photo was taken about two weeks after the storm. The devastation is nearly complete.

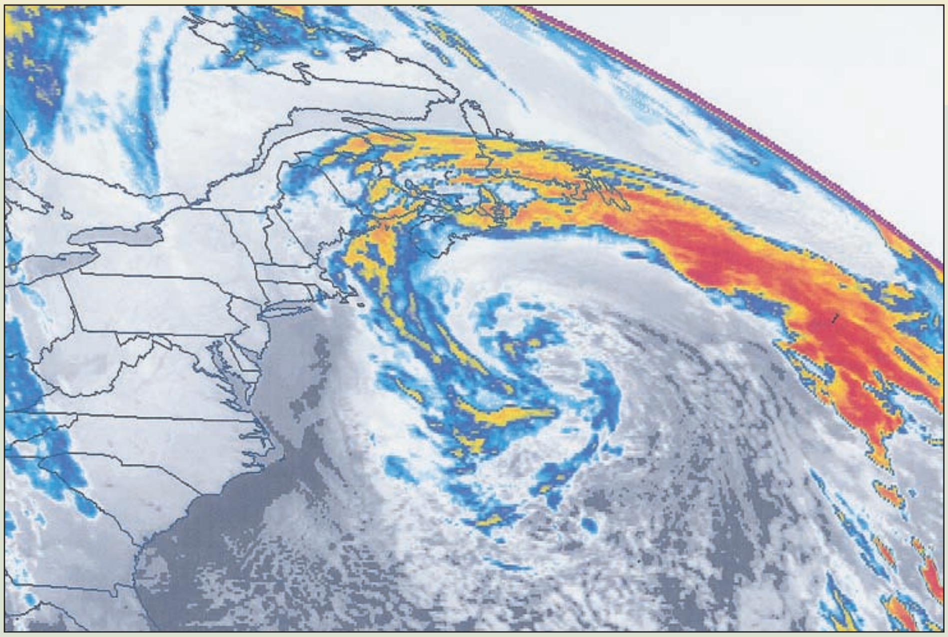
CONCEPT CHECK STOP

What are the characteristic features of a tropical cyclone?

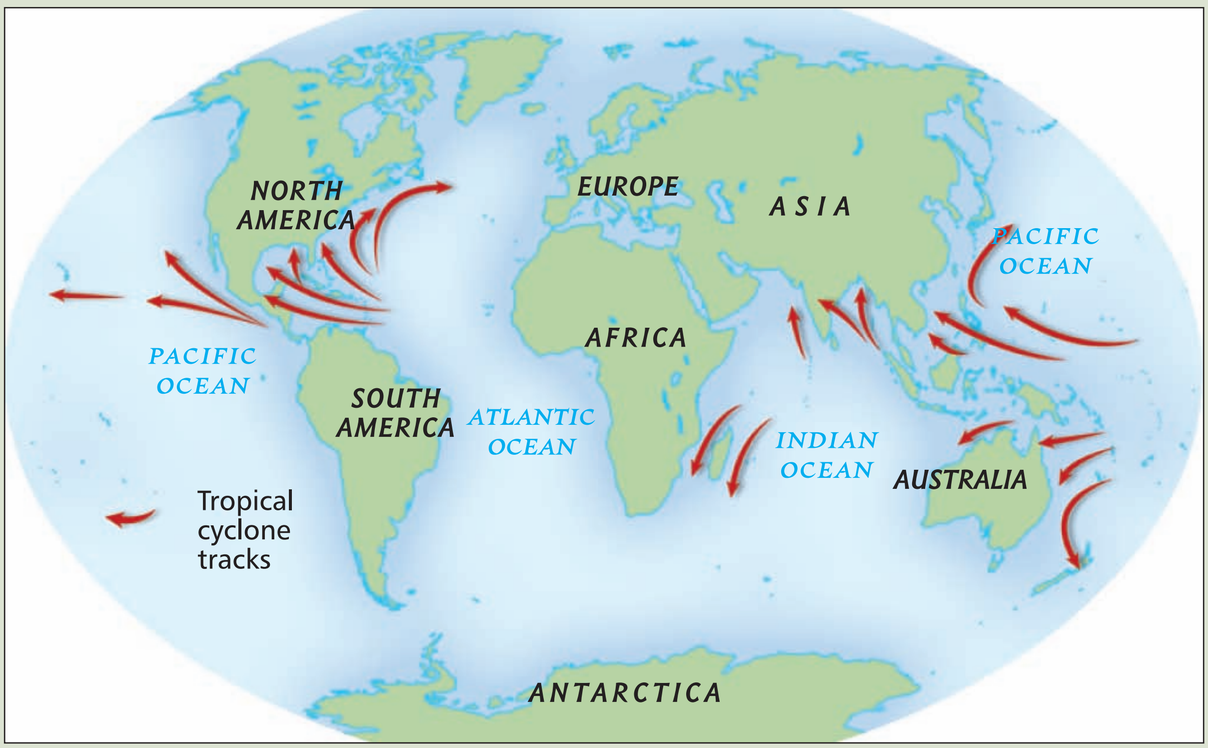
What weather effects can they cause?

WAVE CYCLONES

Wave cyclones are common features of midlatitude weather. They can be strong storms, bringing rain, snow, and winds. Strong wave cyclones off the eastern North American coast are known as "nor'easters."



◀ **The Perfect Storm**
This intense wave cyclone is the first phase of the "Perfect Storm," imaged here on October 30, 1991 by the NOAA GOES-7 weather satellite. Yellow and red areas indicate intense convection where the storm swallowed the remnants of Hurricane Grace. Later it drifted southward, picking up energy from waters of the warm Gulf Stream, to become a tropical cyclone—the "unnamed hurricane" of 1991.

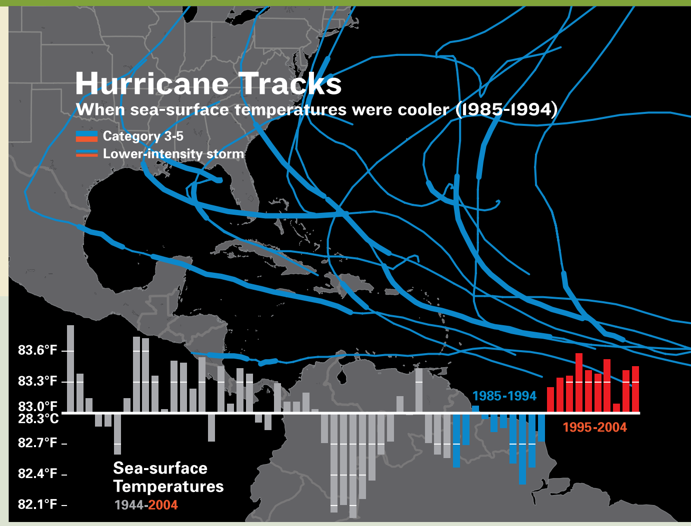


◀ **Cyclone paths**
Tropical cyclones form over warm, tropical oceans and are typically carried westward by easterly trade winds. Many eventually turn poleward and eastward.

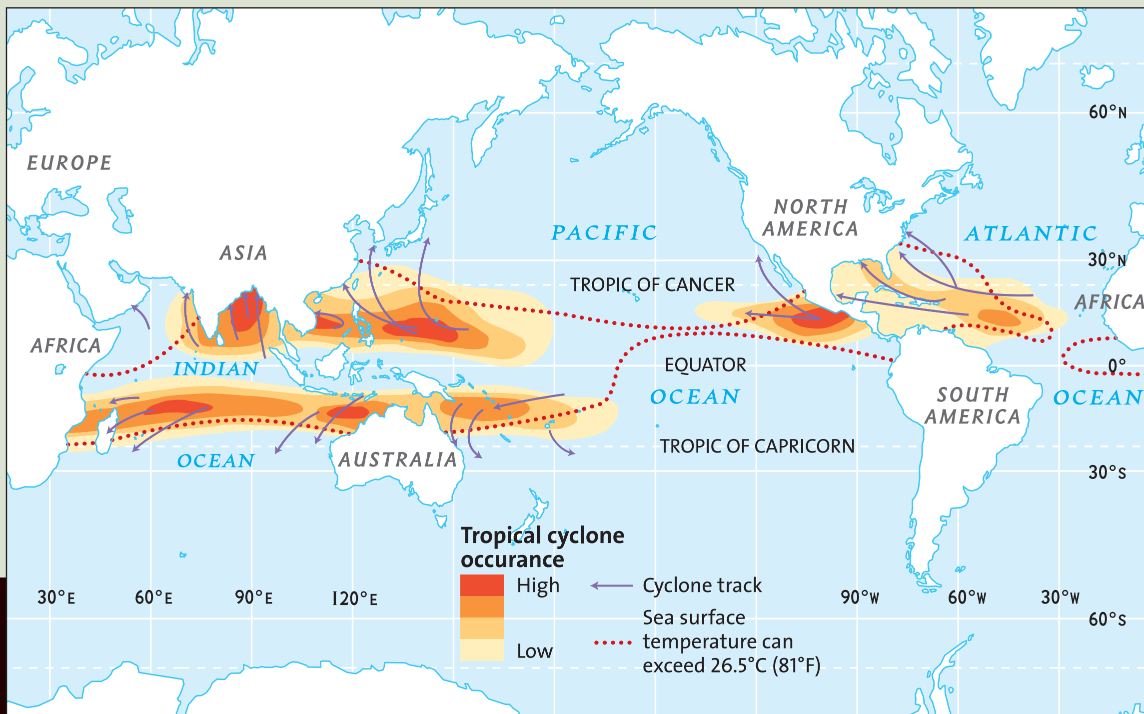
Visualizing
Wave Cyclones and Tropical Cyclones

TROPICAL CYCLONES

Tropical cyclones form over warm, tropical oceans. They can be very intense storms that devastate islands and coasts. In the Atlantic, they are known as "hurricanes." In the Pacific, they are "typhoons" and known as just "cyclones" in the Indian Ocean.



▶ Hurricane tracks Along the southeastern coast of the U.S., many tropical cyclones approach from the east then turn and head back out to sea. The number and intensity of storms increases when sea surface temperatures increase. Upper map: 1985–1994. Lower map: 1995–2004.



▶ Oceans and Cyclones Tropical cyclones are most likely to occur in areas of greatest heating. Dotted lines show where the sea surface temperature can be greater than 26.5°C (81°F). Cyclones last until they move over cooler waters or hit land. When a cyclone encounters warmer waters, as Hurricane Katrina did in 2005 in the Gulf of Mexico, it picks up energy and intensifies.

Cloud Cover, Precipitation, and Global Warming

LEARNING OBJECTIVES

Explain how global cloud cover could change in the long term.

Describe the effect of increased cloud cover on precipitation and global warming.

So far in this book, we have looked at climatic change from several different perspectives. Let's now focus on how global climate might be influenced by an increase in clouds and precipitation (FIGURE 6.19). Recall that 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. What effect will this have on climate?

Water has several roles in global climate. First, in its vapor state it is one of the greenhouse gases. That is, it absorbs and emits 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 can condense or deposit, forming clouds. Will more clouds increase or decrease global temperatures? That question is still being debated by the scientists who study and model the atmosphere. Clouds can have two different effects on the surface radiation balance. As large, white bodies, they can reflect a large proportion of incoming shortwave radiation back to space, cooling global temperatures. But cloud droplets and ice 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 much stronger for water as cloud droplets or ice particles than as water vapor. So, clouds also act to warm global temperatures by enhancing longwave reradiation from the atmosphere to the surface.

Which effect, longwave warming or shortwave cooling, will dominate? The best information at present, obtained from satellite measurements, is that the average flow of shortwave energy reflected by clouds back to space is about 50 W/m^2, while the greenhouse warming effect of clouds amounts to about 30 W/m^2. So, at the moment, the net effect of clouds is to cool the planet by about 20 W/m^2.

But what will happen when surface temperature increases, water vapor in the atmosphere increases, and more clouds form? Computer models of global climate generally agree that longwave warming will be enhanced more than shortwave cooling. After a small temperature increase, the effect of clouds will still be to cool the planet but not at so great a rate. Another way to put it is to say that with global warming, the cooling effects of clouds on climate will be reduced somewhat, making the temperature rise 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. Think, however, about what might happen if precipitation increases in arctic and subarctic zones. In this case, more of the Earth's surface could be covered by snow and ice. Since snow is a good reflector of solar energy, this would increase the Earth's albedo, thus tending to reduce global temperatures. Another effect might be to increase the depth of snow, tying up more water in snow packs and reducing runoff to the oceans. Reducing runoff would reduce the rate at which sea level rises.

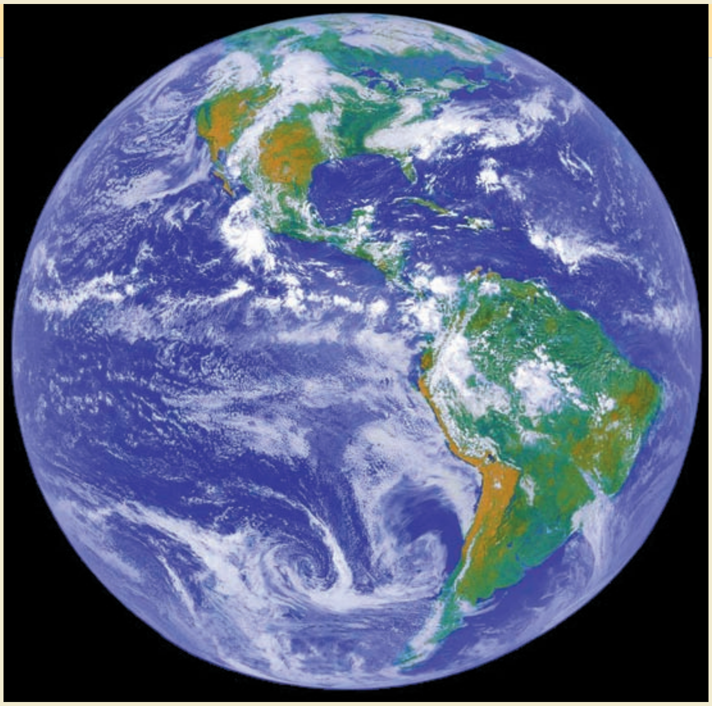
You can see that the situation is complicated. At this time, scientists are unsure how the global climate system will respond to global warming induced by the CO_2 increases predicted for the 21st century. Perhaps increased cloud cover and enhanced precipitation will slow the warming trend—or perhaps they will enhance it. But as time goes by, our understanding of global climate and our ability to predict its changes are certain to increase.

CONCEPT CHECK STOP

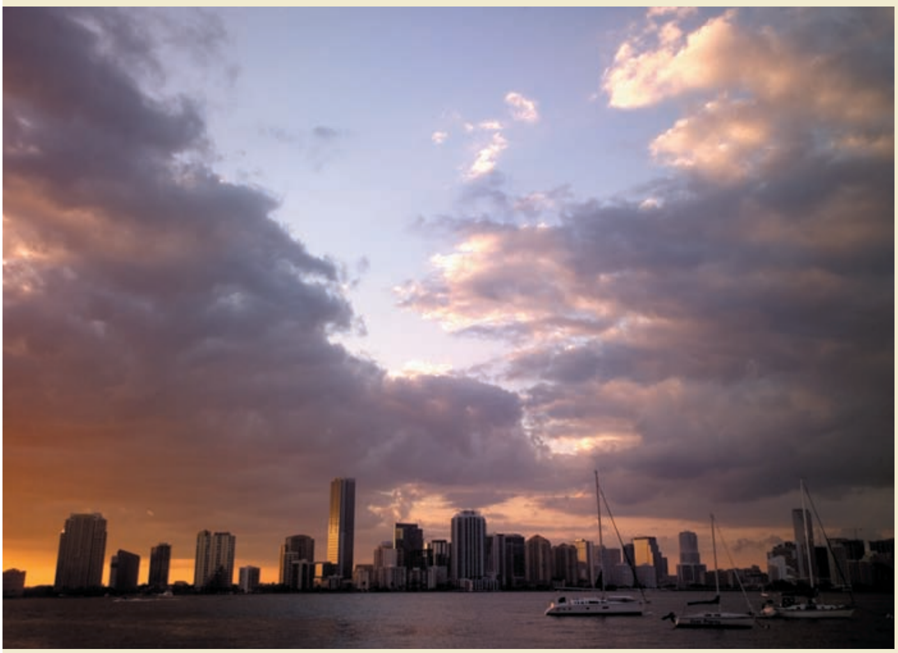
How and why will the amount of cloud cover change if global temperatures rise?

How might this affect global climate? Give three effects.

Clouds and global climate FIGURE 6.19



A Earth mantled by clouds The GOES-8 geostationary satellite acquired this image of the Earth from space. Cloud height and cloud cover are important factors in determining global climate.



B 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.

C 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.

What is happening in this picture ?

- The photograph shows a line of cumulus clouds advancing from left to right. The clouds were formed when warm, moist air was pushed aloft.
- Can you explain why the warm air was forced upwards? The clouds mark an advancing front. What type of front might this be?

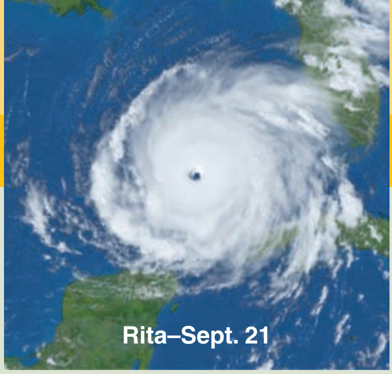
VISUAL SUMMARY

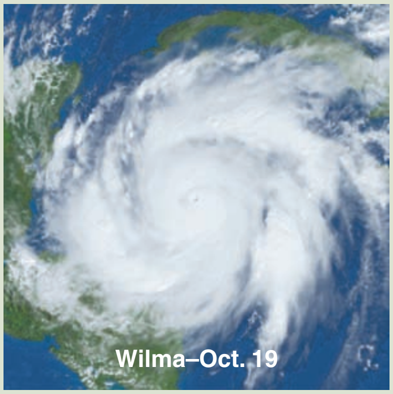
1 Air Masses

1. Air masses are distinguished by their latitudinal location and by their source regions.
2. Fronts are the boundaries between air masses. They 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 above the surface.

2 Traveling Cyclones and Anticyclones

1. Traveling cyclones include wave cyclones, tropical cyclones, and tornadoes.
2. The traveling anticyclone is typically a fair-weather system.
3. Wave cyclones form in the midlatitudes at the boundary between cool, dry air masses and warm, moist air masses.
4. Tornadoes are very small, intense cyclones that occur as a part of thunderstorm activity. Their high winds can be very destructive.





3 Tropical and Equatorial Weather Systems

1. Tropical weather systems include easterly waves and weak equatorial lows.
2. Easterly waves occur when a weak low-pressure trough develops in the easterly wind circulation of the tropical zones, producing convergence, uplift, and shower activity.
3. Weak equatorial lows occur near the intertropical convergence zone. In these areas of low pressure, convergence triggers abundant convectional precipitation.
4. Tropical cyclones can be the most powerful of all storms. They develop over very warm tropical oceans and can intensify to become vast inspiraling systems of very high winds with very low central pressures.
5. Tropical cyclones can be very destructive, bringing high winds, storm surges, and heavy rainfall to coastal areas. In 1995, a new phase of increased hurricane activity began in the western Atlantic.

4 Cloud Cover, Precipitation, and Global Warming

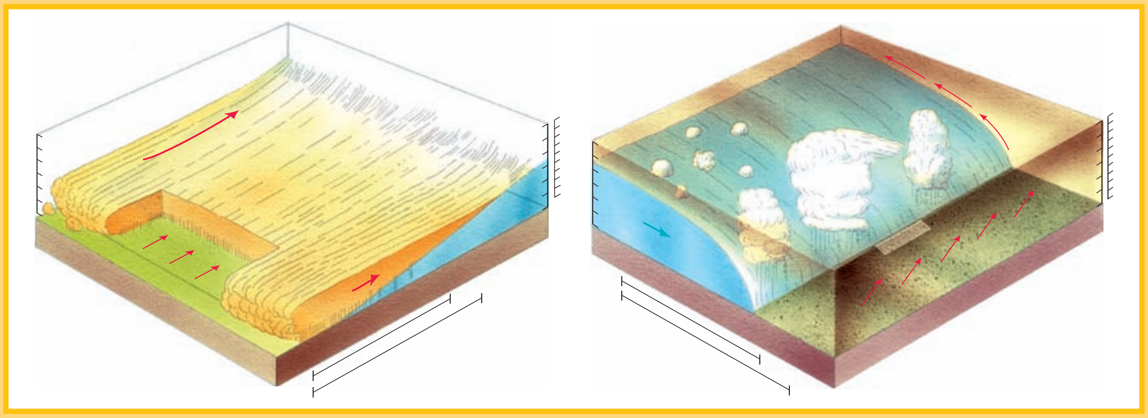
1. Because global warming, produced by increasing CO_2 levels in the atmosphere, will increase the evaporation of surface water, atmospheric moisture levels will increase. This will tend to enhance the greenhouse effect.
2. As the climate warms, more clouds are likely to form, and this should cool the planet.
3. Increased moisture could also reduce temperatures by increasing the amount and duration of snow cover.

KEY TERMS

- **air mass** p. 154
- **front** p. 157
- **cold front** p. 157
- **warm front** p. 157
- **occluded front** p. 158
- **cyclonic storm** p. 159
- **wave cyclone** p. 160
- **tornado** p. 164
- **tropical cyclone** p. 166
- **storm surge** p. 169

CRITICAL AND CREATIVE THINKING QUESTIONS

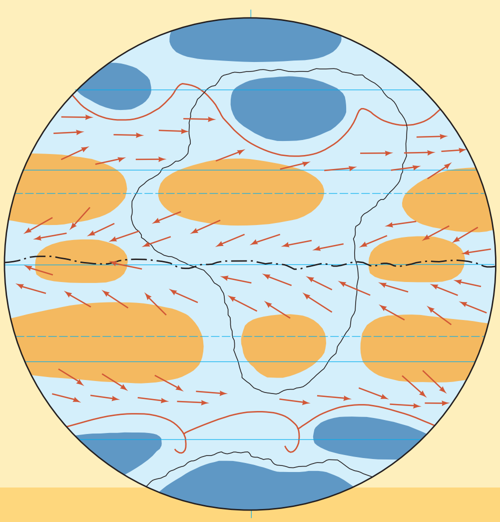
1. What is an air mass? What two features are used to classify air masses?
2. Label the two types of fronts shown below; also, label the air masses, the contacts between them, and the direction of air mass motion.
3. Describe a tornado. Where and under what conditions do tornadoes typically occur?
4. Identify three weather systems that bring rain in equatorial and tropical regions. Describe each system briefly.
5. Describe the structure of a tropical cyclone. What conditions are necessary for a tropical cyclone to develop?
6. Why are tropical cyclones so dangerous?
7. Compare and contrast midlatitude and tropical weather systems. Be sure to include the following terms or concepts in your discussion: air mass, convectional precipitation, cyclonic precipitation, easterly wave, polar front, stable air, traveling anticyclone, tropical cyclone, unstable air, wave cyclone, and weak equatorial low.
8. How does water, as vapor, clouds, and precipitation, influence global climate? How might water in these forms act to enhance or retard climatic warming?



SELF-TEST

1. _______________ air masses generally possess the lowest moisture content.
   a. Maritime tropical
   b. Continental polar
   c. Maritime tropical
   d. Continental tropical

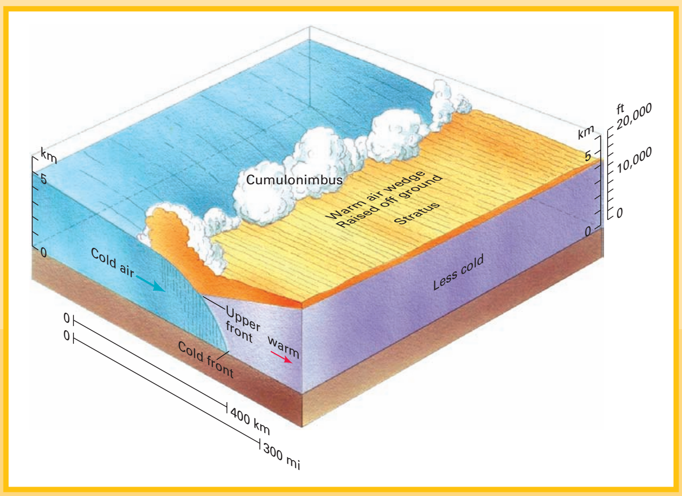
2. The diagram shows the source regions that give global air masses their characteristics. Label the following sources: (a) cA, (b) cAA, (c) cP, (d) cT, (e) mE, (f) mP, and (g) mT.



3. A _______________ forms when a cold air mass penetrates a warm air mass.
   a. warm front
   b. occluded front
   c. cold front
   d. stationary front

4. In _______________, convergence and uplift typically cause condensation and precipitation, while subsidence in _______________ causes the air to warm, producing clear conditions.
   a. cyclones; warm fronts
   b. anticyclones; cyclones
   c. anticyclones; warm fronts
   d. cyclones; anticyclones

5. The diagram shows a front that is formed when a cold front has overtaken a warm front. What is the type of front called?



6. A(n) _______________ is a center of high pressure and is generally responsible for fair weather.

a. anticyclone
b. cyclone
c. trade wind
d. midlatitude storm front

7. A _______________ is a small but intense cyclonic vortex with very high wind speeds.

a. hurricane
b. tornado
c. typhoon
d. cyclone

8. Tropical weather tends to be _______________.

a. based on westerly waves
b. based on divergence of air masses
c. convectional in nature
d. based on the horse latitude divergence

9. The leading edge of a polar outbreak is _______________.

a. a warm front that develops into an occluded front
b. clear weather
c. clear weather followed by warm and occluded fronts
d. a cold front with squalls

10. Hurricanes and typhoons generally develop within the _______________ latitudinal zones.

a. 15 to 30 degrees North and South
b. 10 to 20 degrees North and South
c. 8 to 15 degrees North and South
d. 30 to 45 degrees North and South

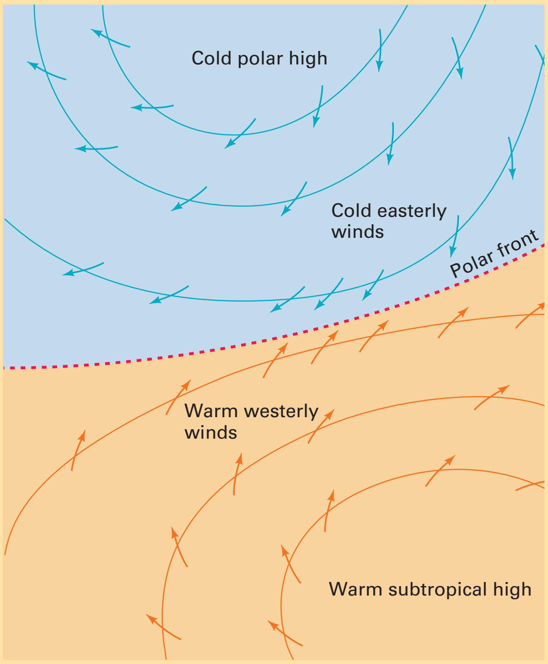
11. The _______________ continent is rarely if ever threatened by hurricanes or typhoons.

a. North American
b. South American
c. African
d. Eurasian

12. A _______________ is a sudden rise of water level caused by a hurricane.

a. storm surge
b. flood
c. tsunami
d. tidal flood

13. The diagram shows two anticyclones in contact on the polar front. Mark the region where a low-pressure trough forms. What type of weather system forms under these conditions?



14. Increased cloud cover, resulting from an increase in water vapor in the atmosphere due to the greenhouse effect, presently results in _______________.

a. warmer troposphere temperatures
b. cooler troposphere temperatures
c. a decrease in tropospheric temperatures
d. a net cooling of the planet

15. Water vapor in the atmosphere _______________.

a. leads to cooler days and warmer evenings, on average
b. releases large amounts of heat to the stratosphere
c. transports heat toward the equator
d. acts as a greenhouse gas and emits longwave radiation

Global Climates

7

Polar bears are uniquely suited to the climate and environment of the high arctic. With their white fur coats and thick layers of fat close to the skin, they are well insulated against the cold of the arctic winter. Roaming the ice sheets of the Arctic Ocean, they hunt and devour the ringed and bearded seals that also inhabit the arctic ice. Polar bears are true masters of their environment and have no natural enemies. None, that is, except global warming.

Today, polar bear populations are under stress from climate change. In the past 25 years or so, the extent and thickness of arctic sea ice have both diminished substantially. Sea ice breakup is now happening earlier in the season, reducing the time during which the bears can hunt for seals. The reduced nutrition produces reduced physical health, which takes its toll on polar bear populations.

Climate change can also affect polar bear reproduction. Cubs are birthed in a den hollowed out from a snow drift. If snow cover is reduced or melts earlier, the dens can be breached, causing a loss of shelter. Since female polar bears reproduce only once in three or four years, even small changes in pup survival may have important long-term effects on population sizes.

As human-induced climate change progresses, climates may shift at rates that are beyond the ability of some species to adapt. The overall population size of the polar bear is expected to decline by more than 30 percent in the next 35 to 50 years. Whether the polar bear will survive into the 22nd century is in doubt.

A polar bear and her cub on the ice near Churchill, Manitoba, Canada.

NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

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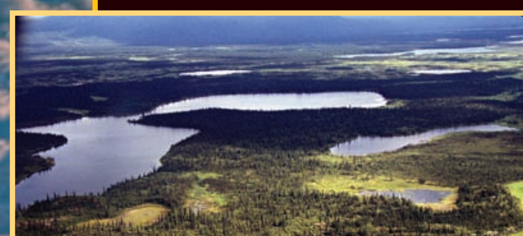
Low-Latitude Climates (Group I) p. 196

Midlatitude Climates (Group II) p. 206



High-Latitude Climates (Group III) p. 216

Keys to Climate

Learning Objectives

Explain the factors that affect climate.

Describe temperature regimes.

Discuss global precipitation.

TEMPERATURE REGIMES

Climate is the average weather of a region. Before tackling the global scope of climate, we need to review some principles that we met in earlier chapters. The primary driving force for weather, as we have seen, is the flow of solar energy received by the Earth and atmosphere. Since that energy flow varies on daily cycles with the planet's rotation and on annual cycles with its revolution in orbit, it imposes these cycles on temperature and precipitation. Remember, too, that latitude and coastal-continental location also influence the annual cycle of air temperature experienced at any place on the globe, and that warm air can hold more moisture than cold air. We review some of these concepts in Figure 7.1.

Climate The annual cycle of prevailing weather conditions at a given place, based on statistics taken over a long period.

The two most important characteristics to note about temperatures around the globe are that: (1) the annual variation in insolation, which is determined by latitude, controls basic temperature patterns, and

Influences on temperature Figure 7.1

A Latitude The annual cycle of insolation varies with latitude. So, in turn, 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.

B Coastal-continental location Ocean-surface temperatures vary less with the seasons than do temperatures of land surfaces. So, regions near the coast show a smaller annual variation in temperature, while the variation is larger inland. Aerial view of Cornwall, England.

C Moisture Air temperature has an important effect on precipitation. Warm air can hold more moisture than cold air. This means that 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.

(2) the effect of location—maritime or continental—moderates that variation.

These factors split the globe into *temperature regimes*, labeled according to latitude zone: equatorial, tropical, midlatitude, and subarctic. Some labels also describe the location of the climate 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. FIGURE 7.2 illustrates these principles.

Temperature regimes around the globe FIGURE 7.2

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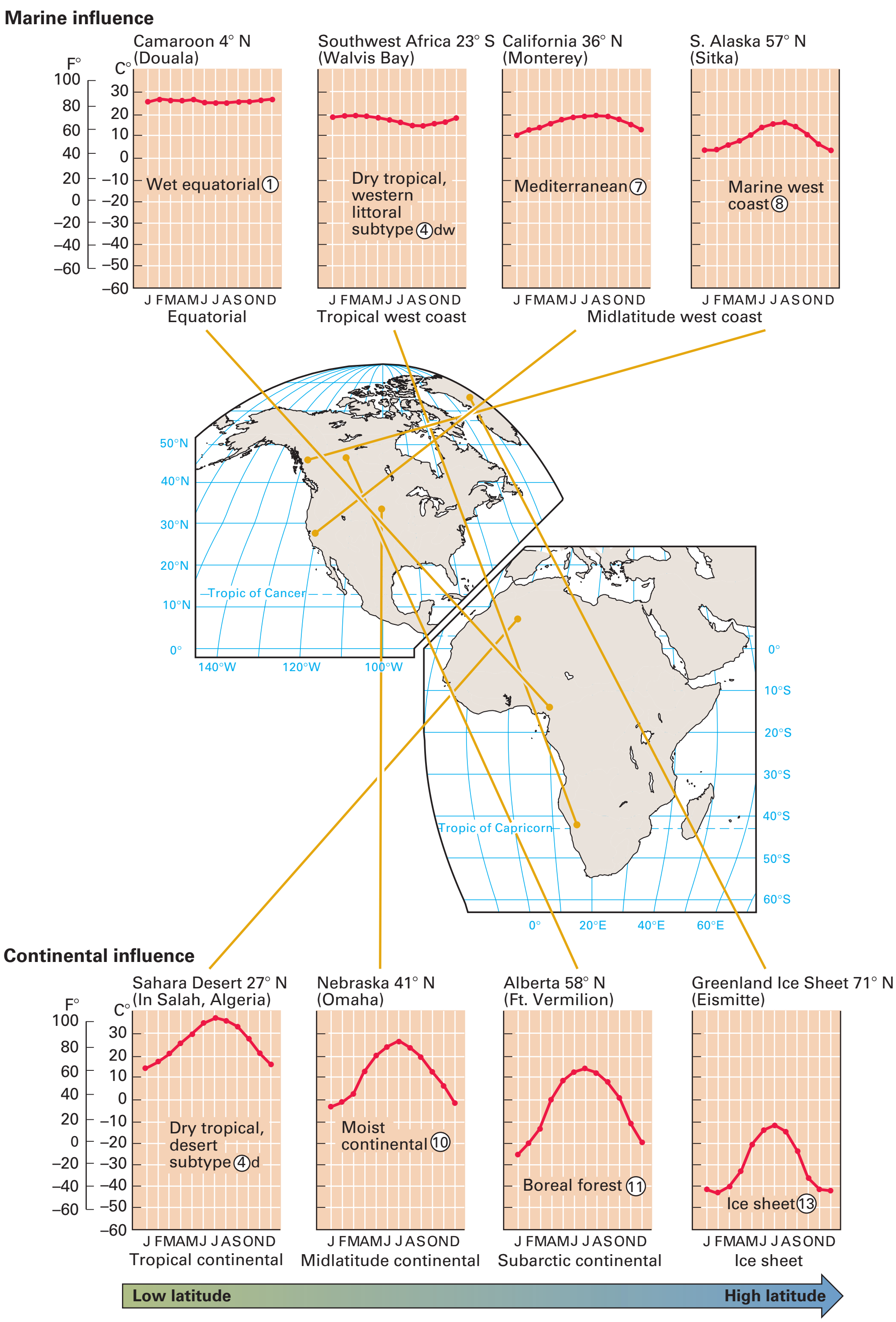
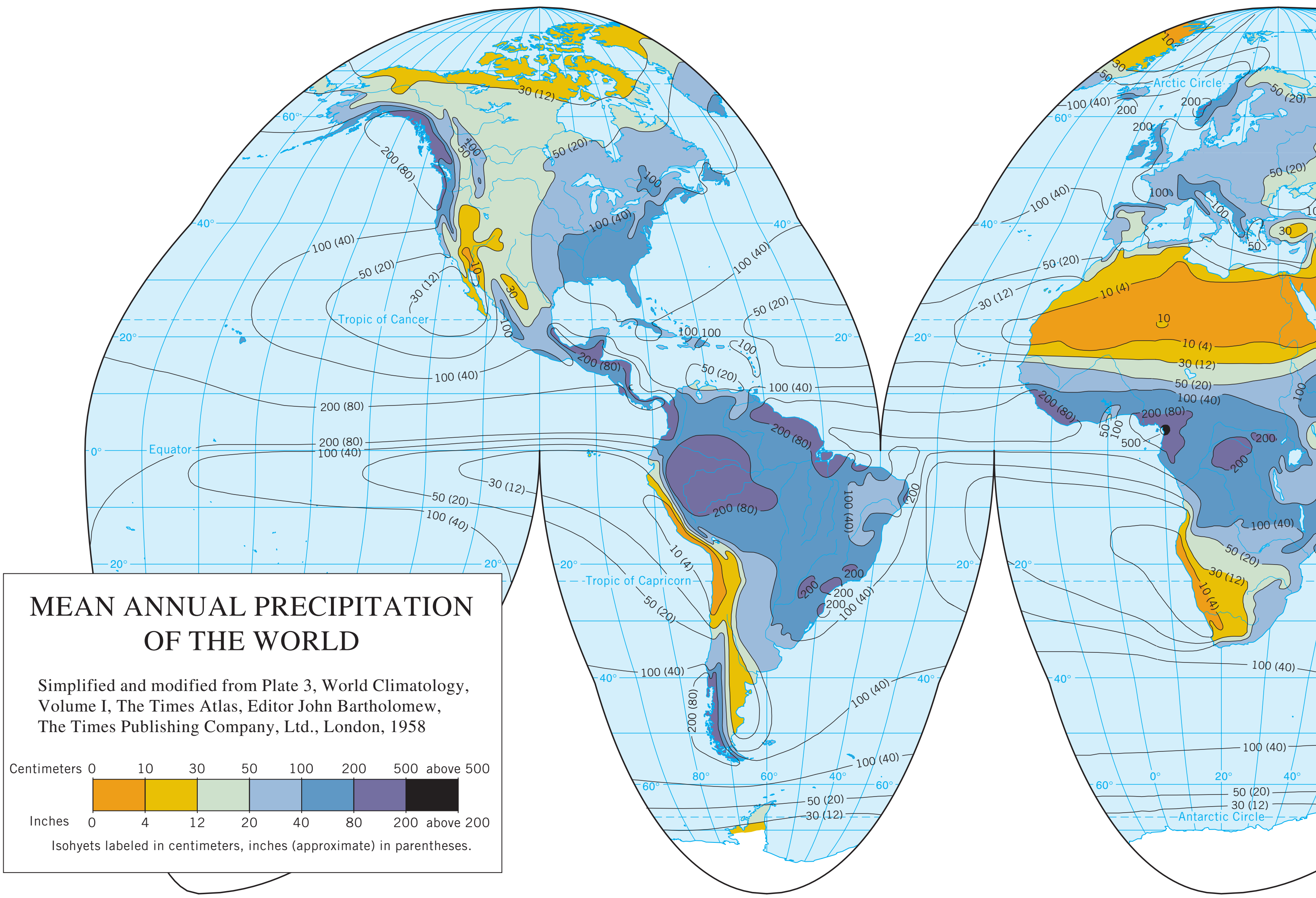
Some important temperature regimes, represented by annual cycles of air temperature. (Based on the Goode Base Map.)



GLOBAL PRECIPITATION

FIGURE 7.3 maps global precipitation patterns across the globe. Looking carefully, we can find at least seven global precipitation regions:

1. **Wet equatorial belt.** Here the temperatures are warm and the mE air masses have a high-moisture content, making this a zone of heavy rainfall—over 200 cm (80 in.) annually. Thunderstorms are frequent year-round. The belt 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.
2. **Trade-wind coasts.** Narrow coastal belts 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. The trade winds bring moist mT air masses from warm oceans over the

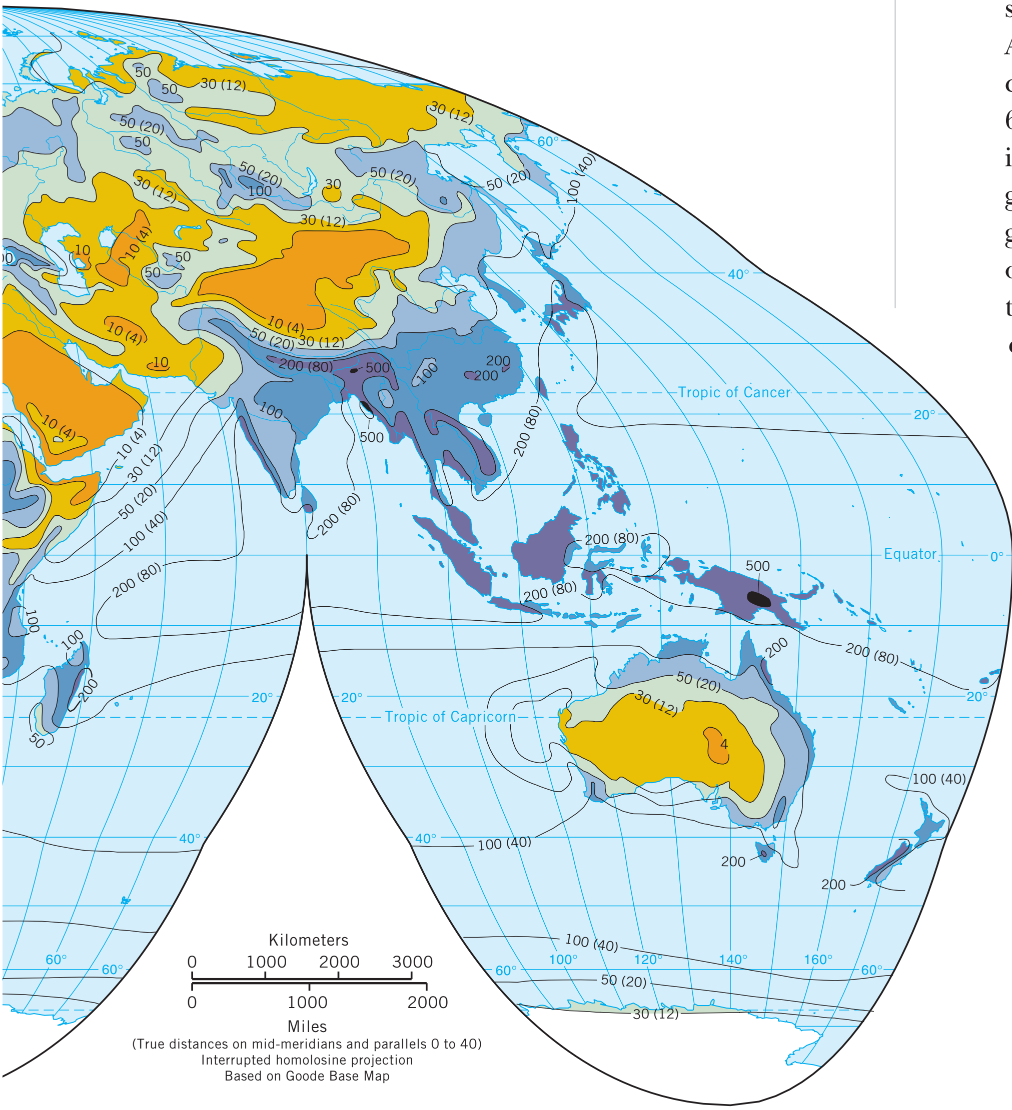


Global precipitation FIGURE 7.3

This global map of mean annual precipitation uses *isohyets*—lines drawn through all points having the same annual precipitation—labeled in cm (in.). Global precipitation patterns are largely determined by the movement of air masses, which in turn are produced by global air circulation patterns.

land, which produce heavy orographic rain of 150 to 200 cm (about 60 to 80 in.), as they rise over coastal hills and mountains.

3. **Tropical deserts.** There are two zones of vast tropical deserts lying approximately on the Tropics of Cancer and Capricorn. These are hot and barren deserts, with less than 25 cm (10 in.) of rainfall annually. They are caused by the large, stationary subtropical cells of high pressure, in which the cT air mass is adiabatically warmed and dried.



4. **Midlatitude deserts and steppes.** Located in the interiors of Asia and North America between lat. 30° and lat. 50° are great deserts and vast expanses of semiarid grasslands known as *steppes*. Annual precipitation ranges from less than 10 cm (4 in.) in the driest areas to 50 cm (20 in.) in the moister steppes. The regions are dry because they are far from ocean sources of moisture. They typically lie in the rainshadows of coastal mountains and highlands.

5. **Moist subtropical regions.** On the southeastern sides of the continents of North America and Asia, in lat. 25° to 45° N, are the moist subtropical regions, with 100 to 150 cm (about 40 to 60 in.) of rainfall annually. They are also found in the southern hemisphere in Uruguay, Argentina, and southeastern Australia. These regions are on the moist western sides of the oceanic subtropical high-pressure centers, so they receive moist mT air masses from the tropical ocean. These areas commonly receive heavy rains from tropical cyclones.

6. **Midlatitude west coasts.** Another distinctive wet location lies between about 35° and 65° on all continents. In these zones, mP air masses are forced aloft over hills and mountainous ranges producing abundant orographic precipitation.

7. **Arctic and polar deserts.** Northward of the 60th parallel, annual precipitation is largely under 30 cm (12 in.), except for the west-coast belts. Cold cP and cA air masses cannot hold much moisture, so they do not yield much precipitation.

Total annual precipitation helps us establish climate type. But variations in monthly precipitation are also important. Monthly precipitation values can tell us if there is a pattern of alternating dry and wet seasons. The natural vegetation, soils, crops, and human use of the land will all be different in a region with such seasons compared with a place where precipitation is uniform throughout the year. It also makes a great deal of 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, it will enhance the growth of both native plants and crops. But if the warm season is dry, there will be great stress on growing plants.

There are three types of monthly precipitation patterns: (1) uniformly distributed precipitation; (2) a precipitation maximum during the summer (or season of high Sun), in which daily insolation is at its peak; and (3) a precipitation maximum during the winter or cooler season (season of low Sun), when there is the least daily insolation. FIGURE 7.4 gives some examples of these patterns seen around the world.

Seasonal precipitation patterns FIGURE 7.4

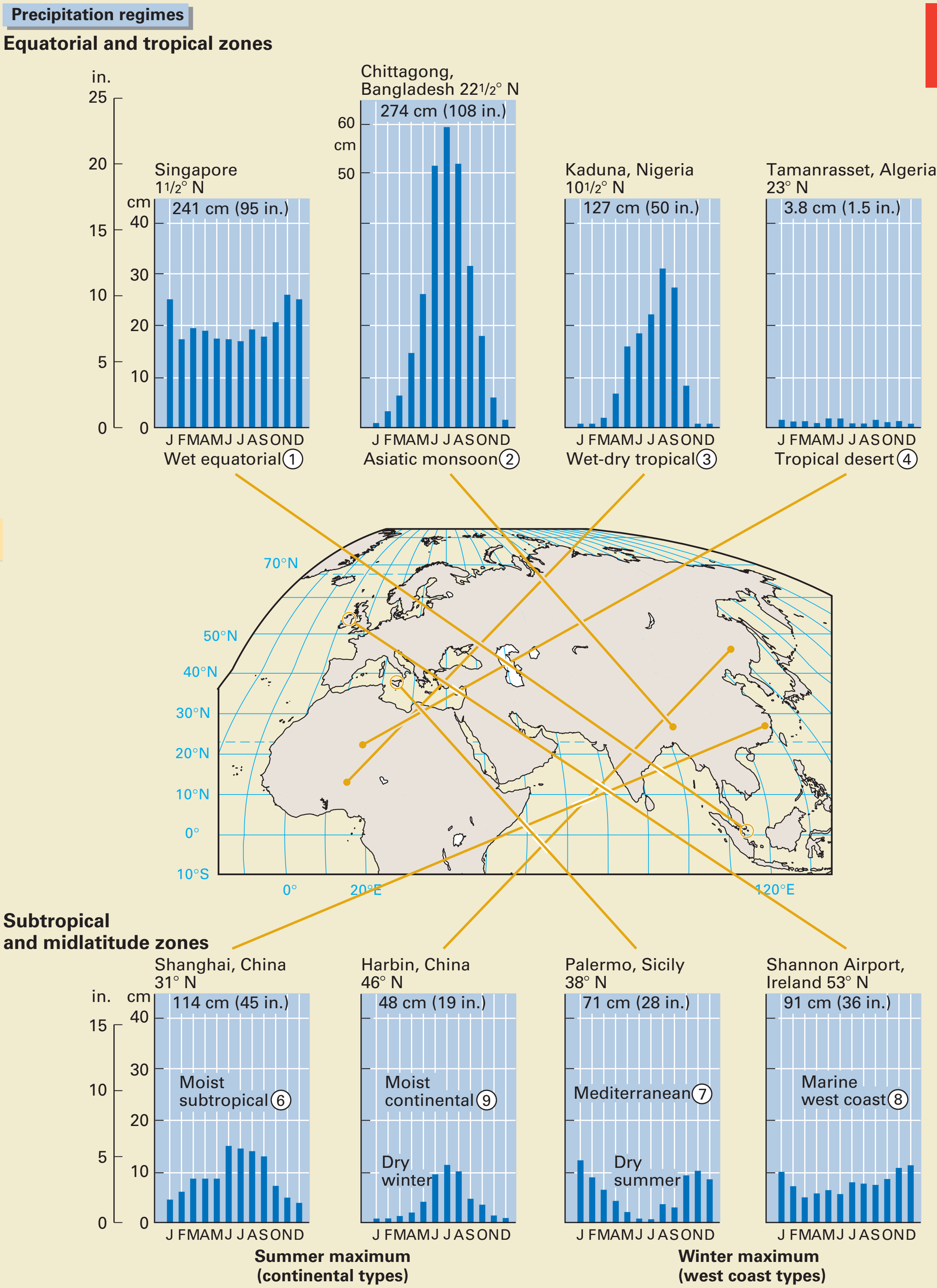
Eight precipitation types selected to show various seasonal patterns. (Based on the Goode Base Map.)

CONCEPT CHECK STOP

What are the key factors that affect climate?

Why do different temperature regimes arise? Identify seven important global precipitation regions.

What are the three types used to describe seasonal precipitation at a weather station? Give an example of a region of each type.



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Climate Classification

LEARNING OBJECTIVES

Describe how air masses and their movements relate to climate.

Explain climate groups.

Discuss dry, moist, and highland climates.

Read and interpret climographs.

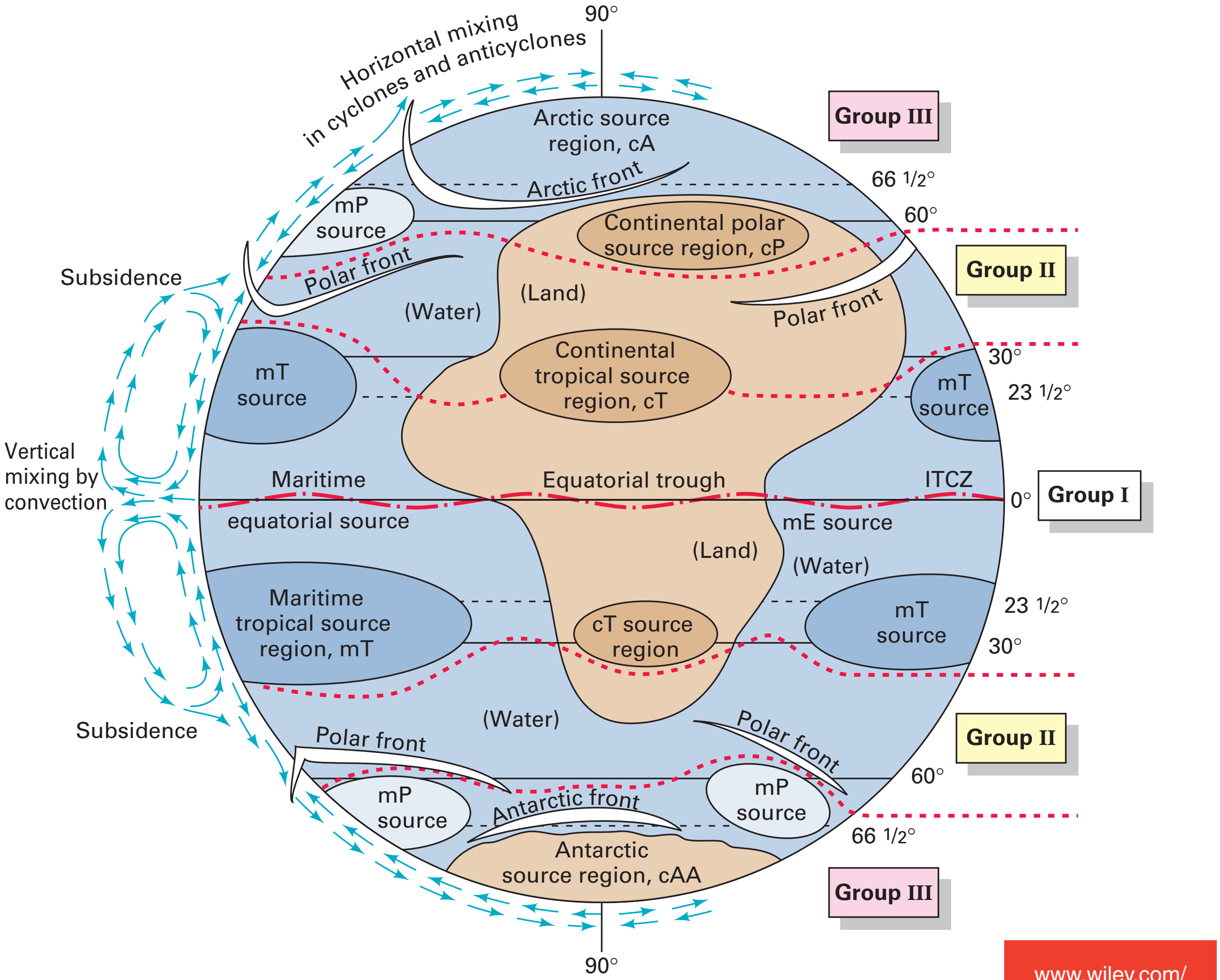
We've seen that we can describe the climate of a weather station and its nearby region pretty accurately using mean monthly values of air temperature and precipitation. Climatologists classify these values into distinctive climate types. To do this, they have developed a set of rules to use when examining monthly temperature and precipitation values. The climatologist uses each station's data to determine the climate to which it belongs, according to these rules. In this book we will discuss 13 distinctive climate types that are designed to be understood and explained by air mass movements and frontal zones. The types follow quite naturally from the principles governing temperature and precipitation that we have discussed.

Air masses are classified according to the general latitude of their source regions and their surface type—land or ocean—within that region. The latitude determines the temperature of the air mass, which can also depend on the season. The kind of surface, land or ocean, controls the moisture content of the air mass. Since the air mass characteristics control the two most important climate variables—temperature and precipitation—we can use air masses as a guide for explaining climates around the globe.

We also know that frontal zones are regions in which air masses are in contact. When unlike air masses are in contact, cyclonic precipitation is likely to develop. But the position of frontal zones changes with the seasons. So the seasonal movements of frontal zones also influence annual cycles of temperature and precipitation.

FIGURE 7.5 shows air mass source regions subdivided into global bands that contain three broad groups of climates: low-latitude (Group I), midlatitude (Group II), and high-latitude (Group III).

- *Group I: Low-Latitude Climates*. Source regions of continental tropical (cT), maritime tropical (mT), and maritime equatorial (mE) air masses dominate the low-latitude climates (Group I). These source regions are related to the three most obvious atmospheric features within the 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.
- *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 are in conflict with polar air masses moving equatorward. This zone may contain as many as a dozen wave cyclones around the globe.
- *Group III: High-Latitude Climates*. Polar and arctic (including antarctic) air masses dominate the high-latitude climates (Group III). 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 wave cyclones. There is no corresponding polar air mass source region in the subantarctic belt, in the southern hemisphere—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.



Climate groups and air mass source regions FIGURE 7.5

Using the map of air mass source regions, we can identify five global bands associated with three major climate groups. Each group has a set of distinctive climates with unique characteristics that are explained by the movements of air masses and frontal zones.

We subdivide these three climate groups to give 13 climate types (or simply, climates)—four low-latitude climates (Group I), six midlatitude climates (Group II), and three high-latitude climates (Group III). In this book, we have numbered the climates to help you identify them on maps and diagrams. We will still refer to each climate by name because the names describe the general nature of the climate and also suggest its global location, but we'll include the climate number next to its name in the text.

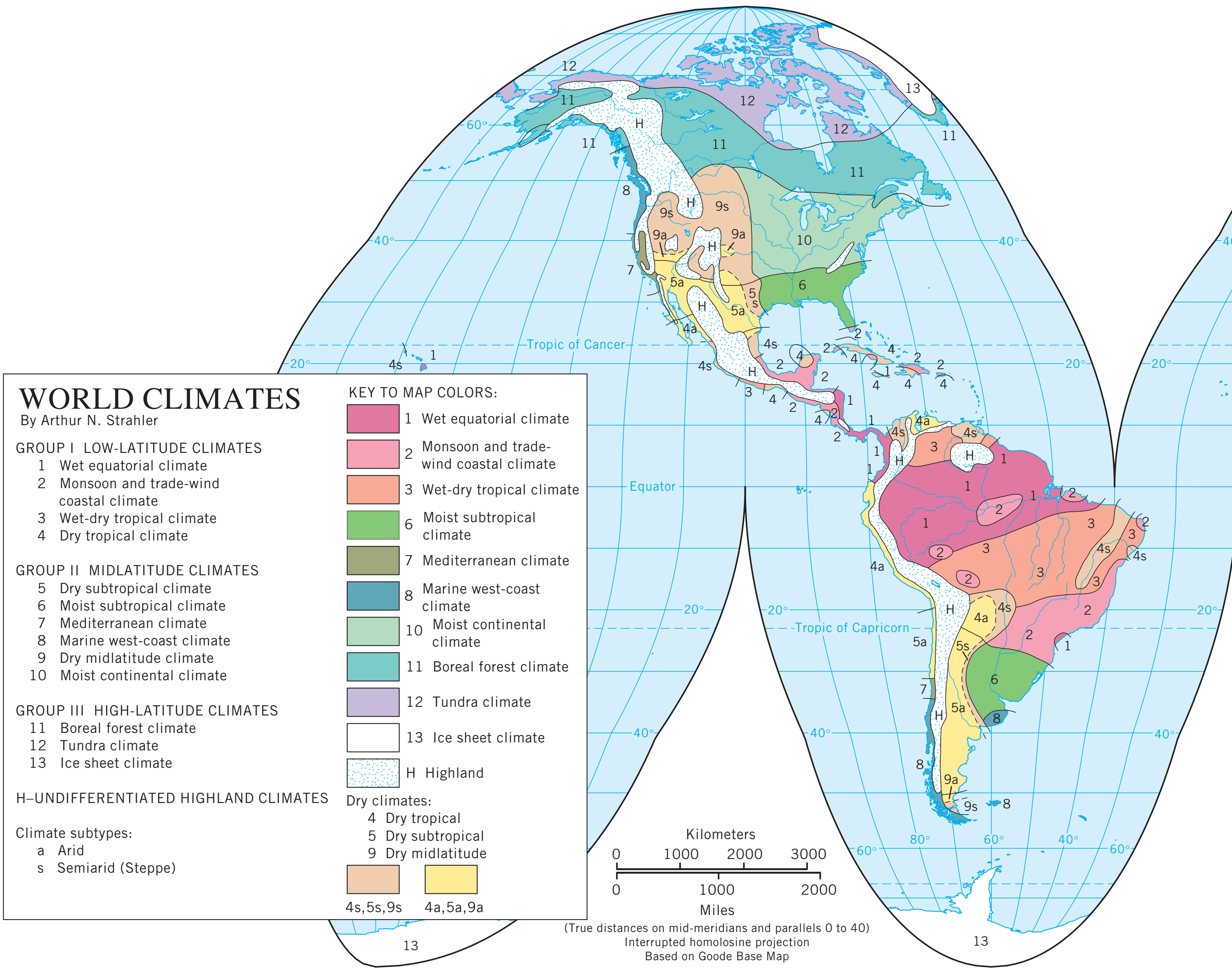
DRY AND MOIST CLIMATES

The world map of climates, **Figure 7.6**, shows the actual distribution of climate types on the continents. All but two of the 13 climate types are either dry climates or moist climates, as we will see in detail later in the chapter.

In dry climates the total annual evaporation of moisture from the soil and from plant foliage greatly exceeds the annual precipitation. Generally speaking, the dry climates do not support permanently flowing streams.

Dry climates range from very dry deserts nearly devoid of plant life to moister regions that support some 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

Climates of the world Figure 7.6



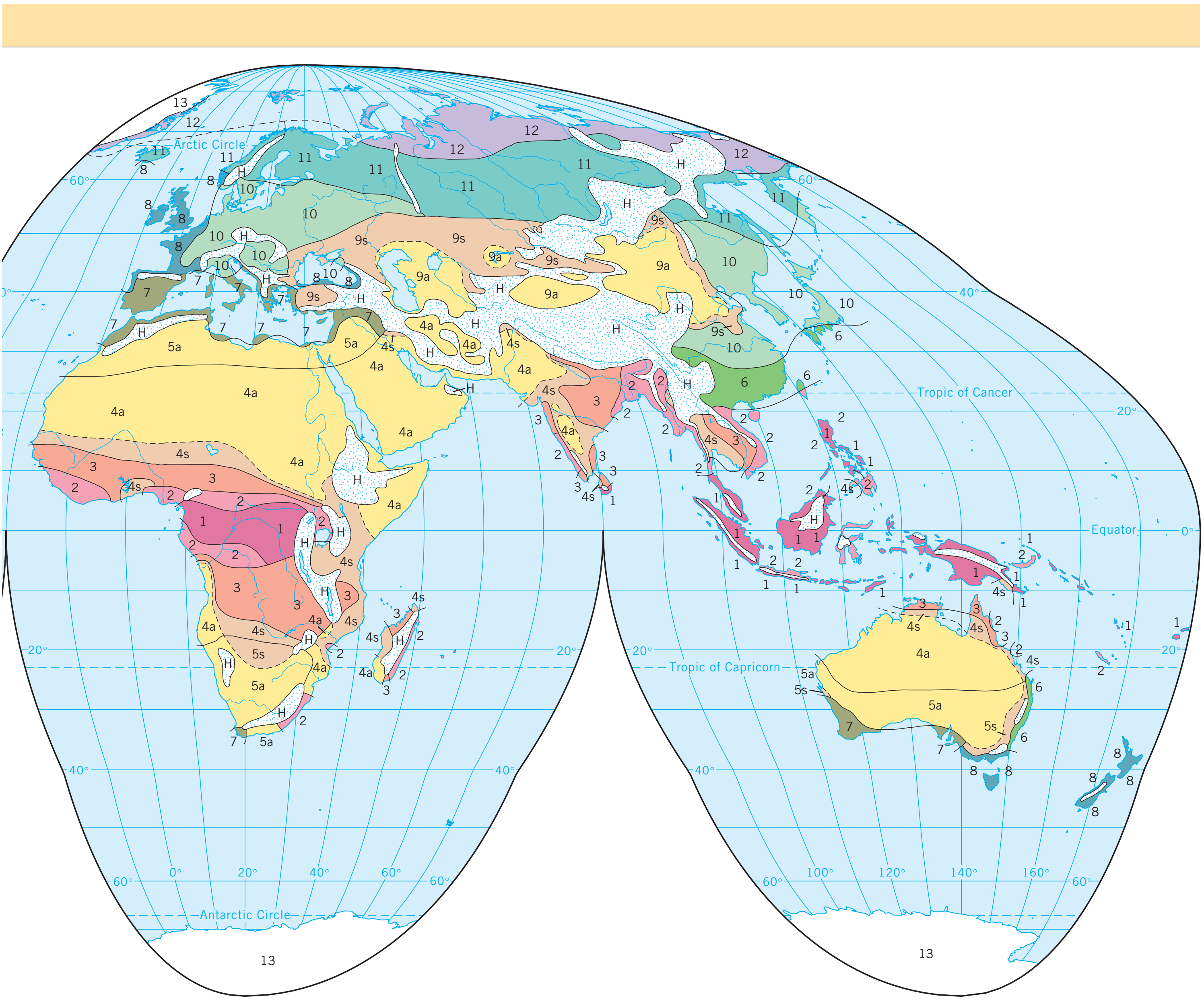
from extremely dry climates to climates that are almost semiarid.

Moist climates have enough rainfall to keep the soil moist through much of the year and sustain the year-round flow of the larger streams. Moist climates support forests or prairies of dense tall grasses.

Two of our 13 climates cannot be accurately described as either dry or moist climates. They alternate between a very wet season and a very dry season, so we will refer to them as wet-dry climates.

HIGHLAND CLIMATES

One climate type that isn't usually included in broad climate classification schemes is the highland climate, which occupies mountains and high plateaus. Many small highland areas simply aren't shown on world maps. Nonetheless, highland climates are interesting, so we will discuss some of their features here. 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, because rainfall increases as air is forced over the mountain ranges, through orographic precipitation.

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 7.7). 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 7.8, 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.

READING A CLIMOGRAPH

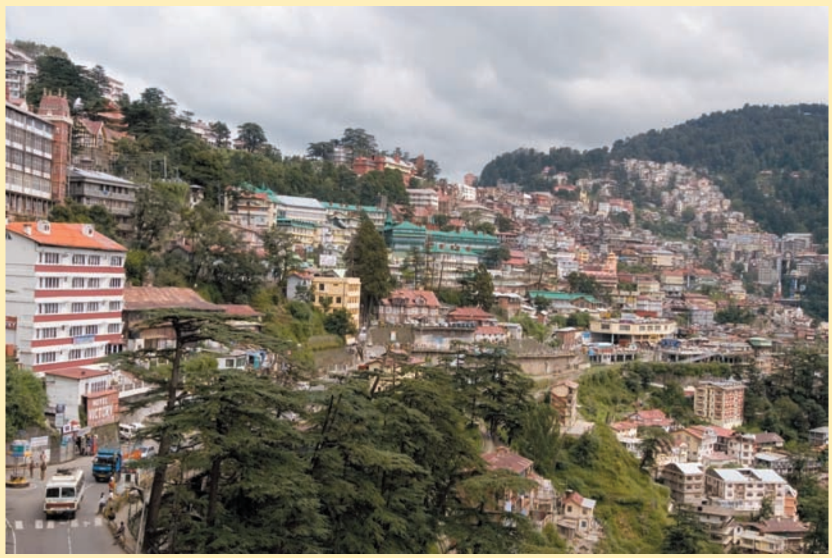
The example of the highland climate also allows us to illustrate the use of the **climograph**—a handy pictorial device that shows the annual cycles of monthly mean air temperature and monthly mean precipitation for a location, along with some other useful information (FIGURE 7.8). We will make frequent use of climographs to provide examples of the 13 climate types discussed in the remainder of this chapter.

Climograph
Graph on which two or more climate variables are plotted for each month of the year.

New Delhi and Simla FIGURE 7.7

Both are in northern India but at different elevations.

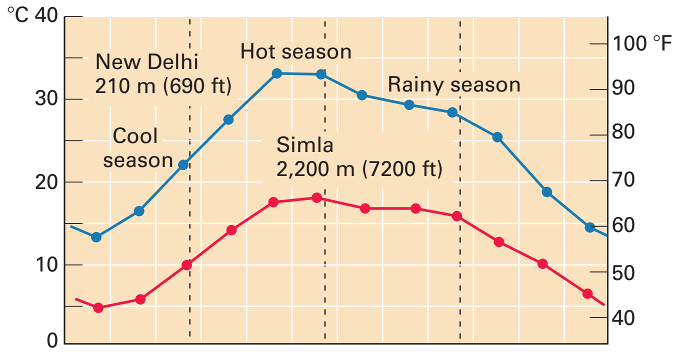
A New Delhi At an elevation of about 300 m (about 1000 ft), New Delhi simmers in the summer's heat.



B 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.

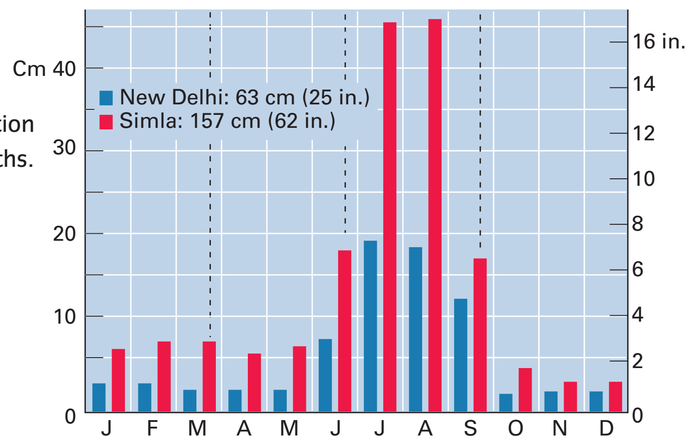
Climograph for New Delhi and Simla FIGURE 7.8

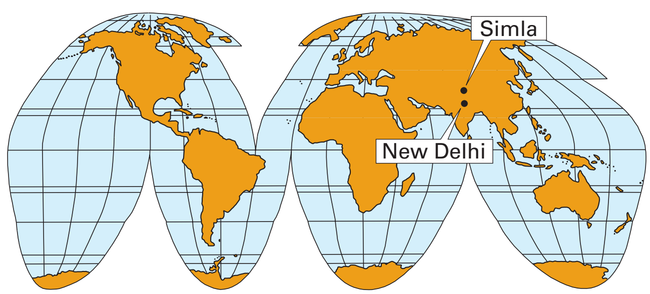
The climograph is a figure that combines graphs of monthly temperature and precipitation for an observing station. This example features two stations plotted together for comparing their climates. Climographs also show total annual precipitation and annual temperature range (omitted here). Many include weather features using picture symbols.



This line graph plots monthly mean temperature for twelve months.

This bar graph shows monthly mean precipitation for twelve months.





CONCEPT CHECK STOP

Identify the three climate groups. How do air masses influence these groups?

How do climatologists classify dry and moist climates?

What are the features of highland climates?

What is a climograph?

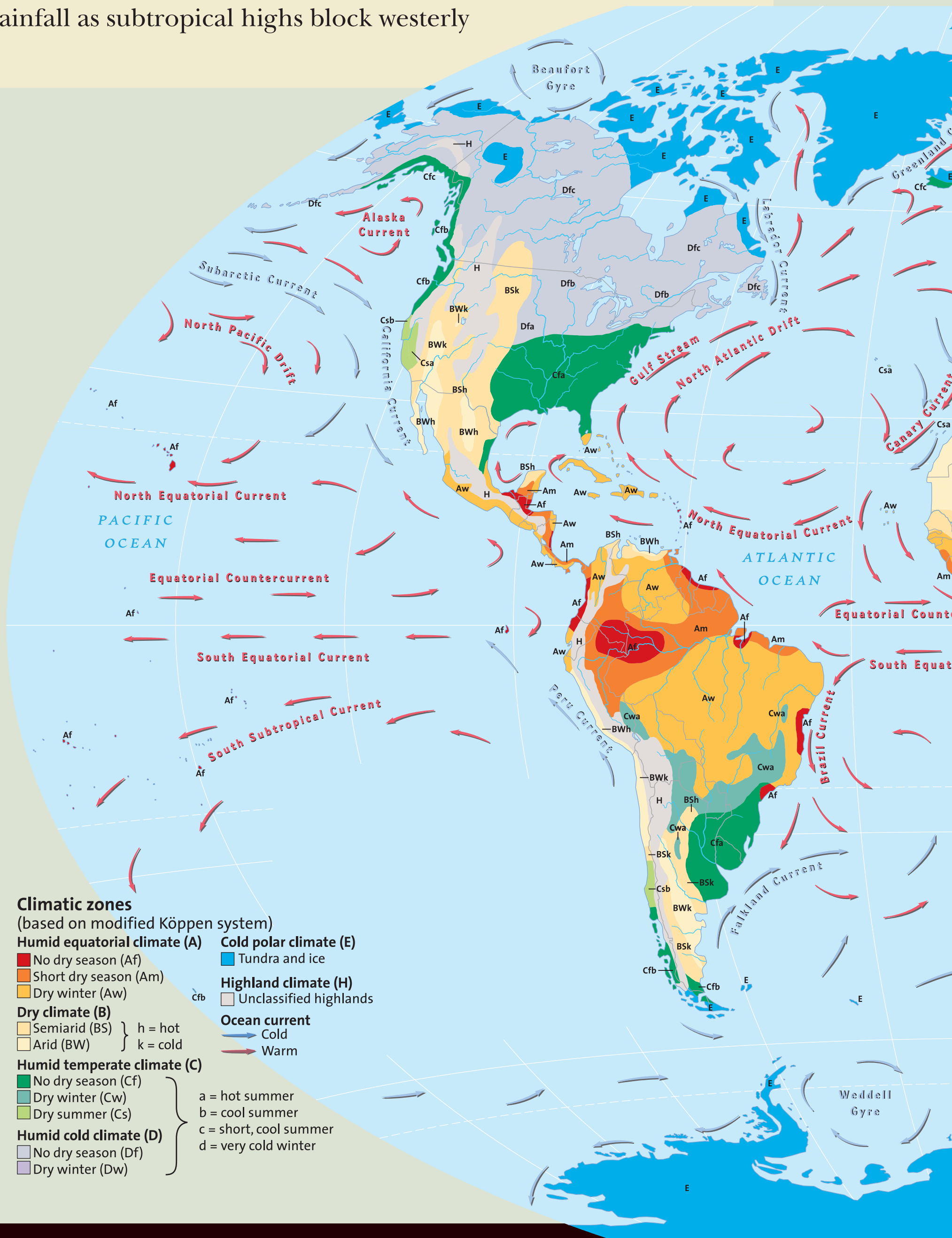
PRECIPITATION

Seasonal precipitation patterns depend on movements of air masses.

- Equatorial regions are wet all year around.
- Trade winds bring rain to equatorial and tropical east coasts.
- Tropical deserts underlie the descending air of subtropical high pressure cells.
- Eastern sides of midlatitude continents receive flows of warm, moist air from the western sides of subtropical highs.
- Midlatitude west coast show *reduced* summer rainfall as subtropical highs block westerly flows of moist, oceanic air.

▲ **Tropical desert**
The climate here is hot and dry all the time.

▲ **Equatorial rainforest**
The climate here is warm and wet all year around.



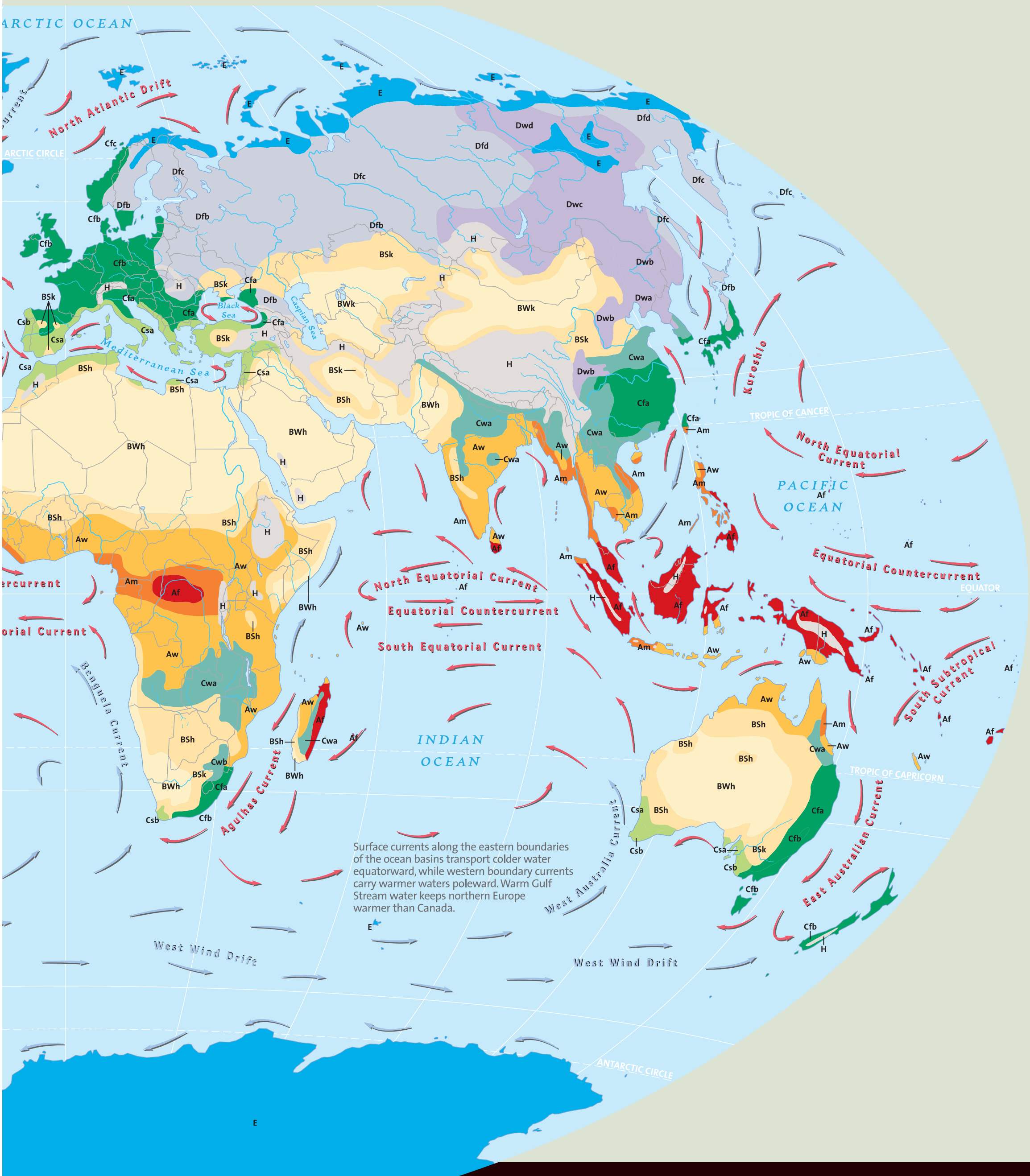
▶ **Climate zones**
Climate types shown here use letter codes to distinguish different climates based on temperature, moisture, and seasonality.

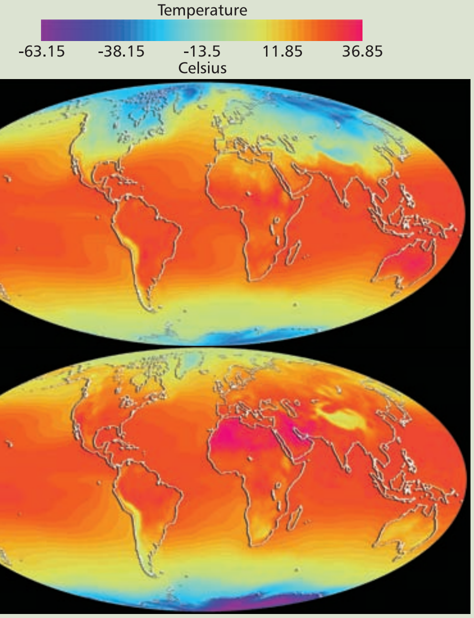
Visualizing
Climate Classification

TEMPERATURE

Seasonal temperature patterns depend on latitude, location, and elevation.

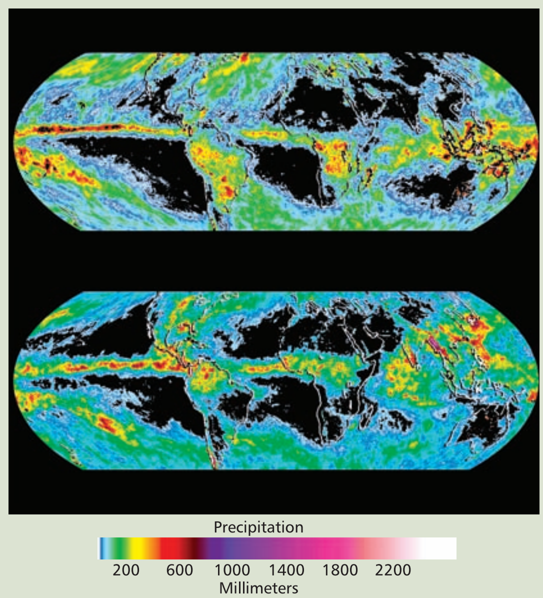
- Latitude: Temperatures drop from the equator toward the poles.
- Location: Continental interiors experience a greater range in temperature with the seasons than coastal locations.
- Elevation: Temperatures drop with elevation.





▲ Temperature
Temperatures vary seasonally and with latitude as the Earth offers first one, then the other, hemisphere to more direct sunlight. Temperatures are modified by ocean currents and vegetation and are depressed by altitude.

▼ Precipitation
Rainfall hugs the equator but migrates alternately north–south to the summer hemispheres, when land is warmer than surrounding seas and rising hot air draws in moisture.



Low-Latitude Climates (Group I)

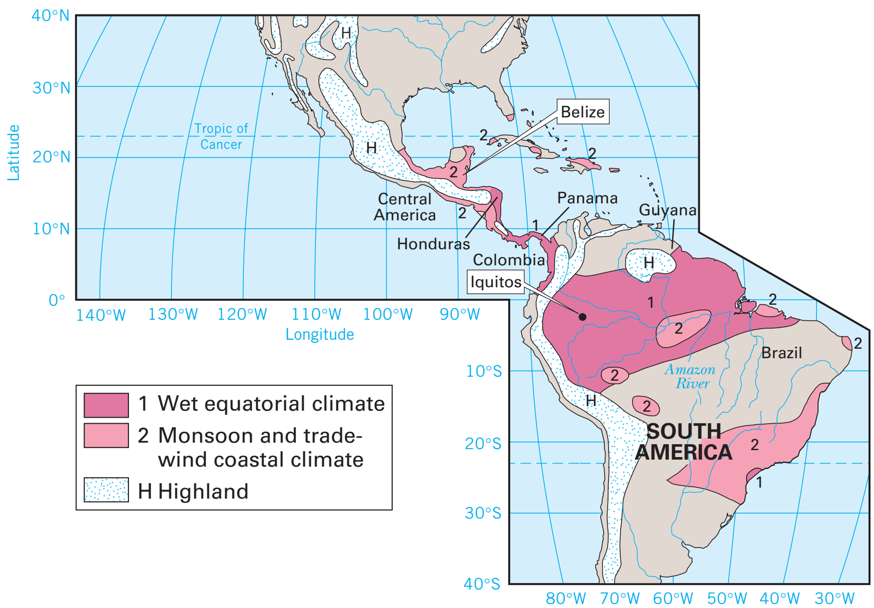
Learning Objectives

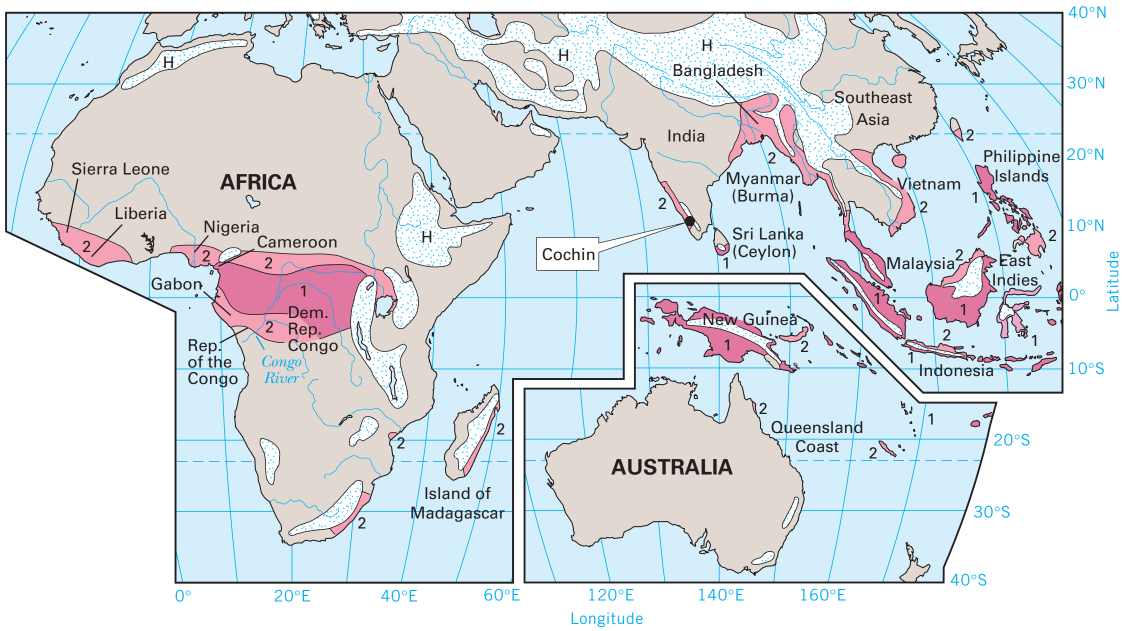
Explain the features of low-latitude climates.

Describe wet equatorial ①, monsoon and trade-wind coastal ②, wet-dry tropical ③, and dry tropical climates ④.

Explain how the movement of the ITCZ through the year affects low-latitude climates.

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.





World map of wet equatorial ① and monsoon and trade-wind coastal climates ② **Figure 7.9**

THE WET EQUATORIAL CLIMATE ①

Figure 7.9 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 Sumatra to New Guinea.

Wet equatorial climate ① Moist climate of the equatorial zone with a large annual water surplus and uniformly warm temperatures through the year.

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 convectional rainfall. There's a large amount of precipitation every month, and the annual total often exceeds 250 cm (about 100 in.). But there is a seasonal rainfall pattern, with heavier rain when the ITCZ migrates into the region. There are uniform temperatures 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 7.10).

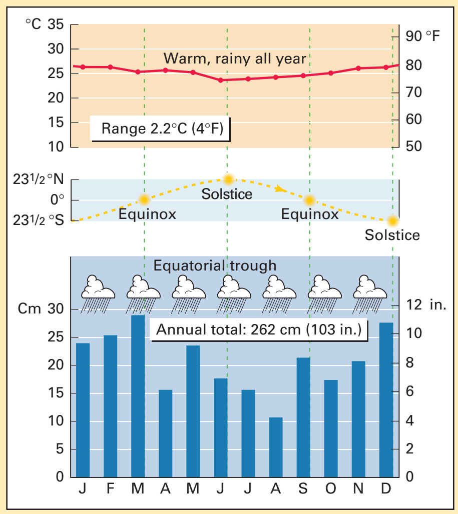
THE MONSOON AND TRADE-WIND COASTAL CLIMATE ②

Monsoon and trade-wind coastal climate ② Moist climate of low-latitudes showing a strong rainfall peak in the high-Sun season and a short period of reduced rainfall in the low-Sun season.

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 (Sun nearest to overhead at noon), 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.

Wet equatorial climate ① FIGURE 7.10

▲ **Iquitos** Frequent rainfall is a way of life on the Amazon River, near Iquitos, Peru. (Iquitos is located on Figure 7.9.)



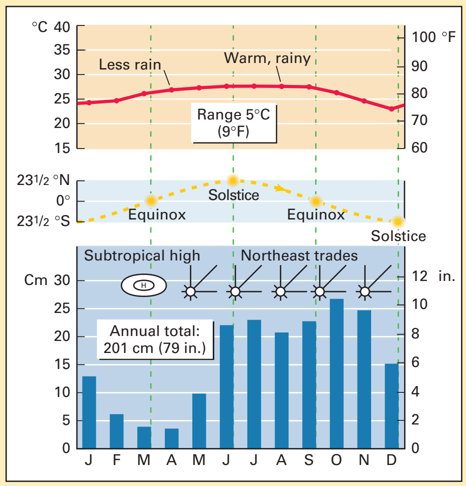
▲ **Iquitos climograph** Iquitos, in Peru (lat. 3° S), is located in the upper Amazon lowland, close to the equator. Temperatures differ very little from month to month, and there is abundant rainfall throughout the year.

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. These 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 orographic effect touches off convectional 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 7.11 is a climograph for the city of Belize, in the Central American country of Belize.

In the Asiatic summer monsoon, the monsoon circulation brings mT air onshore (FIGURE 7.12). 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 air flow. Western India and Myanmar (formerly Burma) are examples. Moist air also penetrates well inland in Bangladesh, providing very heavy monsoon rains.

Trade-wind coastal climate ② FIGURE 7.11

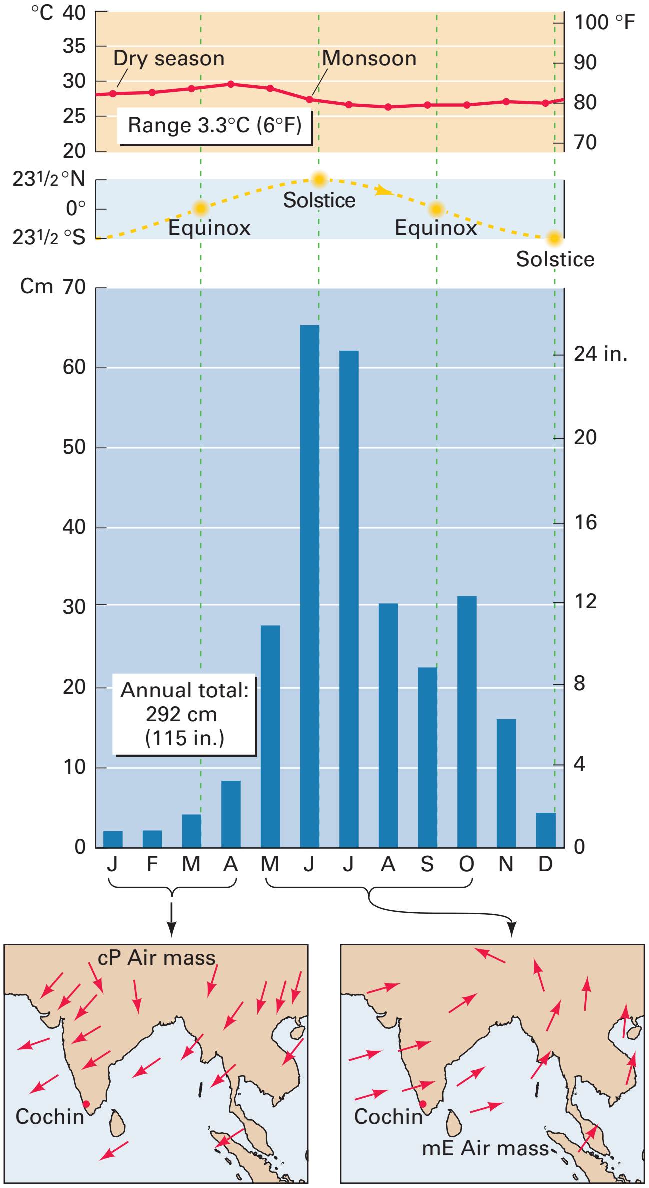
▲ **Belize city** Trade winds bring frequent showers to the coastal capital of Belize City, Belize. (Belize is located on Figure 7.9.)



▲ **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.

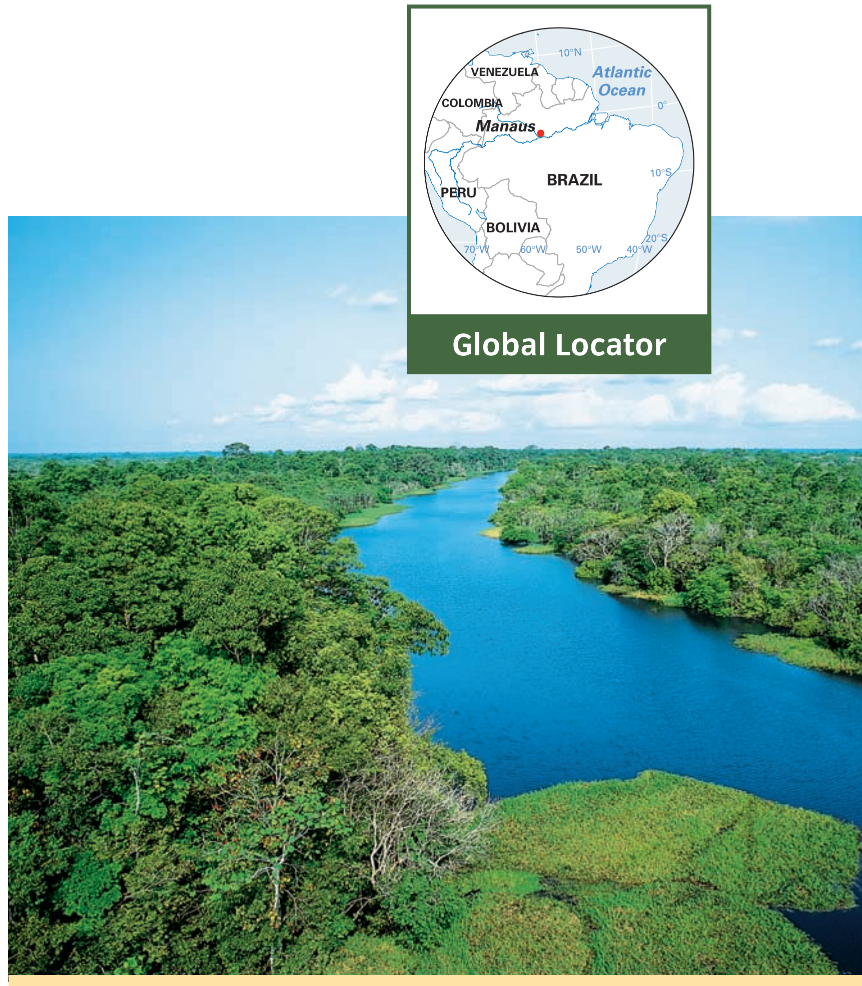
Temperatures in the monsoon and trade-wind coastal climate ② are warm throughout the year. Warmest temperatures occur in the high-Sun season, just before the ITCZ brings clouds and rain, while minimum temperatures are at the time of low Sun.

Our first two climates—wet equatorial ① and monsoon and trade-wind coastal ②—create a special environment—the *low-latitude rainforest* (Figure 7.13). In the rainforest, temperatures are uniformly warm through the year and rainfall is high. Streams flow abundantly throughout most of the year, and the river banks are lined with dense forest vegetation.



Monsoon coastal climate ② FIGURE 7.12

Cochin, on the west coast of lower peninsula 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 7.9.)



Rainforest of the western Amazon lowland, near Manaus, Brazil FIGURE 7.13

The river is a tributary of the Amazon.

THE WET-DRY TROPICAL CLIMATE ③

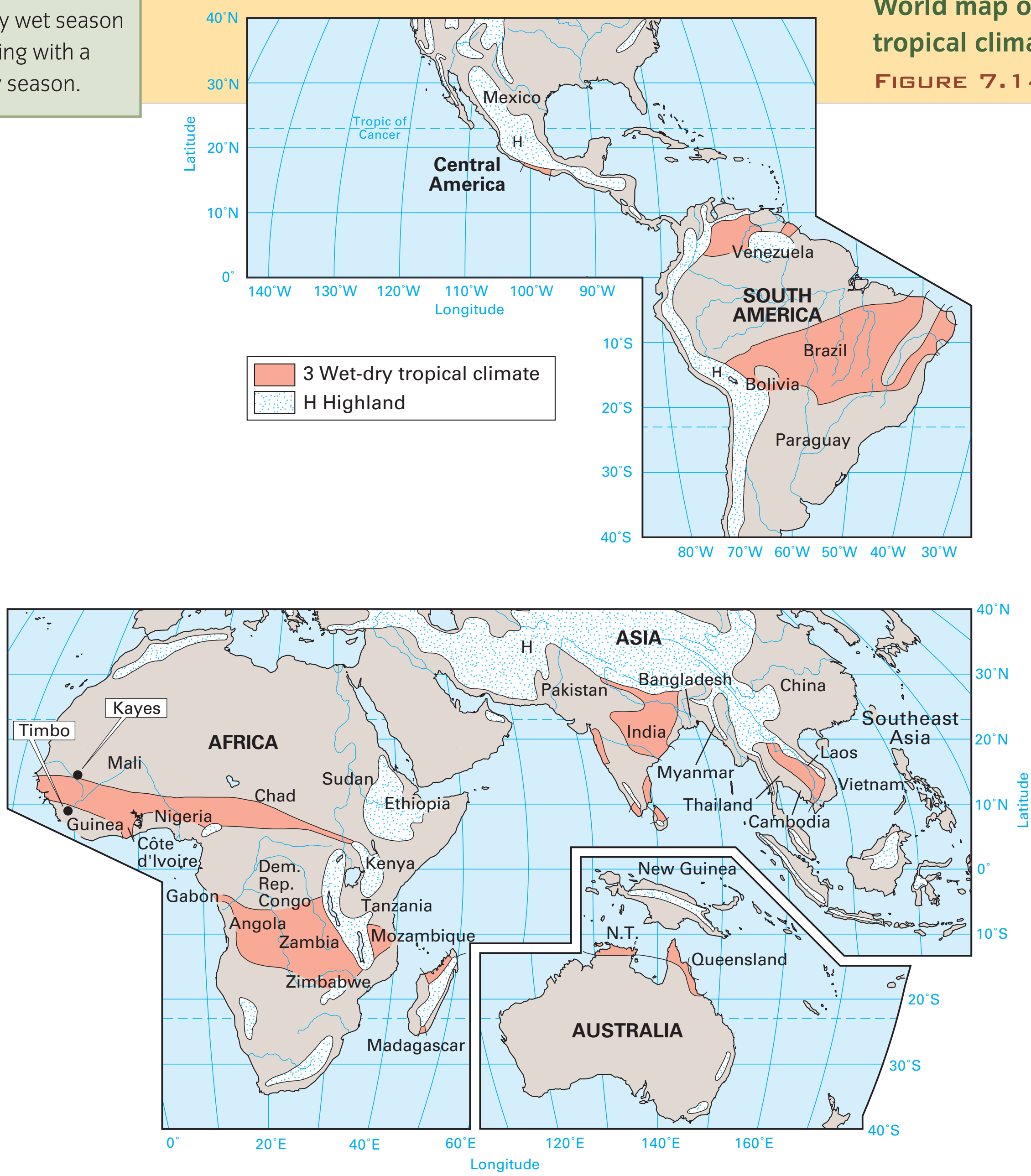
As we move farther poleward, the seasonal cycles of rainfall and temperature become stronger, and the monsoon and trade-wind coastal climate ② grades into the **wet-dry tropical climate** ③.

Wet-dry tropical climate ③ Climate of the tropical zone characterized by a very wet season alternating with a very dry season.

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.

FIGURE 7.14 shows the global distribution of the wet-dry tropical climate ③. This climate region lies be-

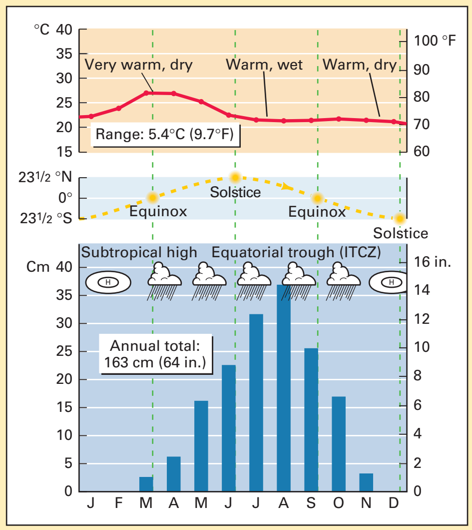
World map of the wet-dry tropical climate ③
FIGURE 7.14



tween 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 and monsoon and trade-wind coastal climates. 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 air flows provided by trade and monsoon winds. These barriers create a rainshadow effect, so that even less rainfall occurs during the rainy season and the dry season is drier still. **FIGURE 7.15** is a climograph for Timbo, Guinea, at lat. 10° N in West Africa.

Wet-dry tropical climate ③ FIGURE 7.15

▲ **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 7.14.)



▲ 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.

Savanna environments FIGURE 7.16

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.

A 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.

B Thorntree-tall grass savanna Thorny Acacia trees are widely spaced on this plain of tall grasses and shrubs.

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 7.16). 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

Dry tropical climate ④ Climate of the tropical zone with high temperatures and low rainfall.

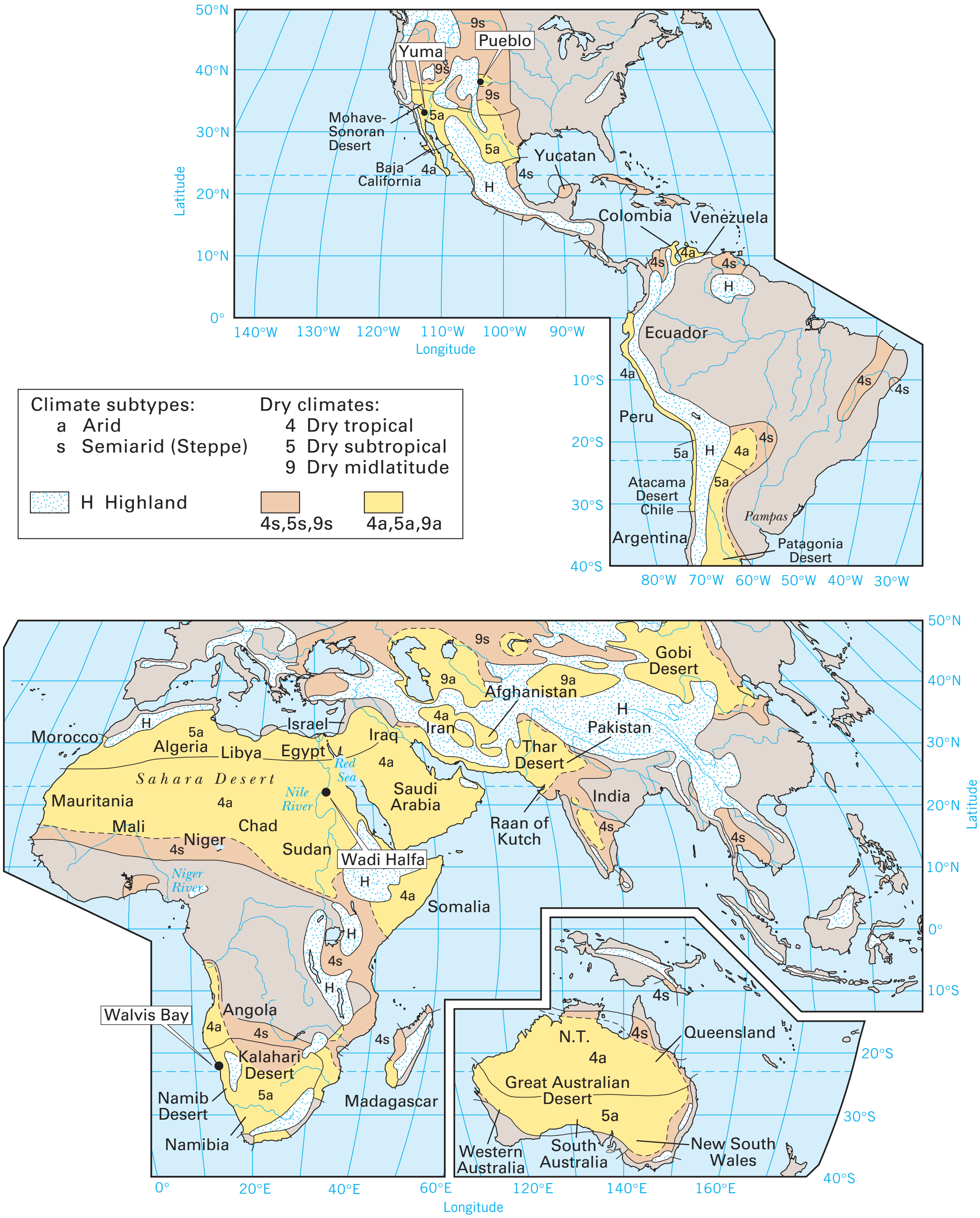
The **dry tropical climate ④** is found in the center and east sides of subtropical high-pressure cells. Here, air descends and warms adiabatically, inhibiting condensation, so rainfall is very rare and occurs only when unusual weather conditions move moist air into the region. Skies are clear most of 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. Travel from the tropics toward the equator and rainfall increases. Continuing in this direction, 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 7.17 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

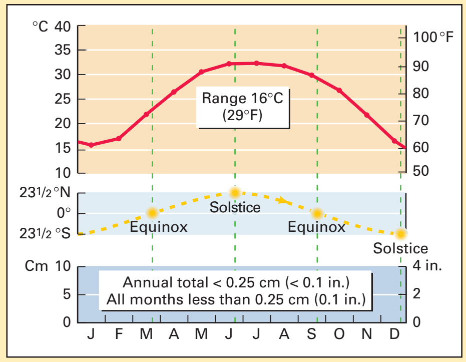
World map of the dry tropical ④, dry subtropical ⑤, and dry midlatitude ⑨ climates FIGURE 7.17

The latter two climates are poleward and eastward extensions of the dry tropical climate ④ with cooler temperatures.



Dry tropical climate ④. Dry desert. FIGURE 7.18

▲ **Wadi Halfa** This aerial view of Wadi Halfa, Sudan, situated on the Nile River, shows the town's flat-roofed residences with walled courtyards, laid out in a rectangular pattern. (Wadi Halfa is located on Figure 7.17.)



▲ 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 0.75 cm (0.3 in.).

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 7.18 is a climograph for a dry tropical station, Wadi Halfa, in Sudan in the heart of the North African desert.

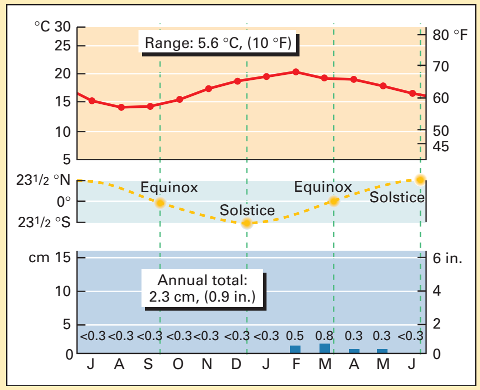
The Earth's desert landscapes are actually quite varied. Although these dry deserts are largely extremely arid (*a*), there are broad zones at the margins that are semiarid (*s*). These steppes have a short wet season that supports the growth of grasses on which animals (both wild and domestic) graze (FIGURE 7.19).

Steppes FIGURE 7.19

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.

Dry tropical climate ④. Western coastal desert subtype. FIGURE 7.20

▲ **Walvis Bay, Namibia** 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 7.17.)



▲ 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.

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 7.20 shows a good example of this, in Walvis Bay, in Namibia.

CONCEPT CHECK STOP

Name and describe the four climate types of the low-latitude climate group. Give an example of each one.

What are the main features of the low-latitude rainforest?

How do they compare with the savanna environment?

Midlatitude Climates (Group II)

LEARNING OBJECTIVES

Describe the features of midlatitude climates.

Describe dry subtropical ⑤, moist subtropical ⑥, Mediterranean ⑦, marine west-coast ⑧, dry midlatitude ⑨, and moist continental climates ⑩.

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 air flow 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.

THE DRY SUBTROPICAL CLIMATE ⑤

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.

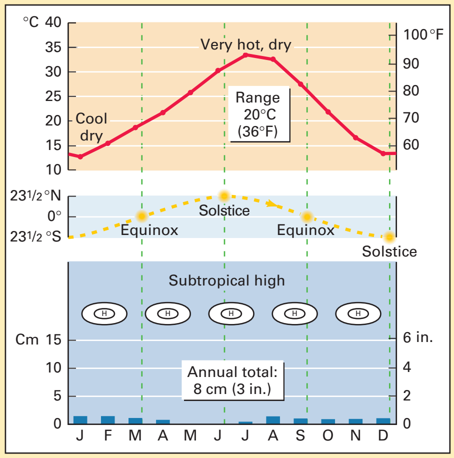
Dry subtropical climate ⑤ Dry climate of the subtropical zone, transitional between the dry tropical climate and the dry midlatitude climate.

The dry subtropical climate ⑤ is found in a broad band of North Africa, connecting with the Near East. Southern Africa and southern Australia also contain this climate. A band of dry subtropical climate ⑤ occupies Patagonia, in South America, and in North America, the Mojave and Sonoran deserts of the American Southwest and northwest Mexico are of this type. FIGURE 7.21 is a climograph for Yuma, Arizona, a city within the arid subtype of the dry subtropical climate ⑤.

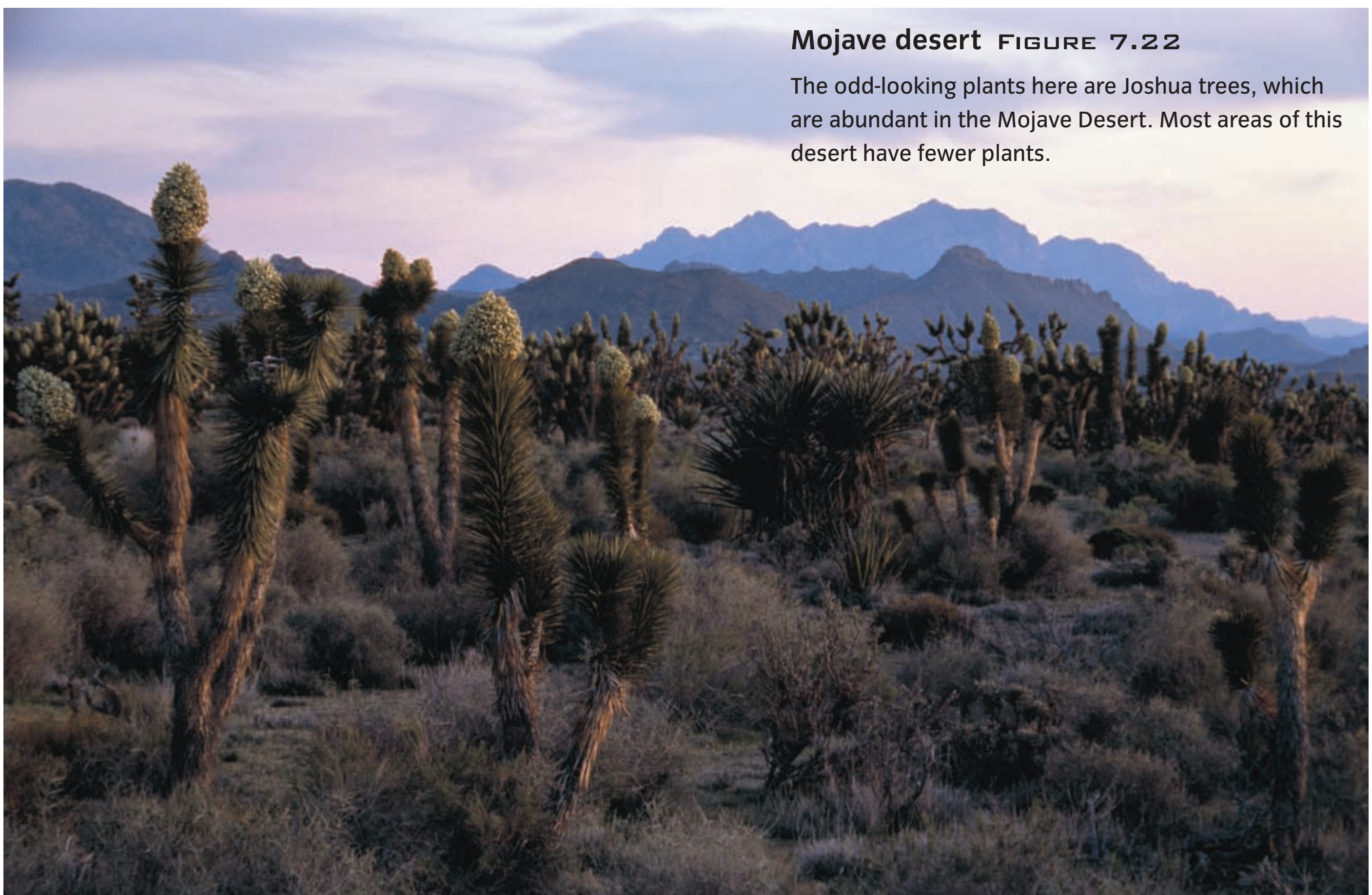
The dry subtropical climate ⑤ environment is similar to that of the dry tropical climate ④. Both are very dry, and the boundary between these two climate types is graded. But if we travel northward in the subtropical climate zone of North America, arriving at about 34° N in the interior Mojave Desert 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 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 7.22).

▲ **Yuma, Arizona** Spanish mission-style architecture is a highlight of this Arizona desert city. (Yuma is located on Figure 7.17.)

Dry subtropical climate ⑤ FIGURE 7.21



▲ 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 8 cm (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.



Mojave desert FIGURE 7.22

The odd-looking plants here are Joshua trees, which are abundant in the Mojave Desert. Most areas of this desert have fewer plants.

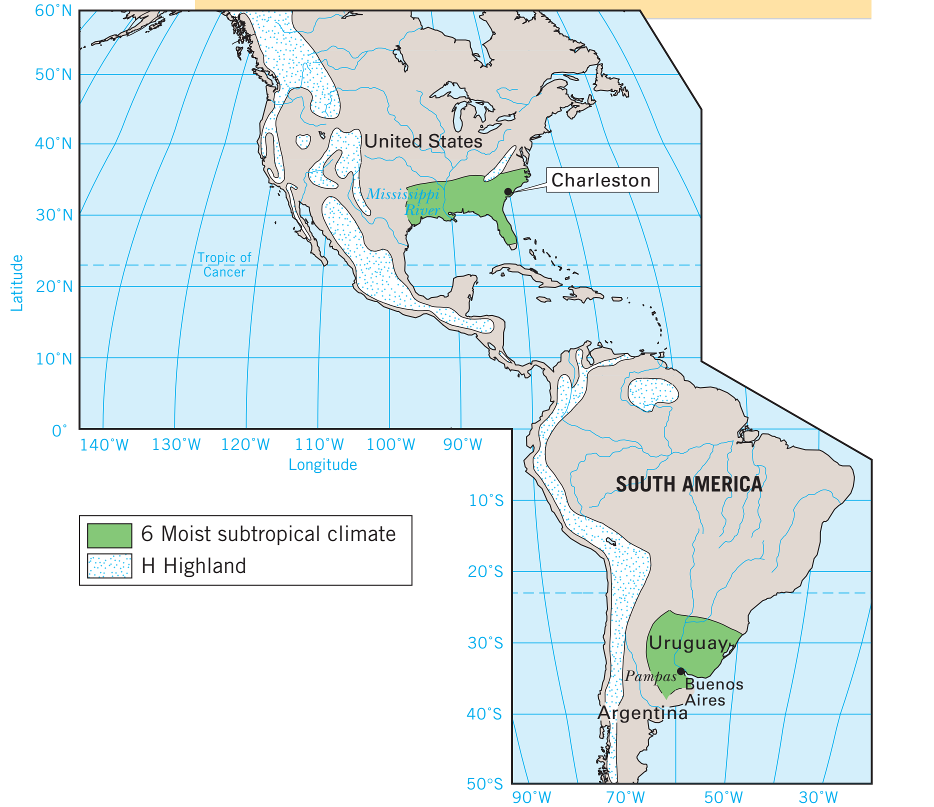
THE MOIST SUBTROPICAL CLIMATE ⑥

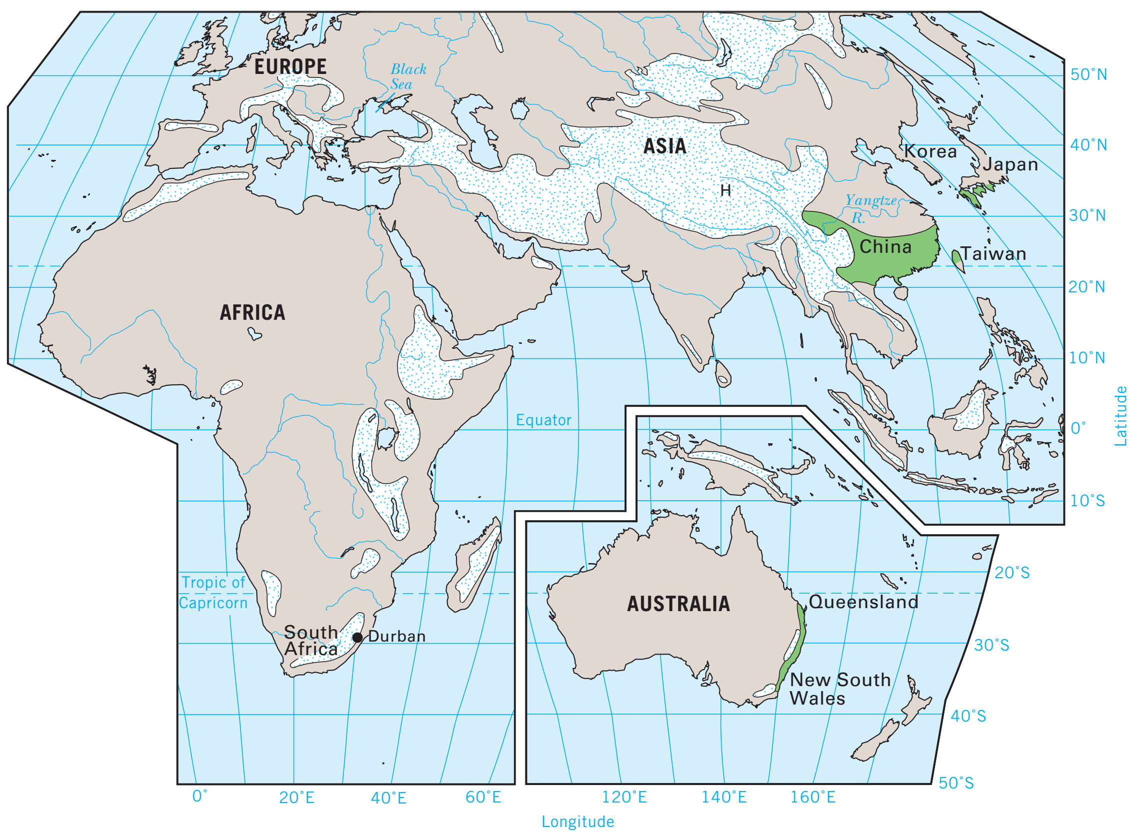
The **moist subtropical climate** ⑥ (FIGURE 7.23) is found on the eastern sides of continents between lat. 20° and 35° N and S. In South America, it includes parts of Uruguay, Brazil, and Argentina. In Australia, it consists of a narrow band between the eastern coastline and the eastern interior ranges. 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 convectional. Occasional tropical cyclones add to this summer precipitation. In Southeast Asia, this climate is characterized by

Moist subtropical climate ⑥ Moist climate of the subtropical zone, characterized by a moderate to large annual water surplus and a strong seasonal temperature cycle.

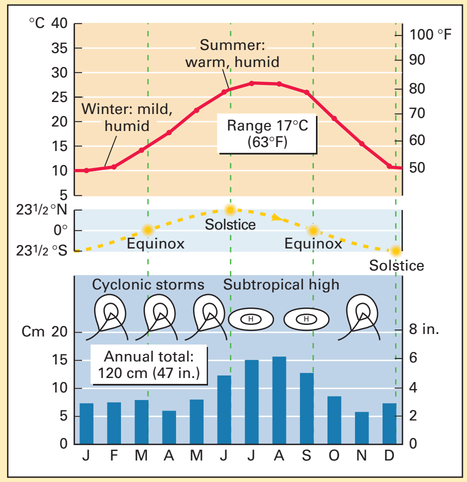
World map of the moist subtropical climate ⑥
FIGURE 7.23





Moist subtropical climate ⑥ FIGURE 7.24

▲ **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 7.23.)



▲ Charleston, South Carolina (lat. 33° N), located on the eastern seaboard, has a mild winter and a warm summer. There is ample precipitation in all months but a definite summer maximum. Total annual rainfall is abundant—120 cm (47 in.)—and ample precipitation falls in every month. 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.

a strong monsoon effect, with much more rainfall in the summer than in the winter. Summer temperatures are warm, with persistent high humidity.

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 7.24 shows a climograph for Charleston, South Carolina. The native vegetation of the moist subtropical climate ⑥ is forest, including several different types (FIGURE 7.25).

Moist subtropical forest FIGURE 7.25

A mix of broadleaf deciduous trees and shrubs (oaks, hickories, poplars, etc.) and occasional pines are quite typical of forests in this climate zone. Broadleaf evergreen trees and shrubs, such as the mountain laurel shown here, can also occur.

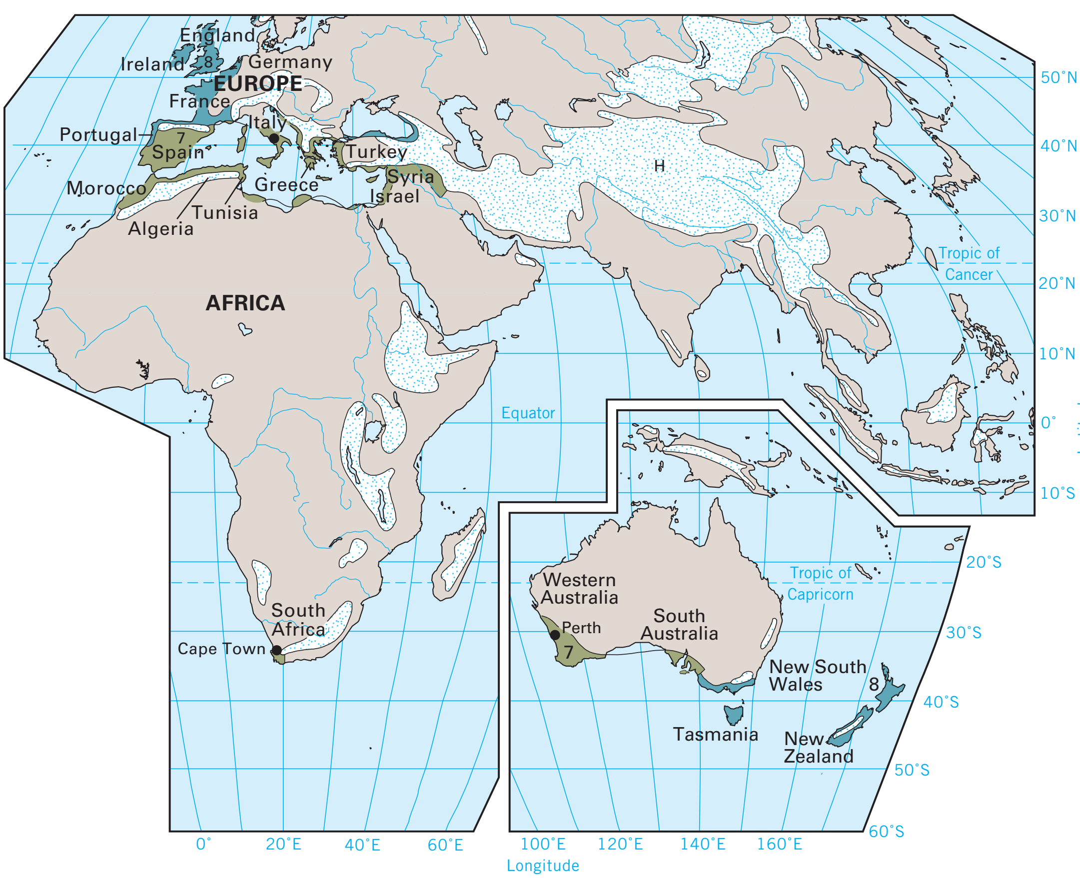
THE MEDITERRANEAN CLIMATE ⑦

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.

A global map of the Mediterranean climate ⑦ is shown in **Figure 7.26**. It is found between lat. 30° and 45° N and S. In the southern hemisphere, it occurs 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

Mediterranean climate ⑦ Climate type of the subtropical zone, characterized by the alternation of a very dry summer and a mild, rainy winter.

World map of the Mediterranean ⑦ and marine west-coast ⑧ climates Figure 7.26

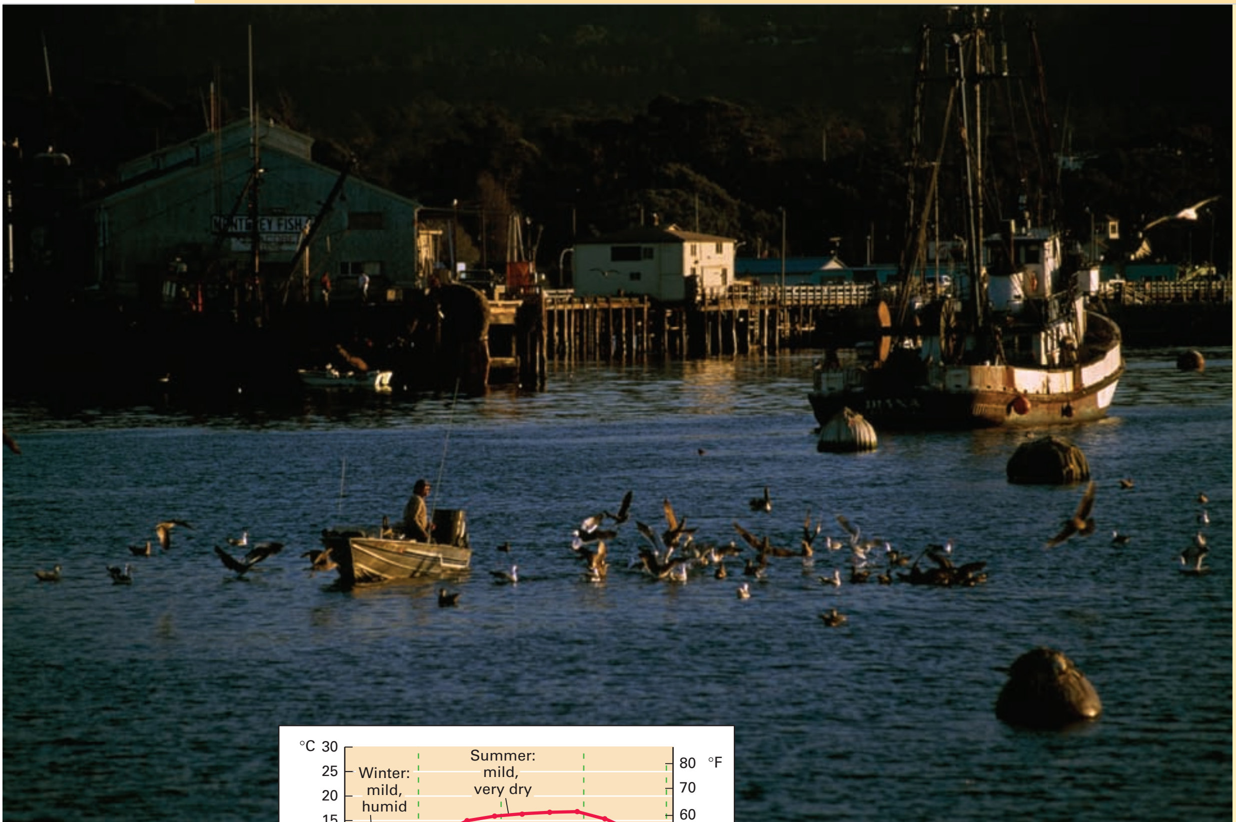


central and Southern California. In Europe, this climate type surrounds the Mediterranean Sea, giving the climate its distinctive name.

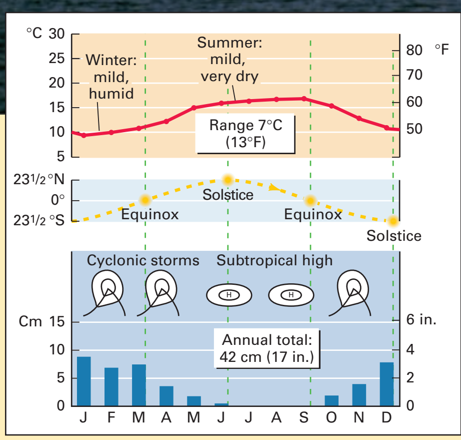
The Mediterranean climate ⑦ spans arid to humid climates, depending on location. Generally, the closer an area is to the tropics, the stronger the influence of subtropical high pressure will be, and thus the drier the climate. The temperature range is moderate, with warm to hot summers and mild winters. Coastal zones between lat. 30° and 35° N and S, such as Southern California, show a smaller annual range, with very mild winters. **Figure 7.27** 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."

Mediterranean climate ⑦ Figure 7.27



◀ **Monterey, California** As evident in this photo of Monterey harbor, the west coasts of the Mediterranean climate ⑦ often support extensive fisheries. (Monterey is located on Figure 7.26.)



◀ 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

Marine west-coast climate ⑧ Cool, moist climate of west coasts in the midlatitude zone, usually with abundant precipitation and a distinct winter precipitation maximum.

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.

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 7.28 shows a climograph for Vancouver, British Columbia.

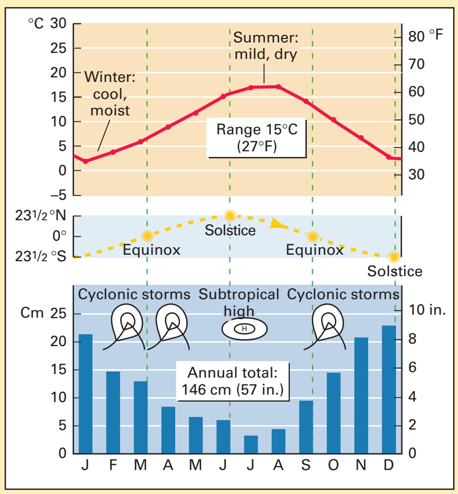
THE DRY MIDLATITUDE CLIMATE ⑨

Dry midlatitude climate ⑨ Dry climate of the midlatitude zone with a strong annual temperature cycle and cold winters.

The **dry midlatitude climate ⑨** is almost exclusively limited to the interior regions of North America and Eurasia, where it lies within the rainshadow of mountain ranges on the west or south. The ranges effectively

Marine west-coast climate ⑧ FIGURE 7.28

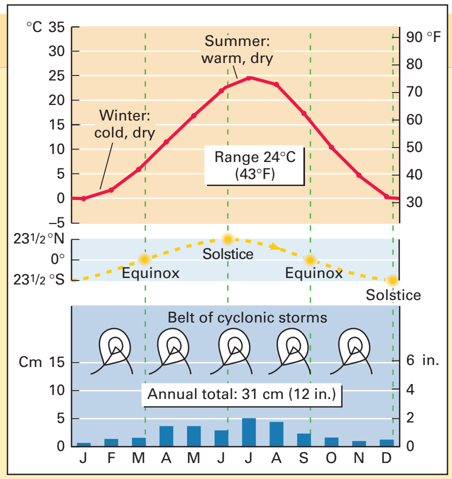
◀ **Vancouver, British Columbia** Situated on the western coast of Canada, Vancouver is a major deep-water seaport. The nearby Coast Mountains are lined with conifer forests. (Vancouver is located on Figure 7.17)



▲ 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.

Dry midlatitude climate ⑨ FIGURE 7.29

▲ **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 7.17)



▲ 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 31 cm (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.

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 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 7.29 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 7.30).

Wheat harvest FIGURE 7.30

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 a good 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.

THE MOIST CONTINENTAL CLIMATE ⑩

Moist continental climate ⑩ Moist climate of midlatitude zone with strongly defined winter and summer seasons and adequate precipitation throughout the year.

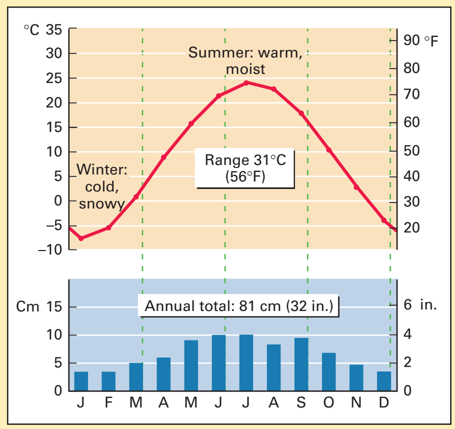
The **moist continental climate** ⑩ is located in central and eastern parts of North America and Eurasia in the midlatitudes. It lies in the polar-front zone—the battleground of polar and tropical air masses. Seasonal temperature contrasts are strong, and day-to-day weather is highly variable. There 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.

China, Korea, and Japan have more summer rainfall and a drier winter than North America does. 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 Atlantic. Madison, Wisconsin, in the American Midwest (FIGURE 7.31), provides an example of the moist continental climate ⑩.

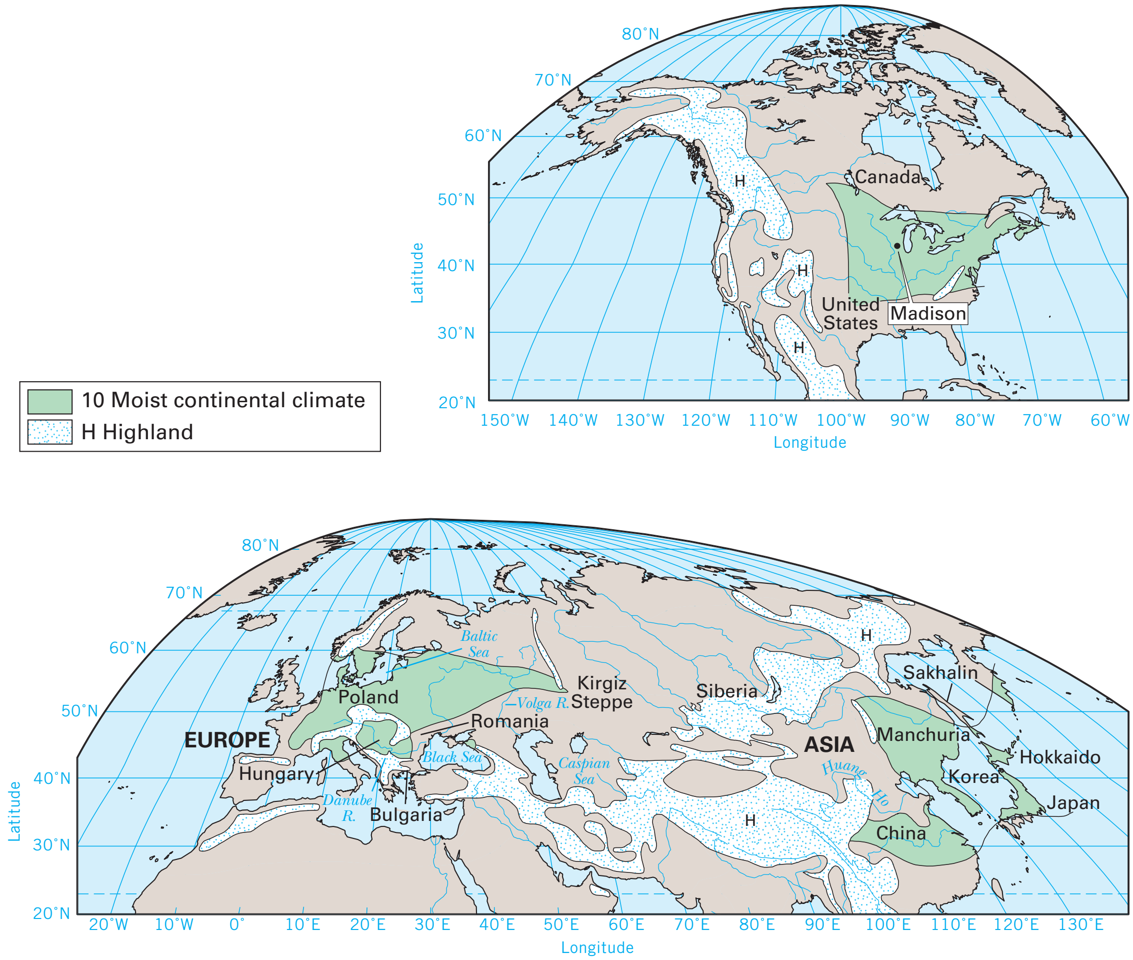
FIGURE 7.32 shows the global locations of the moist continental climate ⑩. It is restricted to the northern hemisphere, between lat. 30° and 55° N in North America and Asia, and in lat. 45° to 60° N in Europe. In Asia, it is found in northern China, Korea, and

Moist continental climate ⑩ FIGURE 7.31

▲ **Madison, Wisconsin** The snowy winters here, offer plenty of opportunity for outdoor recreation. (Madison is located on Figure 7.32.)



▲ 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.



World map of the moist continental climate ⑩ FIGURE 7.32

Japan. Most of central and eastern Europe has a moist continental climate, as does most of the eastern half of the United States from Tennessee to the north, as well as the southernmost strip of eastern Canada.

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.

CONCEPT CHECK STOP

Name and describe the six climate types of the midlatitude climate group. Give an example of each.

What types of vegetation are native to each climate?

High-Latitude Climates (Group III)

Learning Objectives

Describe the features of high-latitude climates.

Describe boreal forest ⑪, tundra ⑫, and ice sheet ⑬ climates.

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.

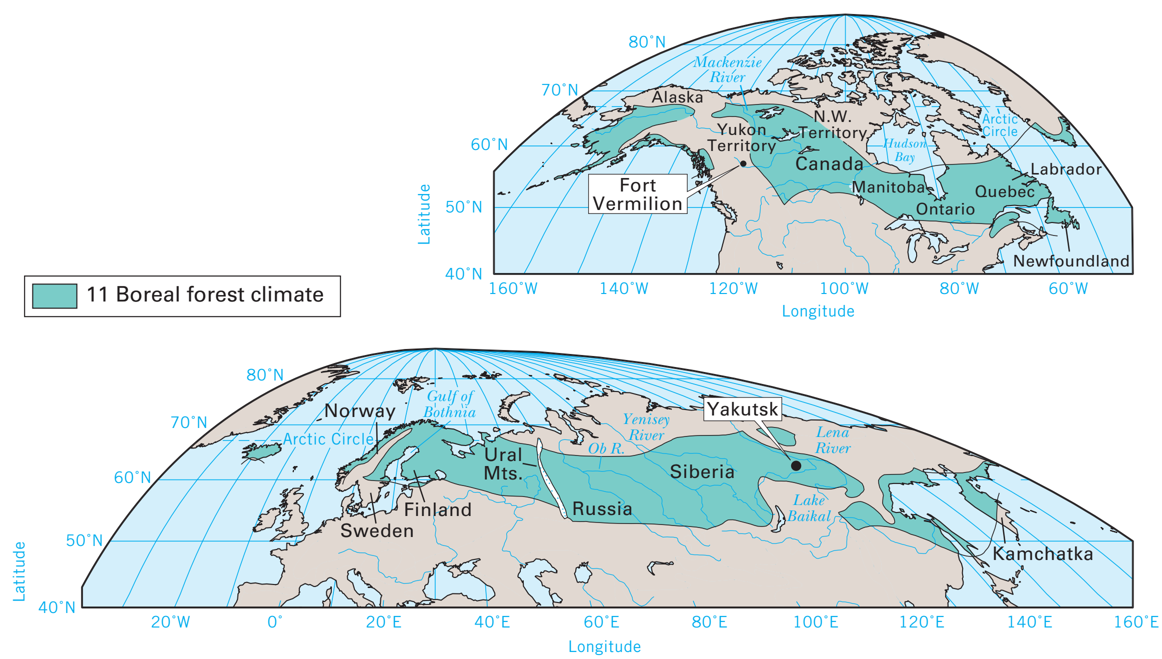
The high-latitude climates coincide closely with the belt of prevailing westerly winds that circles each pole. In the northern hemisphere, this circulation sweeps maritime polar (mP) air masses, formed over the northern oceans, into conflict with continental polar (cP) and continental arctic (cA) air masses on the continents. Rossby waves form in the westerly flow, bringing lobes 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

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.

Boreal forest climate ⑪ Cold climate of the subarctic zone in the northern hemisphere with long, extremely severe winters and several consecutive months of frozen ground.

Precipitation increases substantially in summer, when maritime air masses penetrate the continent with traveling cyclones, but the total annual precipitation is



World map of the boreal forest climate ⑪ FIGURE 7.33

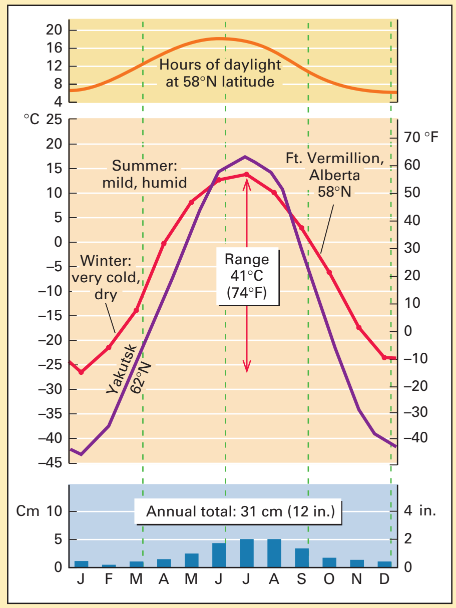
small. Although much of the boreal forest climate is moist, large areas in western Canada and Siberia have low annual precipitation and are therefore cold and dry.

FIGURE 7.33 shows the global extent of the boreal forest climate ⑬. 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.

This climate type ranges from 50° to 70° N in latitude. FIGURE 7.34 shows a climograph for Fort Vermilion, Alberta, plotted alongside temperature data for Yakutsk, a Siberian city.

Boreal forest climate ⑪ FIGURE 7.34

▲ **Yakutsk, Siberia** These well-dressed pedestrians are making their way down a snowy street in winter. (Yakutsk is located on Figure 7.33.)



▲ Extreme winter cold and a very great annual range in temperature characterize the climate of Fort Vermilion, Alberta (lat. 58° N) located on Figure 7.33. 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).

Lakes in a boreal forest FIGURE 7.35

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 land surface features of much of the region of boreal forest climate were shaped beneath the great ice sheets of the last 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 7.35).

The dominant upland vegetation of the boreal forest climate ⑪ region is boreal forest, consisting of needleleaf trees. Although the growing season in the boreal forest climate ⑪ is short, it is still possible to cultivate crops. Farming is largely 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.

THE TUNDRA CLIMATE ⑫

Tundra climate ⑫ Cold climate of the arctic zone with eight or more months of frozen ground.

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 7.36) shows the tundra 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 northernmost fringe of the Scandinavian Peninsula and Siberian coast. The Antarctic Peninsula (not shown in Figure 7.36) 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 7.37).

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 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.

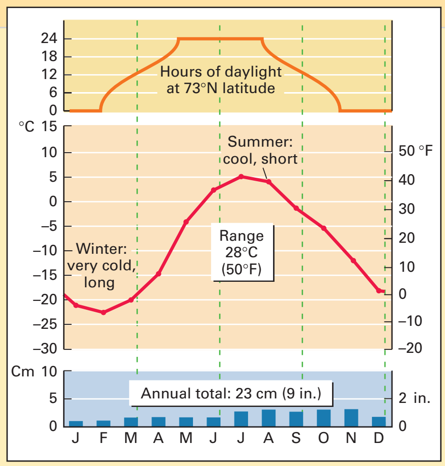
Trees in the tundra are stunted because of the seasonal damage to roots by freeze and thaw of the soil layer and to branches exposed to the abrading action of wind-driven snow. In some places, a distinct tree line—roughly along the 10°C (50°F) isotherm of the warmest month—separates the forest and tundra. 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.

World map of the tundra climate ⑫ **FIGURE 7.36**

Tundra climate ⑫ FIGURE 7.37

▲ **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 7.36.)



▲ 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 7.34*b*). 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.

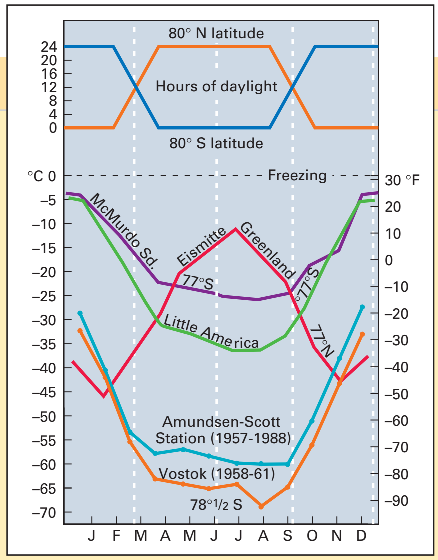
THE ICE SHEET CLIMATE ⑬

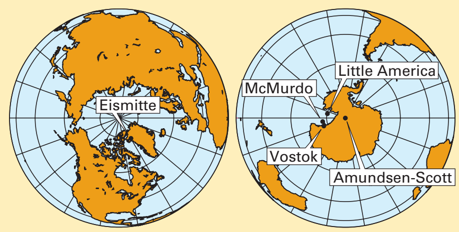
> **Ice sheet climate ⑬** Severely cold climate found on the Greenland and Antarctic ice sheets.

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. Mean annual temperature is much lower than that of 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 7.38 compares temperature graphs for several representative ice sheet stations.

Ice sheet climate ⑬ FIGURE 7.38

▲ **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.





▲ 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.

CONCEPT CHECK STOP

Name and describe the three climate types of the high-latitude climate group. Give an example of each one.

What types of vegetation, if any, are native to each climate?

What is happening in this picture?

If this home near Fairbanks, Alaska, looks a little askew, that's because it is. The reason is not that it was built with a broken carpenter's level, but that it has settled and sunken into the ground. Heat from the house, combined with the effect of blocking the access of cold, winter air to the land surface, has caused the permafrost underneath the house to thaw. The released water turned the soil to soft mud, no longer capable of supporting the weight of the structure.

VISUAL SUMMARY

1 Keys to Climate

1. Climate is the average weather of a region, based on annual patterns of monthly averages of temperature and precipitation.
2. Temperature regimes depend on latitude, which determines the annual pattern of insolation, and on location—continental or maritime—which enhances or moderates the annual insolation cycle.
3. Global precipitation patterns are largely determined by air masses and their movements.
4. The global precipitation regions are: a wet equatorial belt; trade-wind coasts; tropical deserts; midlatitude deserts and steppes; moist subtropical regions; midlatitude west coasts; polar and arctic deserts.
5. Annual precipitation falls into three patterns: uniform; high-Sun (summer) maximum; and low-Sun (winter) maximum.

2 Climate Classification

1. 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).
2. 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.
3. Highland climates are cold and wet, and derive their characteristics from surrounding lowlands.

3 Low-Latitude Climates (Group I)

1. Wet equatorial climates ① are warm to hot with abundant rainfall. This is the steamy climate of the Amazon and Congo basins.
2. Monsoon and trade-wind coastal climates ② are warm to hot with very wet rainy seasons. They occur in coastal regions that are influenced by trade winds or a monsoon circulation. The climates of Vietnam and Bangladesh are good examples.
3. Wet-dry tropical climates ③ are warm to hot with very distinct wet and dry seasons. The monsoon region of India falls into this type, as does much of the Sahel region of Africa.
4. Dry tropical climates ④ describe 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. The Sahara Desert, Saudi Arabia, and the central Australian desert are of this climate.

4 Midlatitude Climates (Group II)

1. Dry subtropical climates ⑤ also include desert climates. But they are found farther poleward than the dry tropical climate ④, and so aren't as hot. This type includes the hottest part of the American Southwest desert.

2. Moist subtropical climates ⑥ include the southeastern regions of the United States and China—hot and humid summers, with mild winters and ample rainfall year-round.

3. Mediterranean climates ⑦ are marked by hot, dry summers and rainy winters. Southern and central California, Spain, southern Italy, Greece, and the coastal regions of Lebanon and Israel are prime examples.

4. Marine west-coast climates ⑧ have warm summers and cool winters, with more rainfall in winter. Climates of this type include the Pacific Northwest—coastal Oregon, Washington, and British Columbia.

5. Dry midlatitude climates ⑨ are dry climates found in midlatitude continental interiors. The steppes of central Asia and the Great Plains of North America are familiar locales with this climate—warm to hot in summer, cold in winter, and with low annual precipitation.

6. Moist continental climates ⑩ are found in the eastern United States and lower Canada—cold in winter, warm in summer, with ample precipitation through the year.

5 High-Latitude Climates (Group III)

1. Boreal forest climates ⑪ are snowy climates with short, cool summers and long, bitterly cold winters. Northern Canada, Siberia, and central Alaska are regions of boreal forest climate.

2. Tundra climates ⑫ have a long, severe winter. Temperatures on the tundra are somewhat moderated because they are near the Arctic Ocean. This is the climate of the coastal arctic regions of Canada, Alaska, Siberia, and Scandinavia.

3. Ice sheet climates ⑬ are bitterly cold. Temperatures of this climate, restricted to Greenland and Antarctica, can drop below –50°C (–58°F) during the sunless winter months. Even during the 24-hour days of summer, temperatures remain well below freezing.

KEY TERMS

- **climate** p. 182
- **climograph** p. 192
- **wet equatorial climate** ① p. 197
- **monsoon and trade-wind coastal climate** ② p. 197
- **wet-dry tropical climate** ③ p. 200
- **dry tropical climate** ④ p. 202
- **dry subtropical climate** ⑤ p. 206
- **moist subtropical climate** ⑥ p. 208
- **Mediterranean climate** ⑦ p. 210
- **marine west-coast climate** ⑧ p. 212
- **dry midlatitude climate** ⑨ p. 212
- **moist continental climate** ⑩ p. 214
- **boreal forest climate** ⑪ p. 216
- **tundra climate** ⑫ p. 218
- **ice sheet climate** ⑬ p. 220

CRITICAL AND CREATIVE THINKING QUESTIONS

1. Describe three temperature regimes. How are they related to latitude and location? Give examples.

2. Identify seven important features of the global map of precipitation. What factors produce them? 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.

3. What are the three climate groups? How is each group influenced by air masses and global circulation patterns?

4. Why is the annual temperature cycle of the wet equatorial climate ① so uniform? The wet-dry tropical climate ③ has two distinct seasons. What factors produce the dry season? And the wet season?

5. 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?

6. 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? Describe some of the features of the Mojave Desert environment.

7. 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?

8. 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?

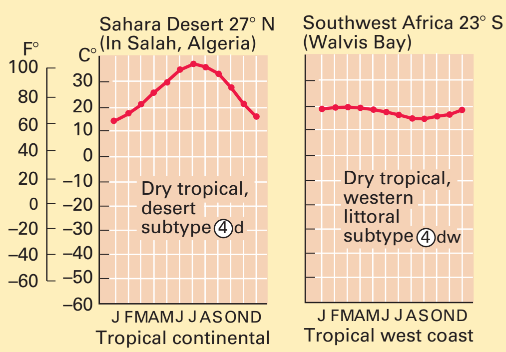
9. Sketch climographs for the Mediterranean climate ⑦ and the dry midlatitude climate ⑨. What are the essential differences between them? Explain why they occur.

10. Both the boreal forest ⑪ and tundra ⑫ climate are climates of the northern regions, but the tundra is found fringing the Arctic Ocean and the boreal forest is located further inland. Compare these two climates from the viewpoint of coastal-continental effects.

11. 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.

SELF-TEST

1. Walvis Bay in Southwestern Africa (right graph) is at nearly the same latitude as In Salah in Algeria (left graph) and so has about the same insolation cycle. Why does Walvis Bay have a weak annual temperature cycle, when compared with In Salah, and no extreme heat?



2. In contrast to the equatorial temperature regime, the tropical continental temperature regime is characterized by ______________.
   a. uniform temperatures all year round
   b. a high annual variation in solar insolation
   c. no annual variation in solar insolation
   d. a very strong temperature cycle

3. The tropical desert climates are caused by ______________.
   a. a lack of moisture
   b. their placement in relationship to the Prime Meridian
   c. their distance from the equator and the Arctic Circle
   d. stationary subtropical cells of high pressure

4. The precipitation region known as the polar desert is noted for:
   a. extremely cold, dry air with high relative humidity
   b. extremely cold, dry air with high specific humidity
   c. extremely cold, wet air with high specific humidity
   d. extremely cold, dry air with low relative humidity

5. There are three types of monthly patterns of precipitation: (1) uniformly distributed precipitation, (2) a precipitation maximum during the high-Sun season, and (3) _______________.

a. a precipitation maximum during the late low-Sun season
b. a precipitation minimum during the late high-Sun season
c. a precipitation maximum during the low-Sun season.
d. a precipitation minimum during the early high-Sun season

6. The _______________ air masses have no influence on low-latitude climates (Group I).

a. cT b. mE c. cP d. mT

7. The region of midlatitude climates (Group II) lies in the _______________, a zone of intense interaction between air masses with significantly different temperature and moisture characteristics.

a. polar-front zone
b. ITCZ
c. tropics
d. subtropics

8. High-latitude climate (Group III) types are dominantly found in the _______________ hemisphere.

a. western
b. eastern
c. northern
d. southern

9. What type of tree is shown here? In which climate are you likely to see this tree? What types of plants tend to be found in this climate?

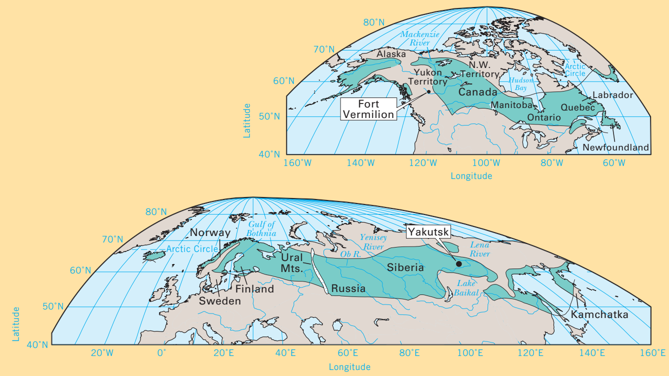
10. A geographic feature common to dry climates is _______________.

a. no permanently flowing streams
b. a surface covered with dry lakes
c. a complete lack of precipitation
d. high surface winds

11. Wet equatorial climates _______________.

a. are significantly influenced by the ITCZ
b. are dominated by warm, moist mE and mT air masses
c. show no seasonal rainfall pattern
d. a and b

12. Which climate is found in the regions colored green on this map?



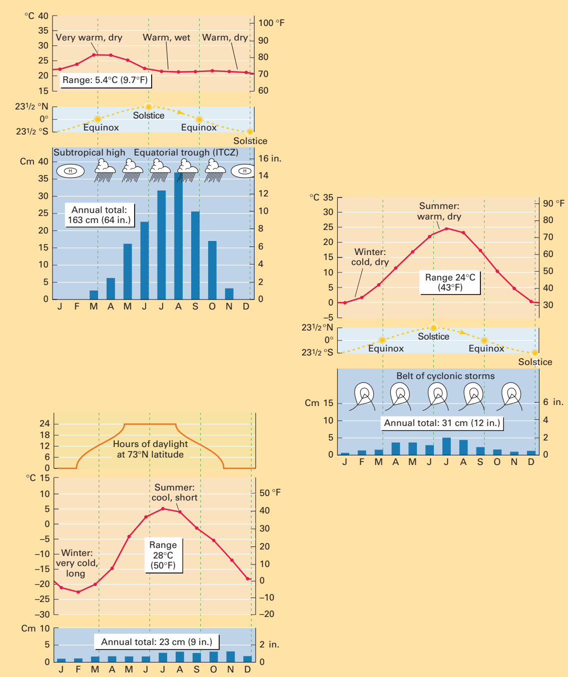
13. Dry tropical climates are generally located in the _______________ and on the _______________ of subtropical high-pressure cells.

a. center; west sides
b. center; north sides
c. center; south sides
d. center; east sides

14. The _______________ climate is renowned for its very scarce precipitation during the summer season.

a. moist subtropical
b. dry subtropical
c. Mediterranean
d. ice-sheet

15. Identify which climographs represent: (a) the dry midlatitude climate at Pueblo, Colorado; (b) the tundra climate of Upernavik, Greenland; and (c) the wet-dry tropical climate of Timbo, Guinea.



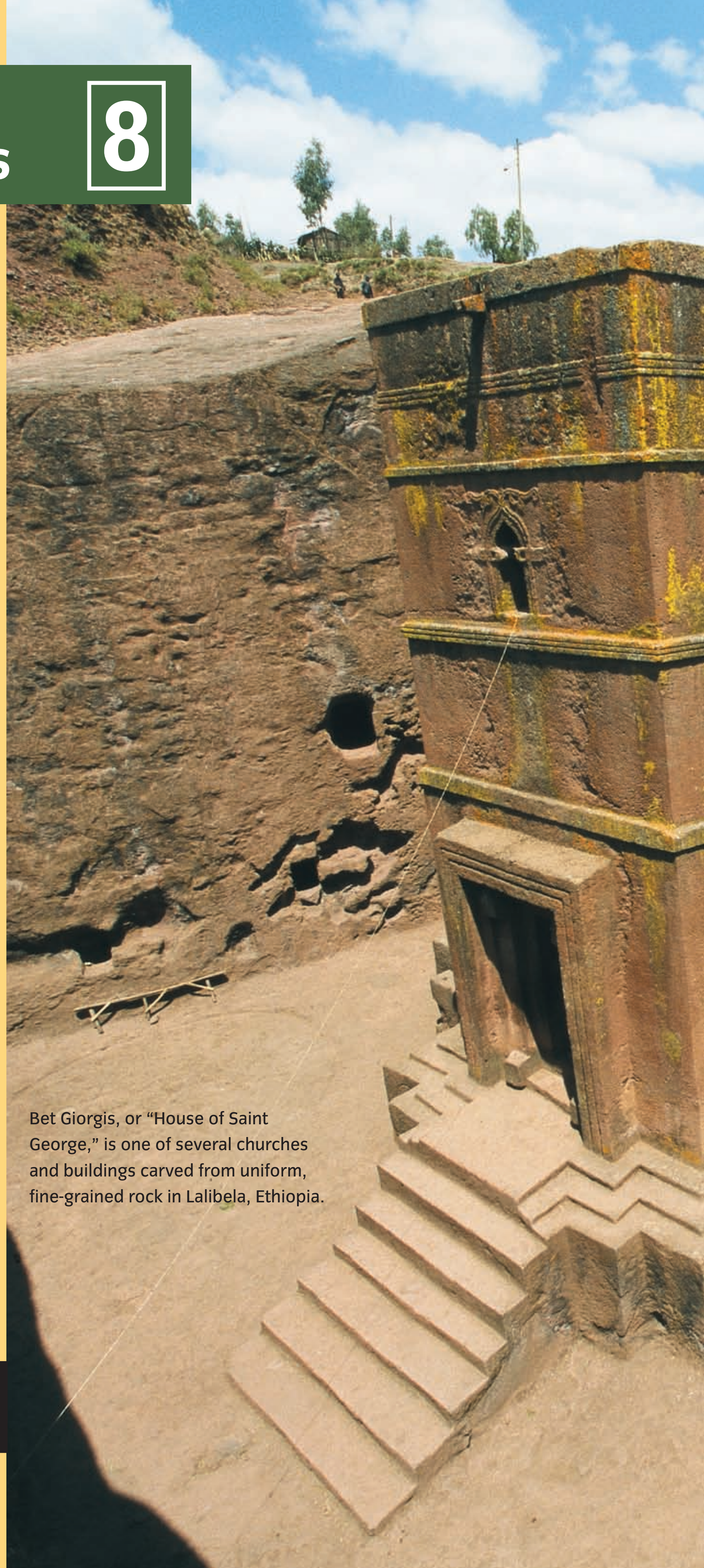
Earth Materials and Plate Tectonics

8

Hidden in the cliffs of Lalibela, in Ethiopia, is a monastic complex with splendid—if unconventional—architecture. Many centuries ago, a volcanic eruption spewed layers of volcanic ash on this mountainside. The ash solidified into red tuff rock, which medieval Ethiopian stone masons used to make 11 churches. But they didn't build these churches stone by stone from the ground up. Instead, they carved the churches out of the rock.

The most famous church is Bet Giorgis, or "House of Saint George," which stands 13 meters high in a well of rock. Stone masons first dug out a trench, isolating a column of rock, and then hollowed the cross-shaped church out of this monolith. As they chiseled out the chambers, doors, and windows, they threw out more than enough rock to make a whole new church.

Legend says that the Ethiopian king, Lalibela, after whom the site is named, was told to build the complex in a dream. Archeologists think that the construction was carried out around AD 1200 and completed within a hundred years. That may sound like a long time, but it pales when we think of the millions of years that nature took to create the rocks from which the churches were built. The processes that crafted the natural landscape are slow and complicated. But they have given us the materials we build with and have sculpted the beautiful natural landscapes that surround us.



Bet Giorgis, or "House of Saint George," is one of several churches and buildings carved from uniform, fine-grained rock in Lalibela, Ethiopia.

NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

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- Major Relief Features of the Earth's Surface p. 238

- Plate Tectonics p. 244

- Continents of the Past p. 252

Rocks and Minerals of the Earth's Crust

LEARNING OBJECTIVES

Describe the structure of the Earth.

Define igneous, sedimentary, and metamorphic rocks.

Outline the cycle of rock formation.

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

Core Spherical central mass of the Earth composed largely of iron; consists of an outer liquid zone and an inner solid zone.

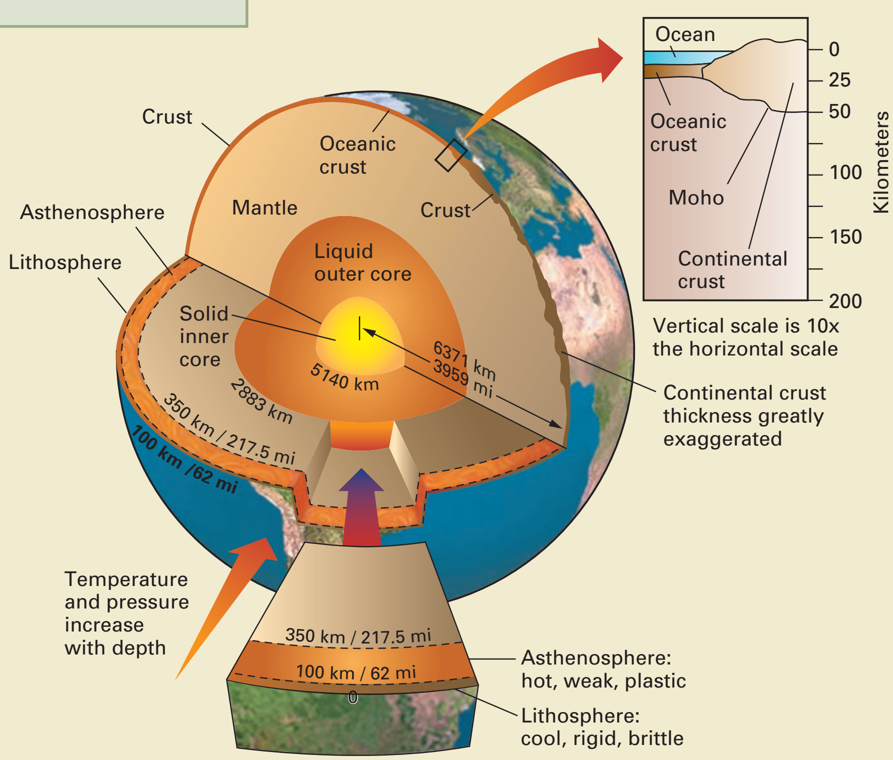
Our planet is almost spherical with a radius of approximately 6400 km (about 4000 mi). Its central **core** is about 3500 km (about 2200 mi) in radius (FIGURE 8.1). We know that the outer core is liquid from measurements of earthquake waves passing through the Earth, which suddenly change behavior when 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 made of *mafic* minerals (silicates of magnesium and iron). Mantle temperatures range from about 2800°C (about 5100°F) near the core to about 1800°C (about 3300°F) near the crust.

Mantle Rock layer of the Earth beneath the crust and surrounding the core, composed of ultramafic igneous rock of silicate minerals.

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

Crust Outermost solid layer of the Earth, composed largely of silicate materials.



The structure of the Earth

FIGURE 8.1

This diagram shows Earth's internal structure and summarizes what scientists have learned from seismic studies and other direct and indirect observations. The upper part of the cutaway shows compositional layers, and the lower part shows layers with differing rock properties. Note that the boundaries between zones that differ in strength, such as the rigid lithosphere and the more plastic asthenosphere, do not always coincide with compositional boundaries.

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ocean basins. It is the source of soil on the lands, of salts of the sea, of gases of the atmosphere, and of all the water of the oceans, atmosphere, and lands.

The crust that lies below ocean floors—*oceanic crust*—consists almost entirely of mafic rocks. But the *continental crust* consists of two continuous zones—a lower zone of mafic rock and an upper zone of felsic rock. Felsic rock is composed of silicates of aluminum, sodium, potassium, and calcium. Another key distinction between continental and oceanic crust is that the crust is much thicker—35 km (22 mi) on average—beneath the continents than it is beneath the ocean floors, where it is typically 7 km (4 mi).

The most abundant elements in the crust are oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium. They can form chemical compounds with a crystalline structure, which we recognize as *minerals* (FIGURE 8.2).

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.

Salt crystals FIGURE 8.2

Minerals are naturally occurring crystalline chemical compounds. Salt, sodium chloride, is an example. Rock salt is a chemically precipitated sediment. This sediment is made of solid inorganic mineral compounds that separate out from saltwater solutions, or from the hard parts of organisms. The salt crystals were deposited near the vent of an underwater volcano. In many rocks, mineral crystals are too small to be seen without magnification.

Rocks fall into three major classes: (1) igneous, (2) sedimentary, and (3) metamorphic rocks. Rocks are constantly being transformed from one class to another in the rock formation cycle, which recycles crustal minerals over many millions of years. We will look at this cycle after we have examined each rock class in detail.

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.

Igneous rock Rock formed from the cooling of magma.

Magma Mobile, high-temperature molten state of rock.

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 (FIGURE 8.3). 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.

Lava FIGURE 8.3

A lava flow on Kilauea volcano. As shown by its red-hot interior, this recent tongue of lava is still cooling. Hawaii Volcanoes National Park.

Quartz crystals FIGURE 8.4

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 appears as a clear or light-colored mineral, and it is often present in sediments such as beach sand or river gravel.

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 8.4). It is quite hard and resists chemical breakdown.

Silicate minerals and igneous rocks FIGURE 8.5

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Only the most important silicate mineral groups are listed, along with four common igneous rocks.

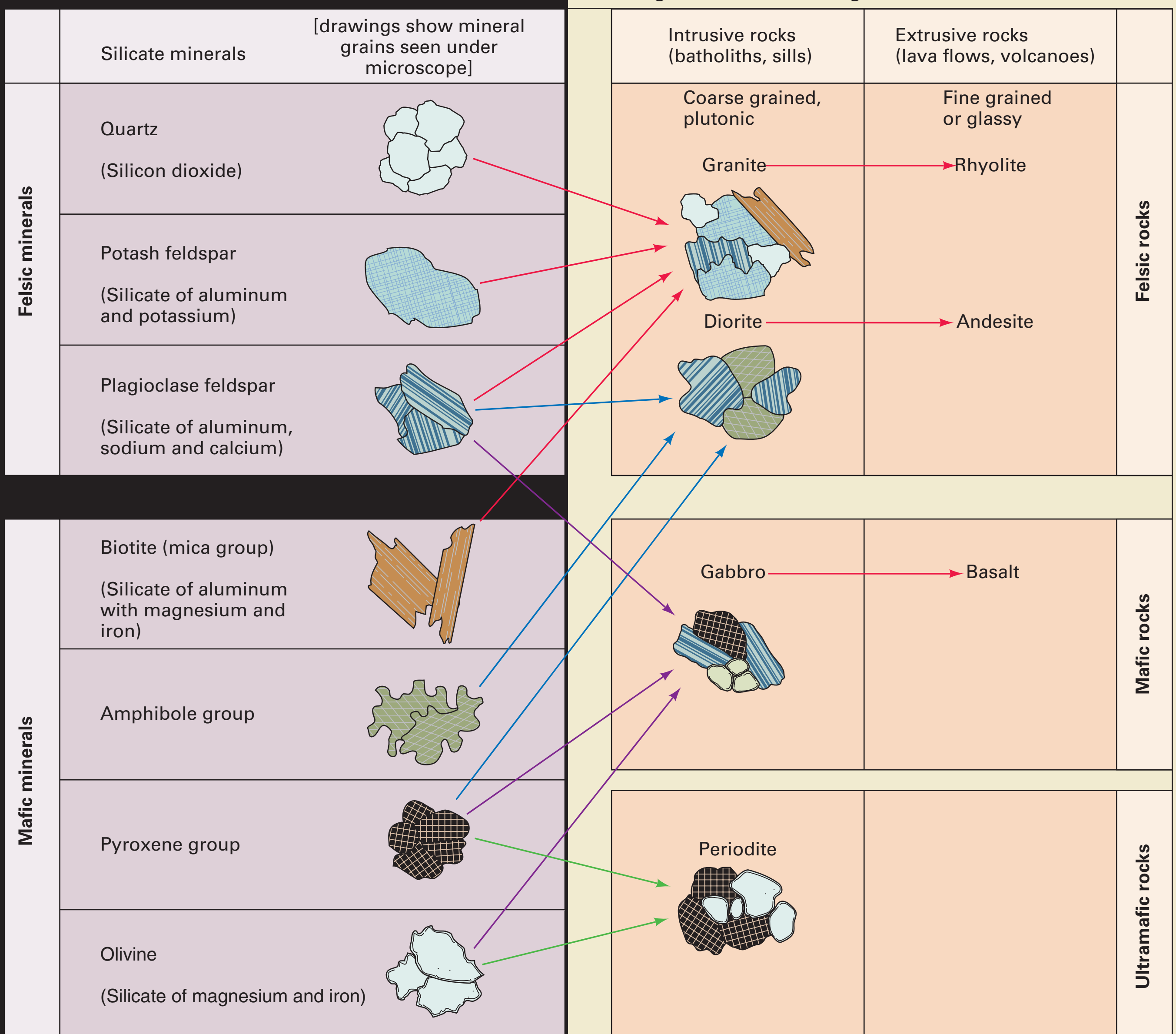


Figure 8.5 shows some other common minerals and the intrusive and extrusive rocks that are made from them. Silicate minerals in igneous rocks are classed as *felsic*, which are light-colored and less dense, and *mafic*, which are dark-colored and more dense. *Felsic rock* contains mostly felsic minerals, 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.

SEDIMENTS AND SEDIMENTARY ROCKS

Now let's turn to the second great rock class, the **sedimentary rocks**. Sedimentary rocks are made from layers 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.

When rock minerals are weathered, their chemical composition is changed, weakening the solid rock. The rock fragments 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. Sediments usually accumulate on shallow seafloors bordering continents, but they also collect in inland valleys, lakes, and marshes. Wind and glacial ice can also transport sediments. Over long spans of time, the sediments become compacted and harden to form sedimentary rock, with distinctive visible characteristics.

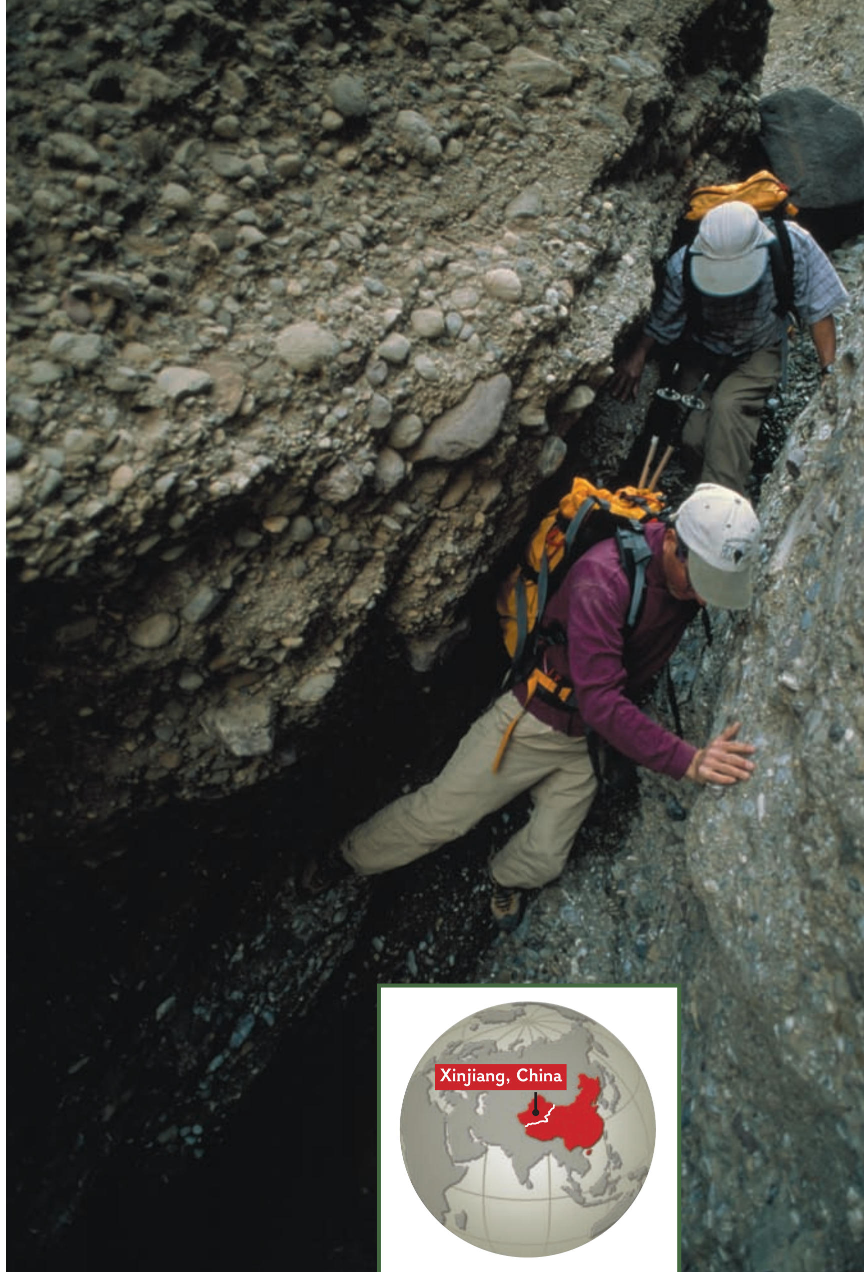
Sedimentary rock Rock formed from the accumulation of sediment.

There are three major classes of sediment: *clastic sediment*, *chemically precipitated sediment*, and *organic sediment* (**Figure 8.6**). Clastic sediment is made up of inorganic rock and mineral fragments, called *clasts*. These can come from igneous, sedimentary, or

Some common sedimentary rock types **Figure 8.6**

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

▲ **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. It was originally deposited in layers by moving sand dunes.



▶ **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.

Global Locator

◀ **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.

Some important varieties of clastic sedimentary rocks FIGURE 8.7

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.

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 8.7 shows some important varieties of clastic sedimentary rocks.

Rock salt is an example of a chemically precipitated sediment. This type of sediment is made of solid inorganic mineral compounds that separate out from saltwater solutions, or from the hard parts of organisms. One of the most common sedimentary rocks formed by chemical precipitation is limestone (FIGURE 8.8).

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

Chalk cliffs FIGURE 8.8

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.

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 8.9). We often find natural gas and petroleum in open interconnected pores in a thick sedimentary rock layer, such as in a porous sandstone (FIGURE 8.9B).

These **fossil fuels**, as they are known, took millions of years to build up. But our industrial society is consuming them rapidly. These fuels 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.

Fossil fuels
Naturally occurring hydrocarbon compounds produced from remains of organic matter enclosed in rock; examples are coal, petroleum (crude oil), and natural gas.

Fossil fuels FIGURE 8.9

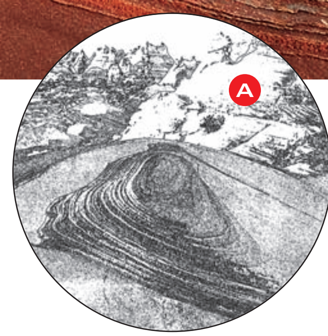
A Strip mine In strip mining, layers of coal are mined by removing overlying rock, allowing direct access to the coal deposit. Man, West Virginia.

B 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.

Sandstone strata

This photo shows an eroded sandstone formation on the Colorado Plateau. The individual layers you see are known as *strata*. Because sediments build up in more-or-less horizontal layers, strata are a characteristic feature of sedimentary rocks.

These fine sedimentary beds (A) are crossed at angles by other beds. A geographer would recognize this *cross-bedding* as a sign that the layers were originally deposited by moving sand dunes. As the sand dune moved forward, sand layers built up on its sloping surface. Later, when the wind eroded the dune, a new surface formed across the beds, cutting them at an angle. That surface was then covered by more sand layers, creating this distinctive pattern.



METAMORPHIC ROCKS

The mountain-building processes of the Earth's crust involve tremendous pressures and high temperatures. These extreme conditions alter igneous or sedimentary rock, transforming it so completely in texture and structure that we have to reclassify it as **metamorphic rock** (see table below). In many cases, the mineral components of the parent rock are changed into different mineral varieties. In some cases, the original minerals may recrystallize.

Metamorphic rock Rock altered in physical or chemical composition by heat, pressure, or other processes taking place at a substantial depth below the surface.

Extreme heat and pressure transform shale into slate or schist, sandstone into quartzite, and limestone into marble (FIGURE 8.10). Gneiss forms when an intrusive magma cools next to igneous or sedimentary rocks.

Some common metamorphic rock types FIGURE 8.10

▲ **Schist** When a shale is exposed to heat and pressure for long periods, the minerals in the shale recrystallize and grow together to form a strong rock called schist. Granite Gorge, Grand Canyon National Park.

▲ **Quartzite** Under heat and pressure, sandstone recrystallizes to form a very strong rock of connected quartz grains called quartzite. Seneca Rocks, West Virginia.

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

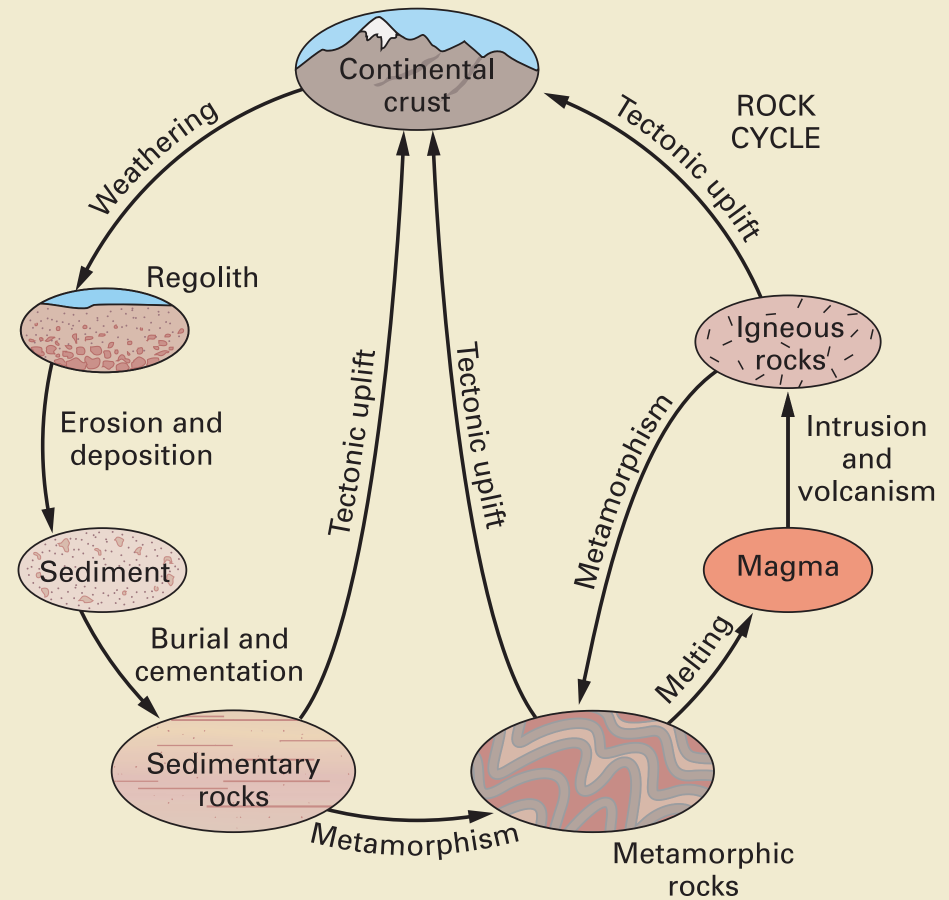
THE CYCLE OF ROCK CHANGE

The rock processes we have seen form a single system that cycles and recycles Earth materials, over geologic time. FIGURE 8.11 describes this cycle.

The cycle of rock change

FIGURE 8.11

The cycle of rock change has been active since our planet became solid and internally stable. It continuously forms and re-forms rocks of all three major classes. Not even the oldest igneous and metamorphic rocks that we have found are the "original" rocks of the Earth's crust, for they were recycled eons ago.



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CONCEPT CHECK STOP

What are the three main layers of the Earth's interior?

Name the three major classes of rock and give examples of each.

How do the rocks in each class form?

Major Relief Features of the Earth's Surface

Learning Objectives

Describe the geologic timescale.

Define lithospheric plate.

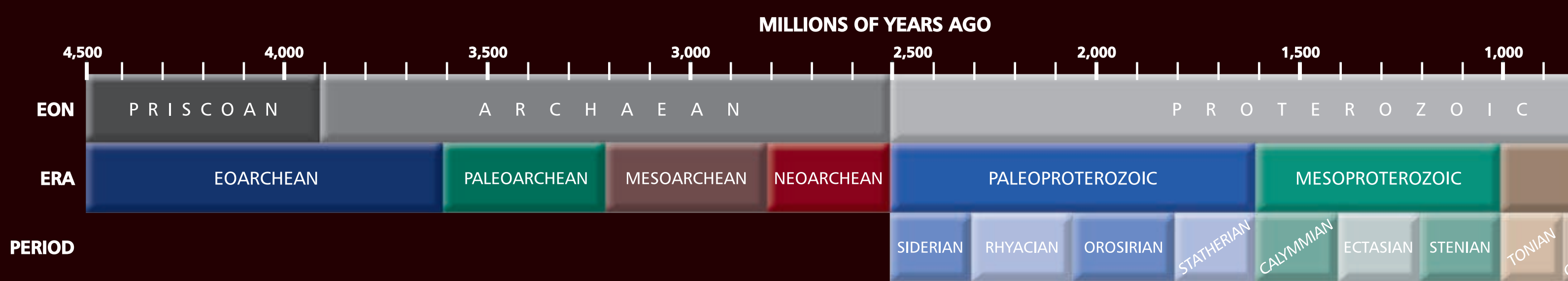
Describe the major relief features of the continents.

Explain the ocean basin's major relief features.

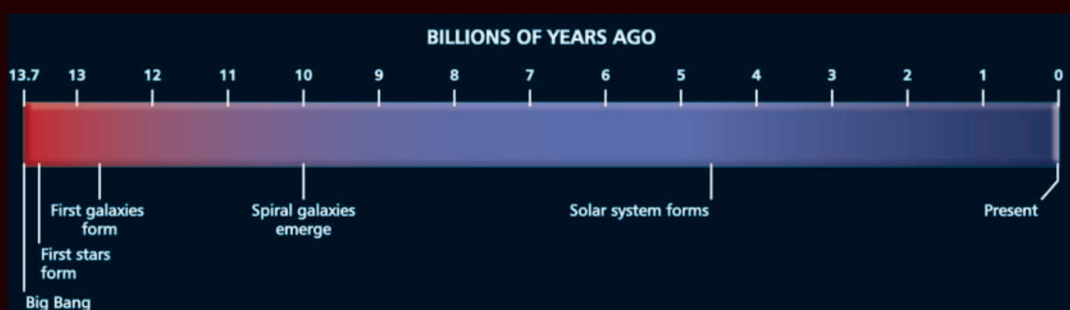
THE GEOLOGIC TIMESCALE

So far we've talked about how rocks are formed. Soon we will look at how many features on the Earth's surface developed—including mountains, oceans basins, and the continents themselves. All of these formation processes took place over millions of years, and in our discussion we will need to refer to some major units in the scale of geologic time. **Figure 8.12** maps out the major geologic time divisions.

Geologic time
Geologists divide the 4.5 billion years since the Earth formed into eons, eras, and periods. Eons are vast chunks of time divided into eras, which in turn are divided into periods. The divisions are broad in the early parts of Earth's history, but much narrower in the past few hundred million years, which we know more about. Many of their names describe the world or ecosystems at the time; "Mesozoic" means the era of "middle life" dominated by the dinosaurs. Period names often come from rock formations, like the coals of the Carboniferous period. Many divisions are drawn between rock layers, and their ages may change by millions of years when scientists use new techniques to date the layers.



Age of the Cosmos
Cosmologists measure time from the birth of the universe, an event marked by a truly cosmic explosion—the big bang—about 13.7 billion years ago.



Geologic time Figure 8.12

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 timescale. 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.

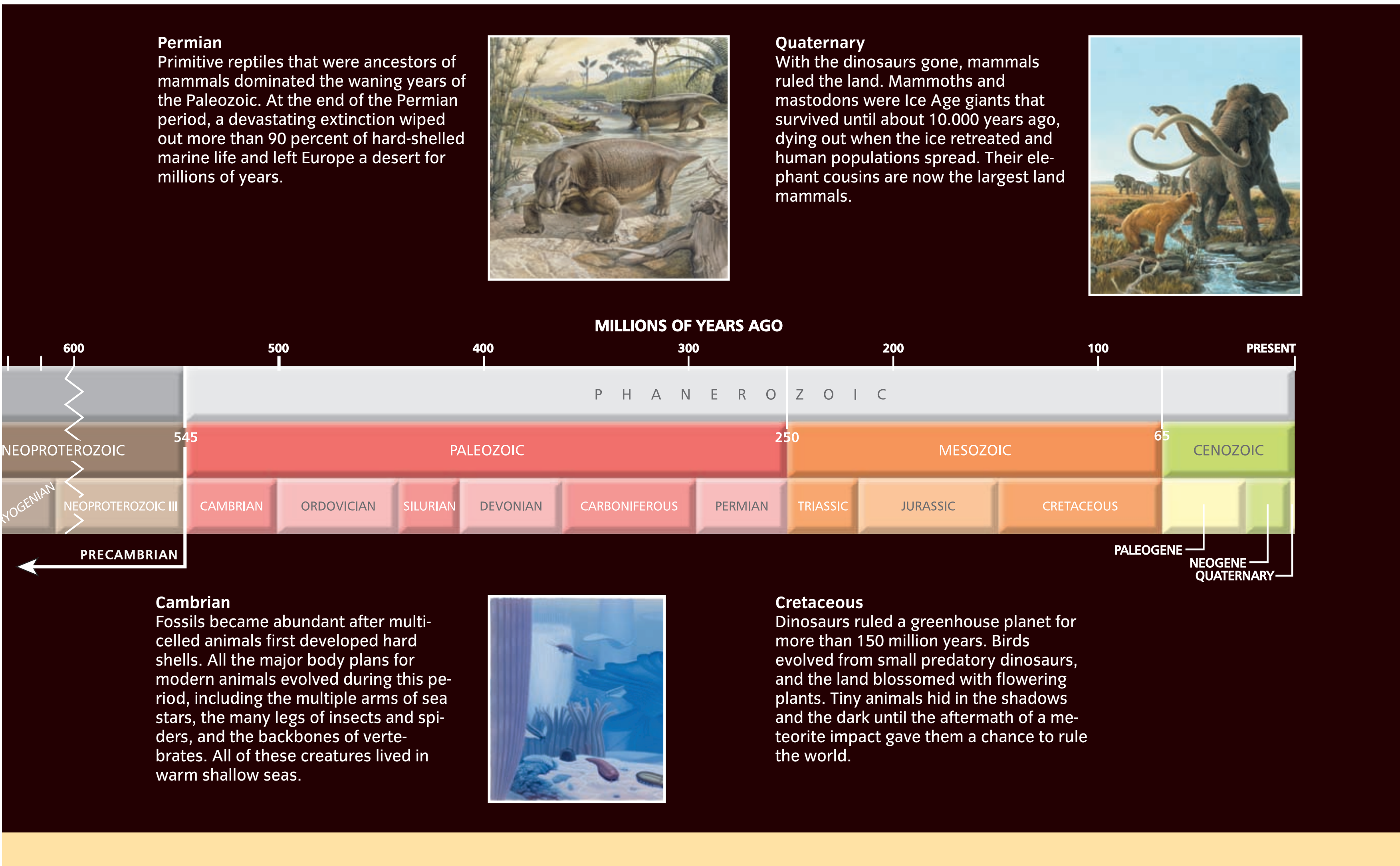
The geologic timescale includes the Paleozoic, Mesozoic, and Cenozoic eras. Nearly all the landscape features visible today have been formed within the Cenozoic Era.

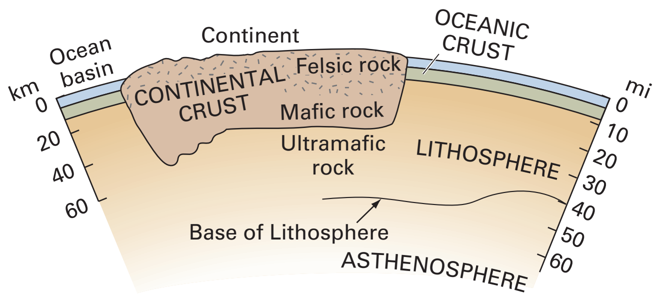
THE LITHOSPHERE AND ASTHENOSPHERE

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. 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





Lithosphere and asthenosphere FIGURE 8.13

Details of the crust, mantle, lithosphere, and asthenosphere at the edge of a continent.

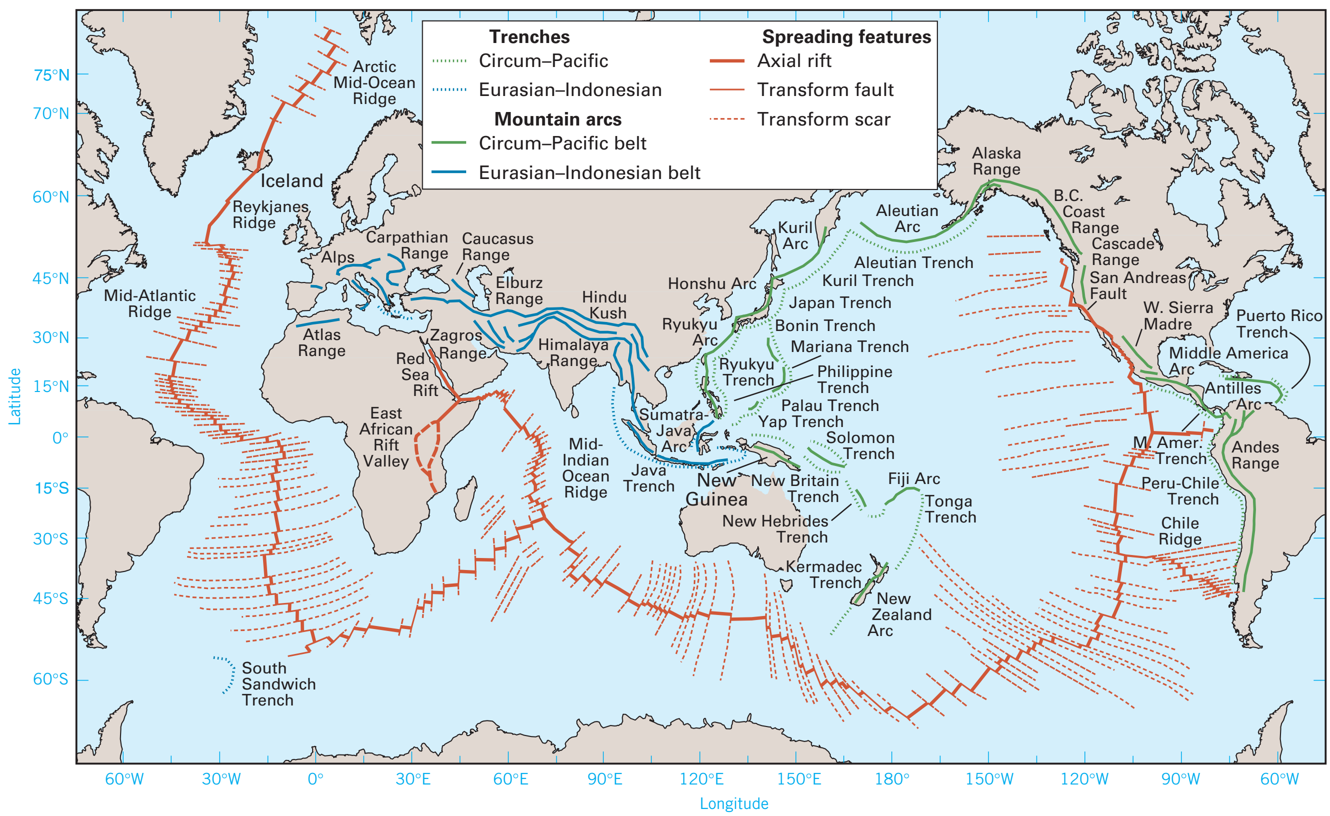
"soft," layer named the *asthenosphere* (FIGURE 8.13). But at still greater depth in the mantle, the strength of the rock material increases again. You can think of the lithosphere on top of the asthenosphere as a hard, brittle shell resting on a soft, plastic underlayer. Because the asthenosphere is soft and plastic, the rigid lithosphere can easily move over it.

The 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 floating ice 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.

Lithospheric plate Segment of lithosphere moving as a unit, in contact with adjacent lithospheric plates along plate boundaries.

RELIEF FEATURES OF THE CONTINENTS

We divide continents into two types of region: active mountain-making belts and inactive regions of old, stable rock (FIGURE 8.14). The mountain ranges in the active belts grow through one of two very different geologic processes. First is *volcanism*, in which massive



Tectonic features of the world FIGURE 8.14

Principal mountain arcs, island arcs, and trenches of the world and the midoceanic ridge.

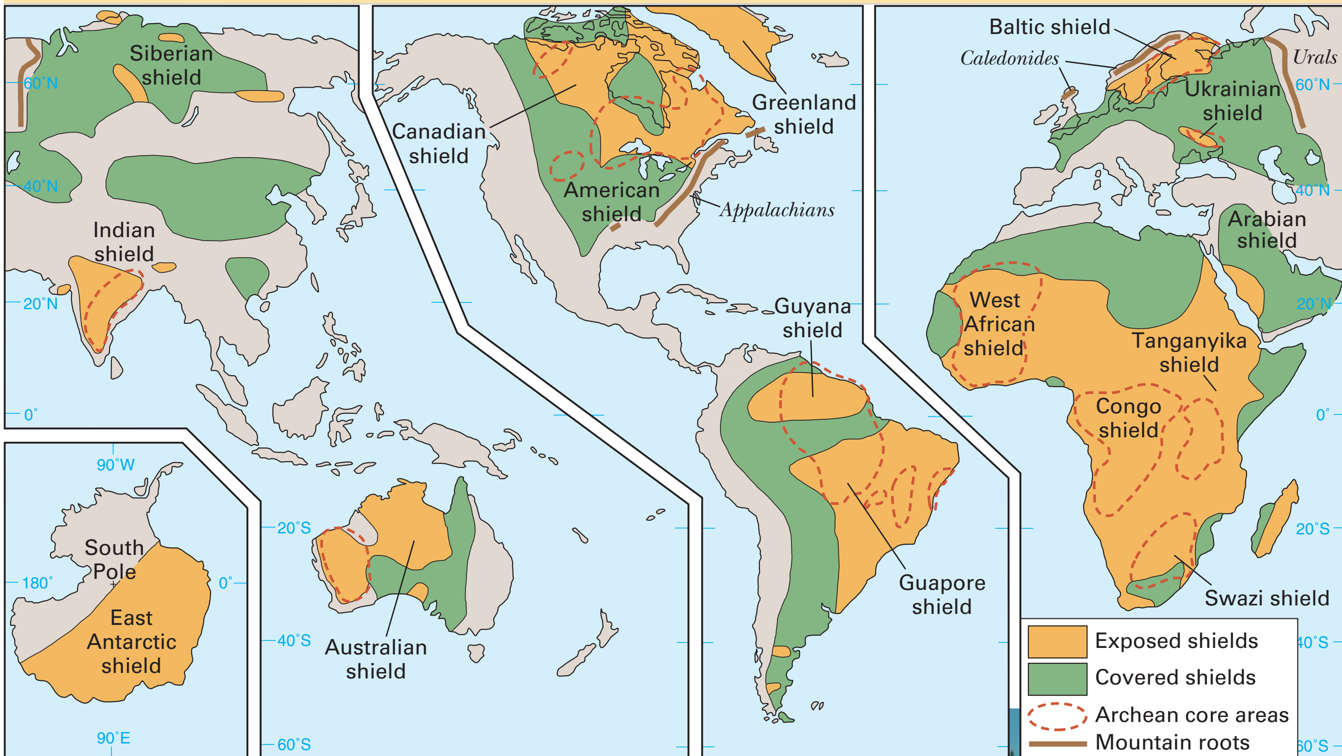
accumulations of volcanic rock are formed by extrusion of magma. Many lofty mountain ranges consist of chains of volcanoes built of extrusive igneous rocks.

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.

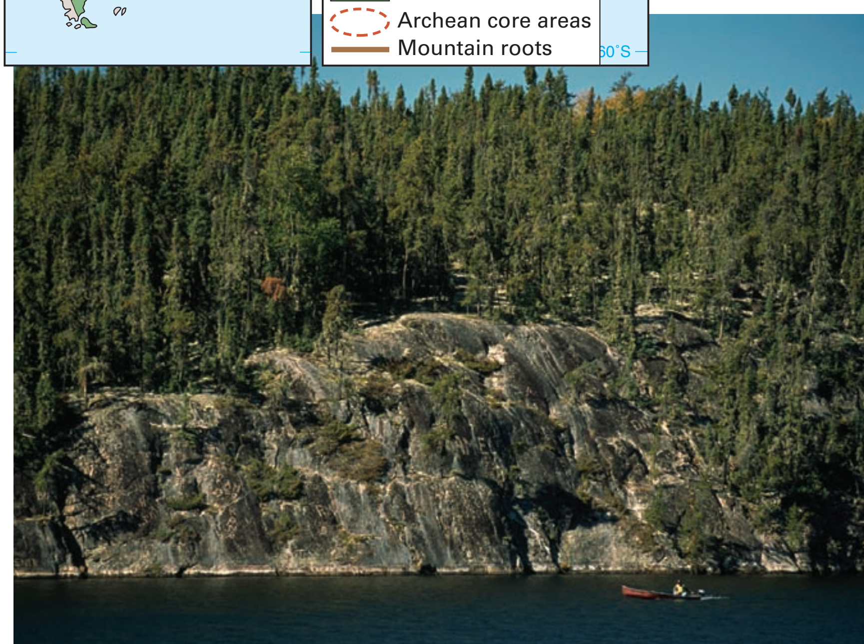
Active mountain-making belts are narrow zones that are usually found along the margins of lithospheric plates. We call these belts *alpine chains* because they are characterized by high, rugged mountains, such as the Alps of Central Europe. Even today, alpine mountain-building continues in many places.

Belts of recent and active mountain-making 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 8.15). Shields may be exposed or covered

Continental shields FIGURE 8.15



▲ **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. Lac La Ronge Provincial Park, Saskatchewan.

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.

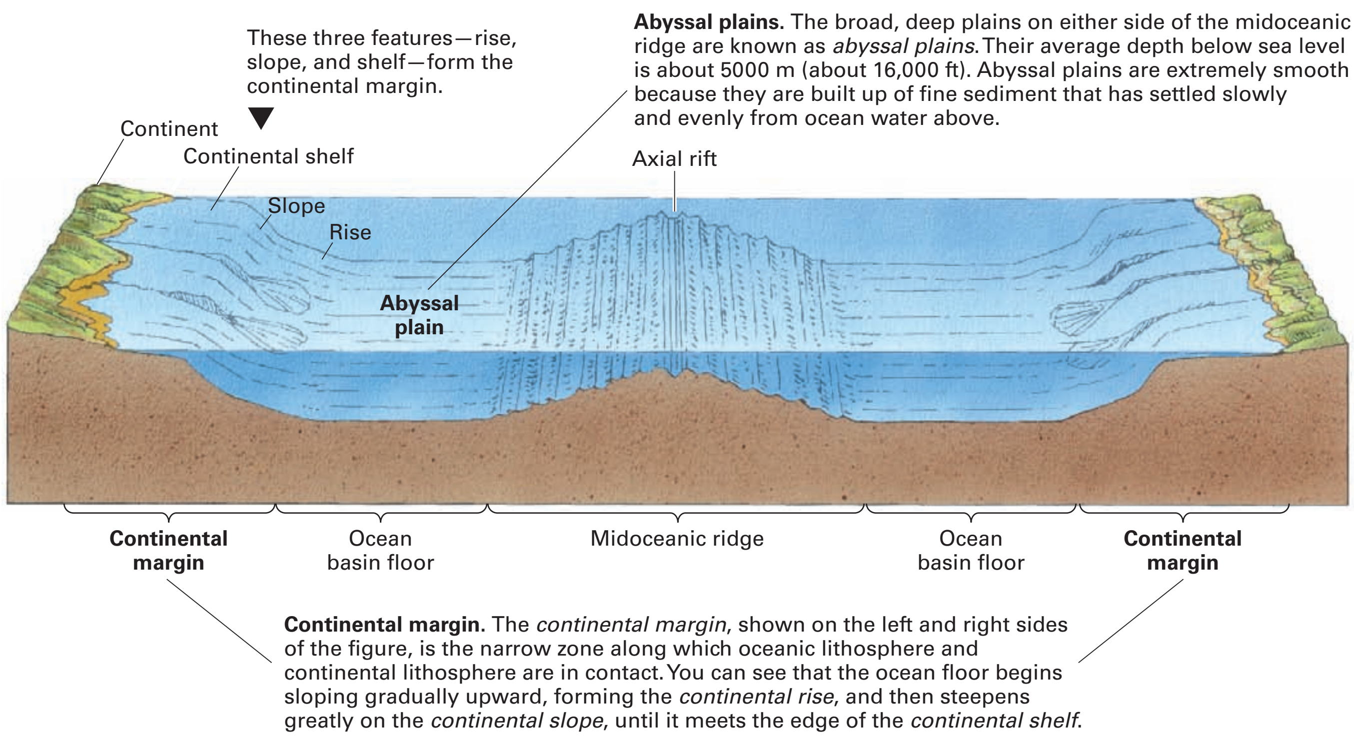
Remains of older mountain belts lie within the shields in many places. These mountain roots are mostly formed of Paleozoic and early Mesozoic sedimentary rocks that have been intensely bent and folded, and in some locations changed into metamorphic rocks. Thousands of meters of overlying rocks have been 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.

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 continental crust is of Precambrian 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 8.16 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.

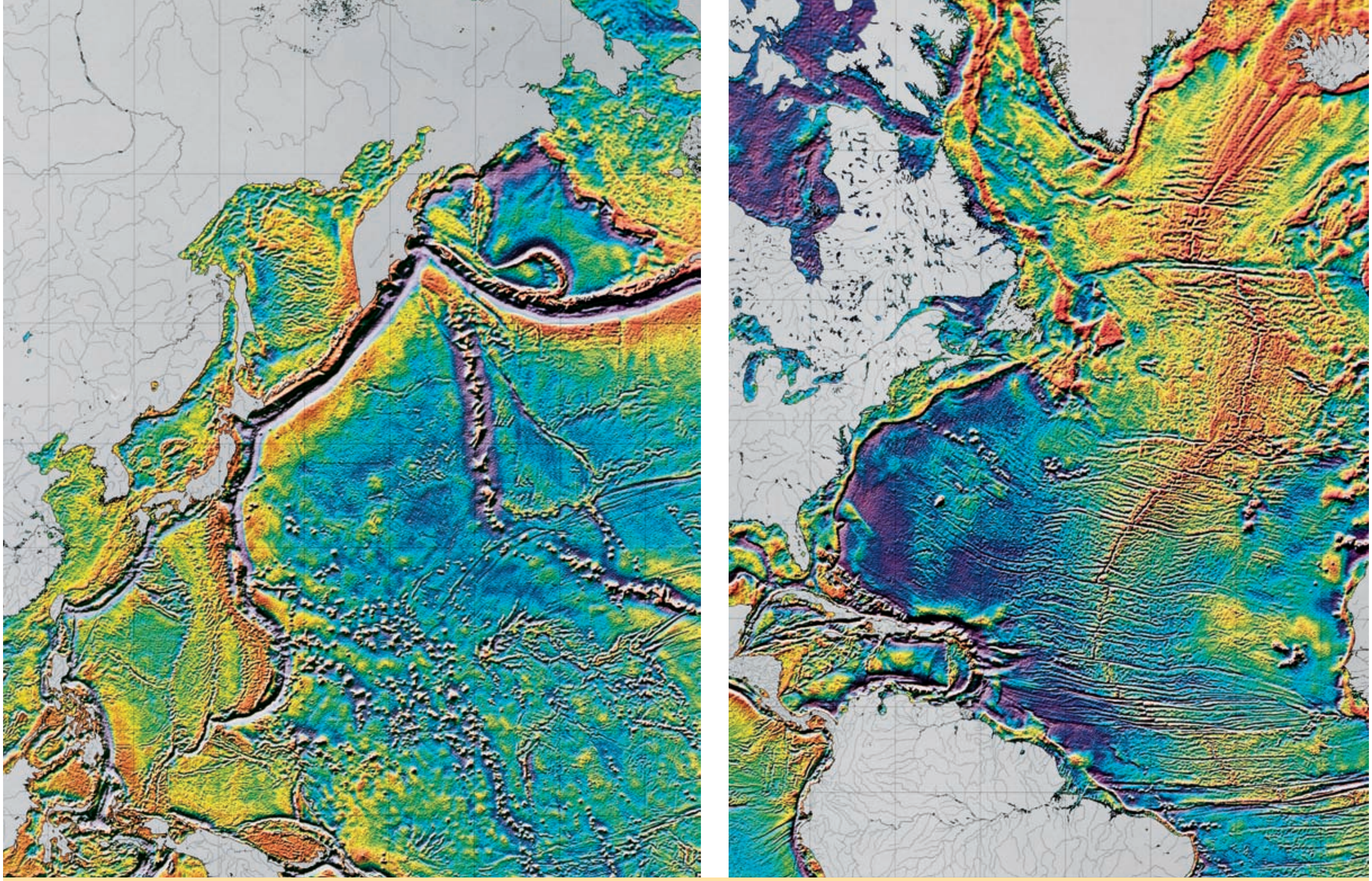
FIGURE 8.17 shows a symmetrical ocean-floor model that fits the North Atlantic, South Atlantic, Indian, and Arctic Ocean basins well. These oceans have *passive continental margins*, which haven't been subjected to strong tectonic and volcanic activity during the last 50 million years. This is because the continental and oceanic lithospheres that join at a passive continental



Ocean basins FIGURE 8.16

www.wiley.com/college/strahler

This schematic block diagram shows the main features of ocean basins. It applies particularly well to the North and South Atlantic oceans.



Undersea topography FIGURE 8.17

This image of the ocean floor was constructed from radar data that measured the surface height of the ocean very precisely. Deeper regions 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 prominent. Here, oceanic crust is being bent downward and forced under continental crust, creating trenches and inducing volcanic activity. On the right, the mid-Atlantic ridge and other features of seafloor spreading are visible. Data were acquired by the U.S. Navy Geosat satellite altimeter.

margin are part of the same lithospheric plate and move together, away from the axial rift.

But unlike the symmetrical ocean floor model of the North Atlantic, the margins of the Pacific Ocean Basin have deep offshore oceanic trenches, as you can see in this image of undersea topography. 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.

CONCEPT CHECK STOP

Name the three eras of geologic time.

What is the lithosphere? What is the asthenosphere? Why are these features important?

How are mountain-belts constructed? Name two processes.

What are the main features of ocean basins?

Plate Tectonics

Learning Objectives

Explain extensional and compressional tectonic activity.

Describe how lithospheric plates move.

Define subduction and continental suture.

Explain continental rupture and the production of new ocean basins.

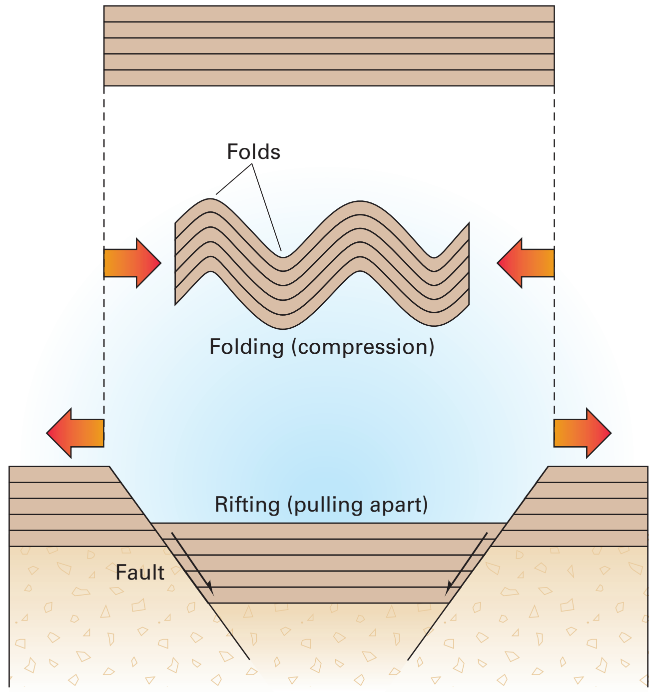
On the globes and maps we've seen since childhood, the outline of each continent is so unique that we would never mistake one continent for another. But why are no two continents even closely alike? The answer lies in the long formation history of the Earth's surface features, which is driven by the movement of lithospheric plates. This motion is called **plate tectonics.**

Plate tectonics Theory of tectonic activity dealing with lithospheric plates and their activity.

Prominent mountain masses and mountain chains (other than volcanic mountains) are created either by *extensional tectonic activity* or by *compressional tectonic activity* (Figure 8.18). 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.

Compressional tectonic activity "squeezes together" or "crushes" plate boundaries, creating an alpine mountain chain. You can re-create the mountain-building process using an ordinary towel laid on a smooth table top. Using both hands, palms down, bring the ends of the cloth together slowly. First, a simple upfold will develop and grow, until it overturns to one side or the other. Then more folds will form, grow, and overturn. The same thing happens when mountain ranges are created. We call the tightly compressed wave-like structures *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. These are called *overthrust faults*.

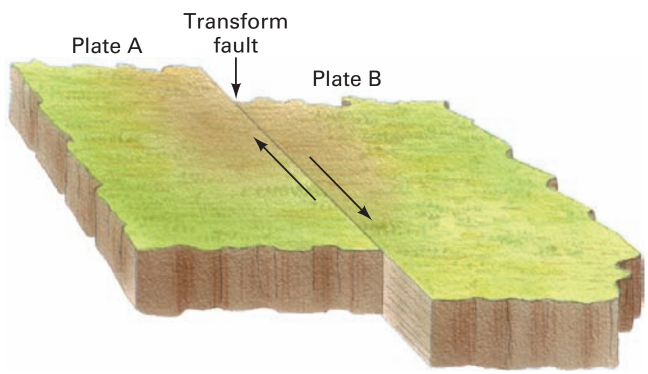
Two types of boundary are described in the process diagram—the *spreading boundary* and the *converging boundary*.



Two basic forms of tectonic activity Figure 8.18

Flat-lying rock layers may be compressed to form folds or pulled apart to form faults by rifting.

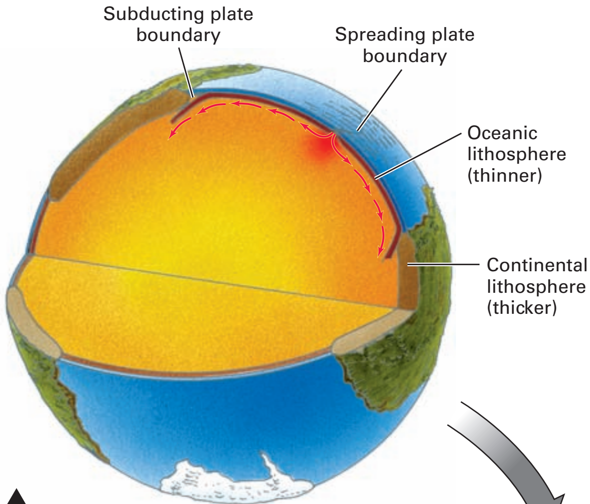
There is a third type of lithospheric plate boundary. Two lithospheric plates may simply slide past each other, with no motion that would cause the plates either to separate or to converge (Figure 8.19). This is a *transform boundary*. The plates move along a *transform fault*—a nearly vertical fracture that extends down through the entire lithosphere. Transform boundaries are often associated with midoceanic ridges.



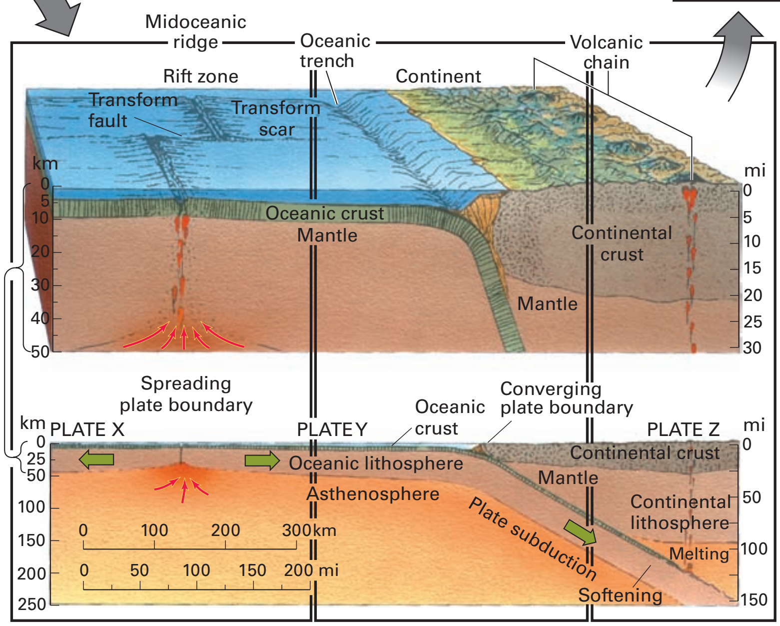
Transform fault Figure 8.19

A transform fault involves the horizontal motion of two adjacent lithospheric plates, one sliding past the other.

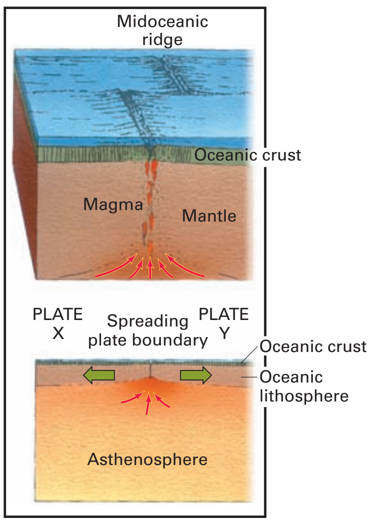
Plate tectonics



A Earth's lithospheric plates The two types of lithospheric plates are different in density and thickness: 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.

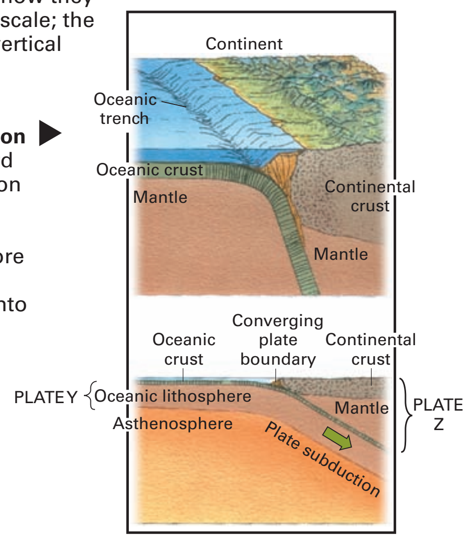


B Relationships between lithospheric plates
These two views show the same section of Earth from different angles and at different scales. Their purpose is to show you both oceanic crust (left) and continental crust (right), and how they interact. (The lower diagram is true to scale; the upper diagram has a 5x exaggerated vertical scale to emphasize crustal features.)

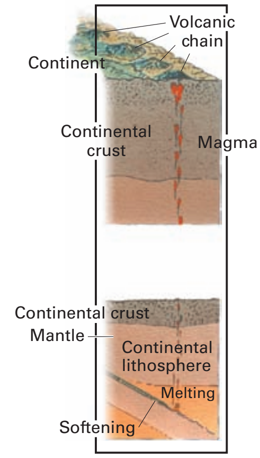


C Spreading boundary Plates X and Y are spreading apart from their common *spreading boundary*, which lies along the axis of a midocean ridge. This creates a crack in the crust that is continually filled with magma rising from the mantle beneath it. The magma emerges as basaltic lava and solidifies into gabbro, continually forming new oceanic crust.

D Converging boundary and subduction ▶
Oceanic Plate Y is slowly moving toward the thick continental plate Z. The collision of these two plates forms a converging boundary. Because the oceanic plate is denser and thinner than the thicker, more buoyant continental plate, the oceanic lithosphere bends down and plunges into the soft layer, or asthenosphere. This is called **subduction**.



E Softening The leading edge of the descending plate is cooler and denser than the surrounding hot, soft asthenosphere. Thus, the slab sinks under its own weight. It is gradually heated by the surrounding hot rock and softens. The underportion, which is mantle rock in composition, reverts to mantle rock as it softens. But the descending plate is covered with a thin upper layer of less-dense oceanic and continental sediments. These melt to become magma. The magma pockets are less dense than the surrounding material, so they rise. When they reach Earth's surface, they form a chain of volcanoes that parallel the converging boundary. ▶



Subduction Descent of the edge of a lithospheric plate under an adjoining plate and into the asthenosphere.

SUBDUCTION TECTONICS

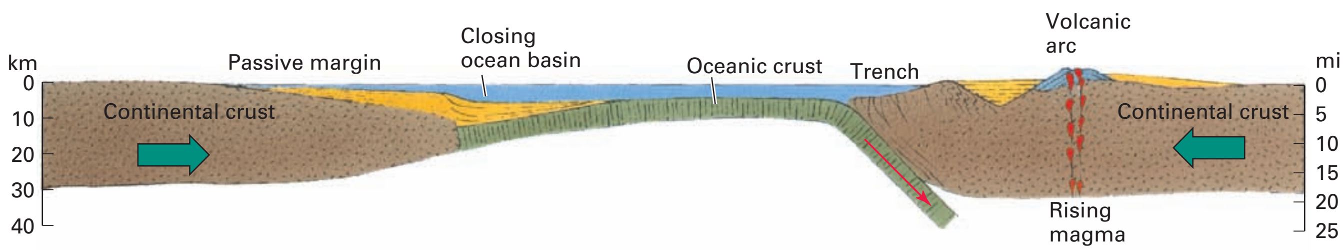
Active continental margins lie above plates undergoing subduction. They are zones of intense tectonic and volcanic activity. The oceanic trench gets sediment from two sources: (1) deep ocean sediment—fine clay and ooze that have settled on the ocean floor—is carried along the moving plate to the oceanic trench, and (2) terrestrial sand and mud is brought to the shore by streams and is then swept into deep water, so that it too collects in the oceanic trench. Both types of sediment are intensely deformed in the bottom of the trench and dragged down with the moving plate. This deformed sediment is then scraped off the plate and shaped into wedges that ride up, one over the other, on steep fault planes. The wedges accumulate at the plate boundary, where they are transformed to metamorphic rock. In this way, new continental crust of metamorphic rock is formed, and the continental plate is built outward.

OROGENS AND COLLISIONS

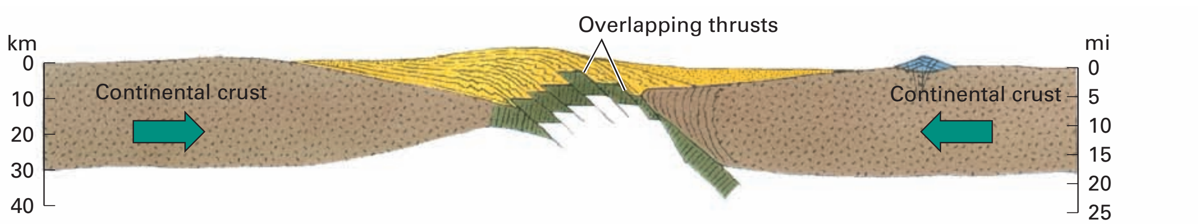
Imagine a situation in which two continental lithospheric plates converge along a subduction boundary. Ultimately, the two masses must collide because they are both too thick and too buoyant for either plate to slip under the other. The result is an *orogeny* in which various kinds of crustal rocks are crumpled into folds and sliced into *nappes*. 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 collision permanently unites the two plates, so that there is no further tectonic activity along that colli-

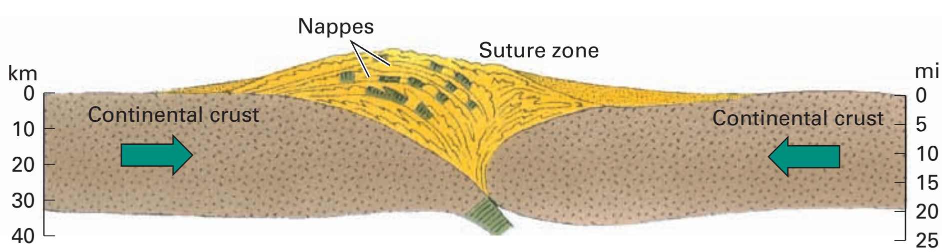
Continent–continent collision FIGURE 8.20



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 thrus 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 suture Long, narrow zone of crustal deformation produced by a continental collision; examples: Himalayan Range, European Alps.

sion 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.

FIGURE 8.20 reconstructs a typical continent–continent collision. The new rock mass formed in the continental suture is a distinctive type of *orogen*.

Continent–continent collisions have occurred many times since the late Precambrian time. 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 Calidonides of Norway, which date from mid-Paleozoic time.

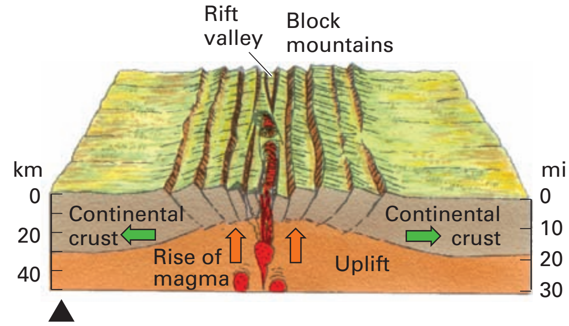
THE GLOBAL SYSTEM OF LITHOSPHERIC PLATES

The Earth's surface is composed of six major lithospheric plates—Pacific, American, Eurasian, African (Nubia), Austral-Indian, and Antarctic. There are also several lesser plates and subplates.

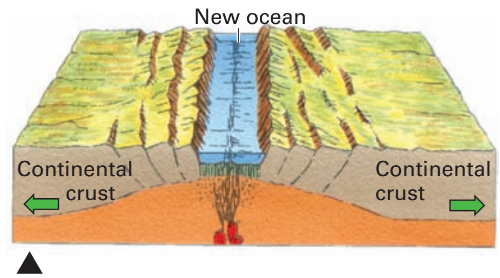
The Visualizing feature shows how the Earth's lithospheric plates have twisted and turned, collided together, and then broken apart over the past 600 million years to create a geography of Earth as we know it today.

CONTINENTAL RUPTURE AND NEW OCEAN BASINS

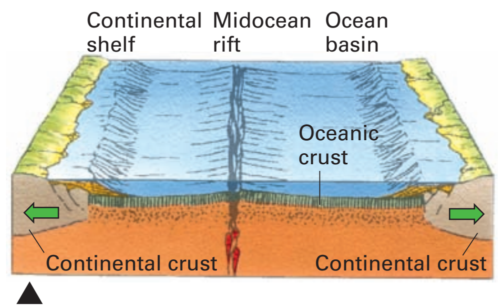
We have already noted that the Atlantic margins have no important tectonic activity. Passive margins such as these are created by a process called continental rupture. FIGURE 8.21 shows how continental rupture takes place.



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.

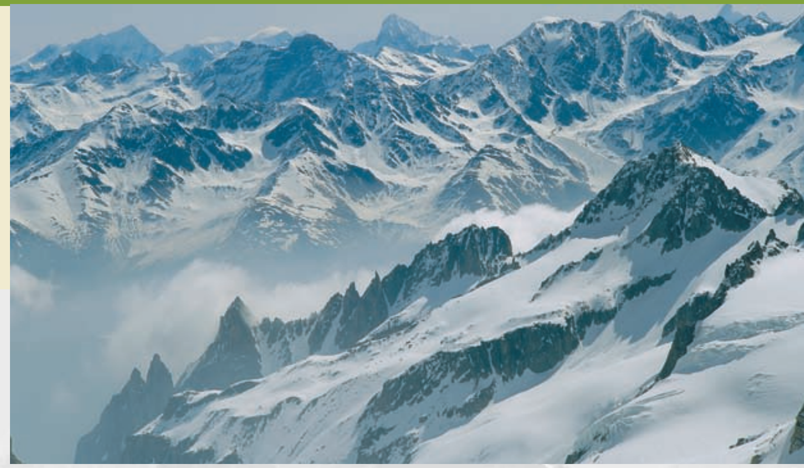


The ocean basin can continue to widen until a large ocean has formed and the continents are widely separated. The ocean basin widens, while the passive continental margins subside and receive sediments from the continents. The vertical scale is greatly exaggerated to emphasize surface features.

Continental rupture and spreading
FIGURE 8.21

LITHOSPHERIC PLATES

The ever-shifting lithosphere is cracked into 16 great slabs of rock or lithospheric plates that are in slow but constant motion. As they grind and grate against each other, they generate volcanoes, earthquakes, and form long chains of mountains.



▶ **Swiss Alps** Where continents collide, mountain arcs form. These peaks gained their sharp edges from glaciation during the Ice Age.

PLATE TECTONICS HISTORY

▲ **600 million years ago** A supercontinent, known as Rodina, split apart and oceans filled the basins. Fragments collided, thrusting up mountain ranges. Glaciers spread, twice covering the Equator. A new polar supercontinent, Pannotia, formed.

▲ **2OO million years ago** Dinosaurs roamed Pangea, 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 drifted 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 took off.

▲ **100 million years ago** Pangea 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, Pangea.

▲ **50 million years ago** A meteorite wiped out the dinosaurs. Moving continental fragments collided—Africa into Eurasia, pushing up the Alps, and India into Asia, raising the Himalayan Plateau. Birds and once-tiny mammals began to evolve rapidly.

NATIONAL GEOGRAPHIC

Visualizing

Lithospheric Plates and Their Motions

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.

▲ **Plate boundaries**
Active spreading and subduction tones are marked by numerous volcanoes and frequent earthquake activity. Map arrows show direction and rate of plate motion (longer equals faster).

▶ **Granite gneiss**
Continental shields are rich In old rock. This rock tower is on Baffin Island, in arctic Canada.

▶ **Volcanoes**
Where oceanic crust is subducted beneath a converging lithospheric plate, rocks melt and make their way to the surface as volcanoes. Mount Mayon, Philippines.

▲ **Present day** Formation of the Isthmus of Panama and the split of Australia from Antarctica changed ocean currents, cooling the air. Ice sheets waxed and waned in many cycles, with sea levels rising and falling.

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 source of this power lies in the heat released by radioactivity.

You may know from basic chemistry that some elements are found in different *isotopes*—that is, they can have different atomic masses. Certain isotopes are unstable, which means they experience radioactive decay. When a nucleus decays, it changes form, and emits matter and energy. This energy is absorbed by the surrounding matter, becoming sensible heat. We call this *radiogenic heat*.

Nearly all radiogenic heat is generated by the decay of isotopes of uranium (^{238}U, ^{235}U), thorium (^{232}Th), and potassium (^{40}K). Most of the radiogenic heat is liberated 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.

Volcanic activity in Antarctica FIGURE 8.22

The southernmost active volcano on Earth is Mount Erebus, in Antarctica, at about 77° S. Pictured here is a volcanic steam vent, or fumarole, emerging from the volcano's flank. Freezing of water vapor from the fumarole has built a chimney of ice around the vent.

We don't know exactly how radiogenic heating produces plate motions. One theory is that plate motions are produced by convection currents in hot mantle rock. Remember that warmer—and thus less dense—air moves upward in the atmosphere by convection. A similar type of convection could be at work in the Earth's interior. Unequal heating would 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 moves horizontally away from the spreading axis under the influence of gravity.

Plate motions are powered by internal Earth forces, so they are independent of surface conditions. This is why we find volcanoes erupting in the cold desert of Antarctica (FIGURE 8.22), as well as near the equator in African savannas.

CONCEPT CHECK STOP

Name three types of boundaries that can arise when lithospheric plates meet. What powers the motion of the plates?

What is subduction?

What is continental suture?

How are new ocean basins produced?

Continents of the Past

LEARNING OBJECTIVES

Describe Wegener's supercontinent theory.

Explain the Wilson cycle.

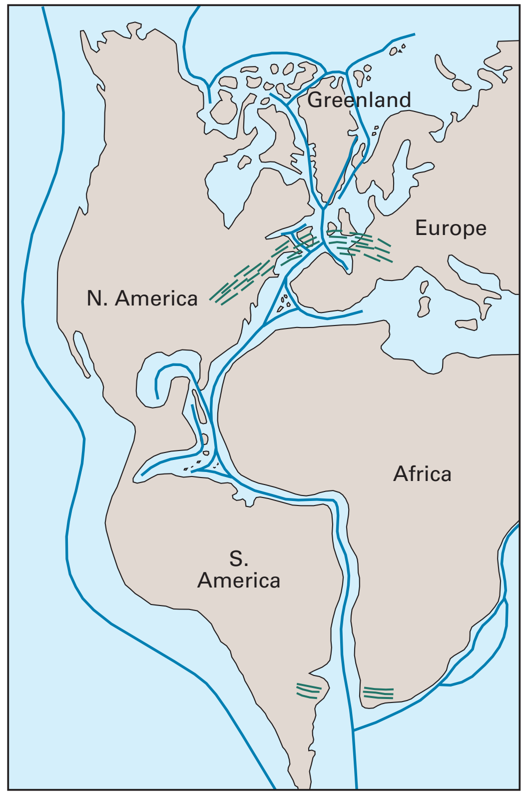
Modern plate tectonic theory is only a few decades old. But as far back as the 19th century, German meteorologist and geophysicist, Alfred Wegener, suggested that our continents are fragments of a single supercontinent. As good navigational charts became available, geographers could see the close correspondence 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 *Pangea*, into multiple continents that drifted apart (FIGURE 8.23). He suggested that Pangea 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 Pangea, including the distribution patterns of fossils and present-day plant 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. Single continents have fragmented into smaller ones, while at other times, small continents have merged to form large ones. Our Visualizing feature, in the previous section, shows a reconstruction of continental motions of the last 600 million years or so.

In fact, over the billions of years of the Earth's geologic history, the union of the continents and their breakup is actually a repeating process—called the *Wilson cycle*—and it has occurred half a dozen times or more. We now know that before Pangea there was an earlier supercontinent, dubbed Rodinia, that was fully formed about 700 million years ago. Rodinia broke apart, and its fragments were carried away in different



Wegener's Pangea FIGURE 8.23

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.

directions. Then they reversed their motions and headed back toward a common center, where many continent–continent collisions bonded them together by sutures to create Pangea. This supercontinent 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, Antartica, Australia, New Zealand, Madagascar, and peninsular India. Some interesting evidence suggests that there may have been yet another supercontinent before Rodinia.

It is important to study the changing continental arrangements and locations over time, because as the continents changed latitude they brought changes in climate, soils, and vegetation to each continent. Geography of the geologic past bears the name "paleogeography."

CONCEPT CHECK STOP

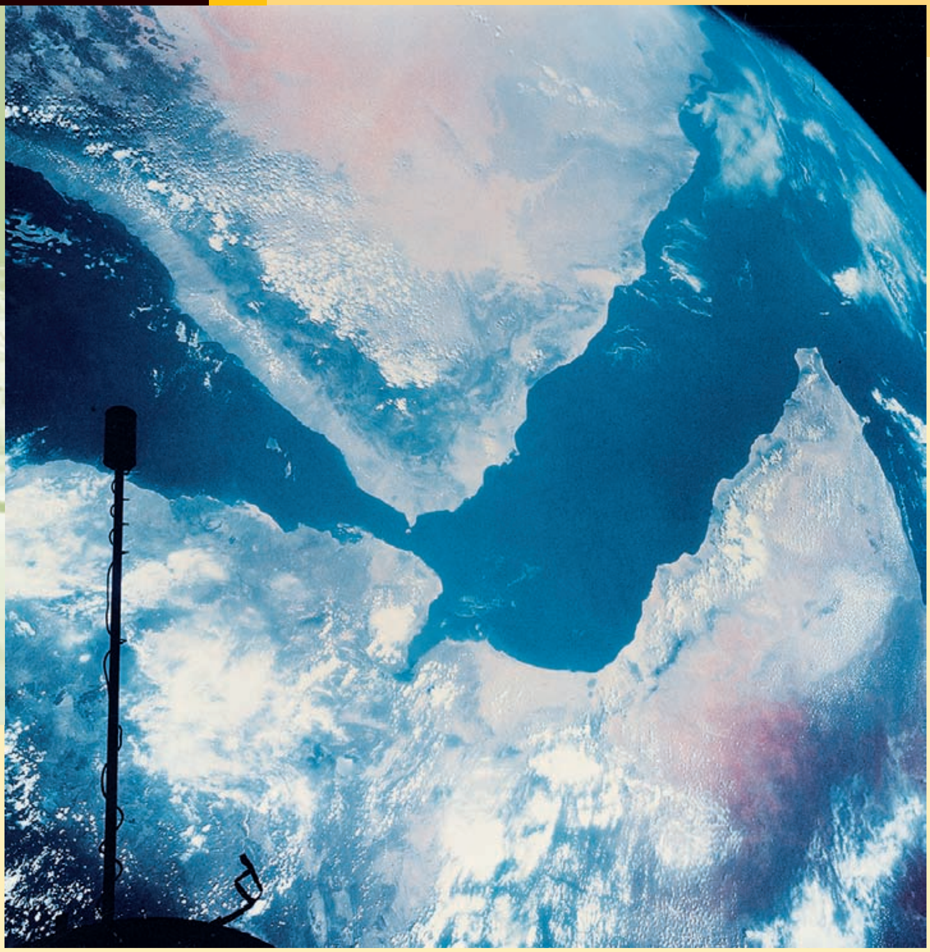
What is Wegener's supercontinent theory? Why wasn't it accepted initially?

What is the Wilson cycle?

What is happening in this picture ?

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. The pieces of land on either side of the ocean almost seem like jigsaw pieces that could fit back together, and it's easy to visualize how the two plates have split apart. How did plate motion create the narrow ocean?



VISUAL SUMMARY

1 Rocks and Minerals of the Earth's Crust

1. The Earth's interior is made up of layers. The core is a dense mass of liquid iron and nickel that is solid at the very center. The mantle surrounds the core. The outermost layer is the crust.

2. Igneous rocks are made from cooled magma. Sedimentary rocks are formed in layers, or strata, as fragments of rocks and minerals are compressed and cemented together. Metamorphic rocks are formed when igneous or sedimentary rocks are exposed to heat and pressure.

3. The cycle of rock change is responsible for transforming these rock types over millions of years.

2 Major Relief Features of the Earth's Surface

1. Geologists trace the history of the Earth through the geologic timescale. Precambrian time includes the Earth's earliest history. It is followed by the Paleozoic, Mesozoic, and Cenozoic eras.

2. The lithosphere includes the crust and an upper layer of the mantle. It is made of rigid, brittle rock. Below the lithosphere is the asthenosphere, in which mantle rock is soft or plastic.

3. Continental masses consist of active belts of mountain-making and inactive regions of old, stable rock. Mountain-building occurs by volcanism and tectonic activity. Continental shields are regions of low-lying igneous and metamorphic rocks. Ocean basins are marked by a midoceanic ridge with a central axial rift.

3 Plate Tectonics

1. The two basic tectonic processes are extension and compression. Both processes can create mountains.

2. The lithosphere is fractured and broken into a set of lithospheric plates that move with respect to each other.

3. Where plates move apart, there is a spreading boundary. At converging boundaries, plates collide. At transform boundaries, plates move past one another on a transform fault. There are six major lithospheric plates.

4. When oceanic lithosphere and continental lithosphere collide, the denser oceanic lithosphere plunges beneath the continental lithospheric plate. This is subduction.

5. In continental rupture, extensional tectonic forces move a continental plate in opposite directions, creating a rift valley and new oceanic crust forms as spreading continues.

6. Plate movements are thought to be powered by convection currents in the plastic mantle rock of the asthenosphere.

4 Continents of the Past

1. During the Permian Period, the continents were joined in a single, large supercontinent—Pangea—that broke apart into the present arrangement of continents and ocean basins.

2. The Wilson cycle describes the merger of continents to create a supercontinent, which then fragments into smaller continents once more. This cycle has occurred at least twice, and maybe more times.

KEY TERMS

- **core** p. 228
- **mantle** p. 228
- **crust** p. 228
- **igneous rock** p. 229
- **magma** p. 229
- **sedimentary rock** p. 231
- **fossil fuels** p. 234
- **metamorphic rock** p. 236
- **lithospheric plate** p. 240
- **plate tectonics** p. 244
- **subduction** p. 245
- **continental suture** p. 247

CRITICAL AND CREATIVE THINKING QUESTIONS

1. Describe the Earth's inner structure. What different types of crust are there? How are they different?

2. What are the three major classes of rocks? Sketch the cycle of rock change and describe how each rock type is formed.

3. What types of sedimentary deposits consist of hydrocarbon compounds? How are they formed? Why are they important?

4. How are mountain belts constructed? Describe two processes.

5. 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.

6. What is a lithospheric plate? Name the six great lithospheric plates. How and why do geologists think these plates move? Sketch a cross section showing a collision between an oceanic and a continental lithospheric plate. Label the following features: oceanic crust, continental crust, mantle, oceanic trench, and rising magma. Indicate where subduction is occurring.

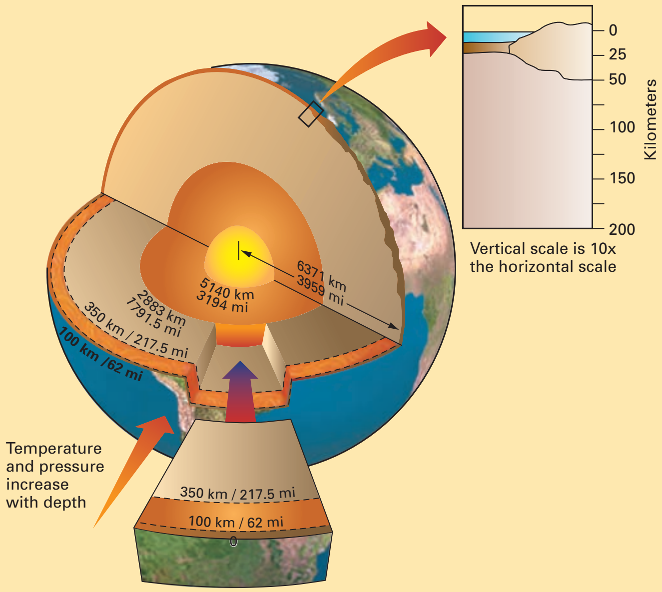
7. What are transform faults? Where do they occur?

8. Sketch a continent–continent collision and describe the formation 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.

9. What was Wegener's theory about "continental drift"? Why was it opposed at the time? What is the Wilson cycle?

SELF-TEST

1. This cutaway diagram of the Earth's interior shows several layers. Label the mantle, outer core, inner core, asthenosphere, and lithosphere. Indicate whether the layer is solid, plastic, or liquid.



2. A _______________ is a naturally occurring, inorganic substance that usually possesses a definite chemical composition and characteristic atomic structure.
   a. crystal
   b. mineral
   c. rock
   d. metamorphic rock

3. Intrusive igneous rocks are noted for their:
   a. large mineral crystals
   b. interesting mineral composition
   c. hardness, compared to extrusive igneous rocks
   d. darker colors

4. The metamorphic equivalent of sandstone is _______________, which is formed by the addition of silica to fill completely the open spaces between the grains.
   a. slate
   b. quartzite
   c. schist
   d. marble

5. Shale, shown in the photograph, is formed from layered accumulations of mineral particles derived mostly by weathering and erosion of preexisting rocks. Which rock class does it belong to?
   a. Sedimentary rocks
   b. Igneous rocks
   c. Metamorphic rocks
   d. Volcanic rocks

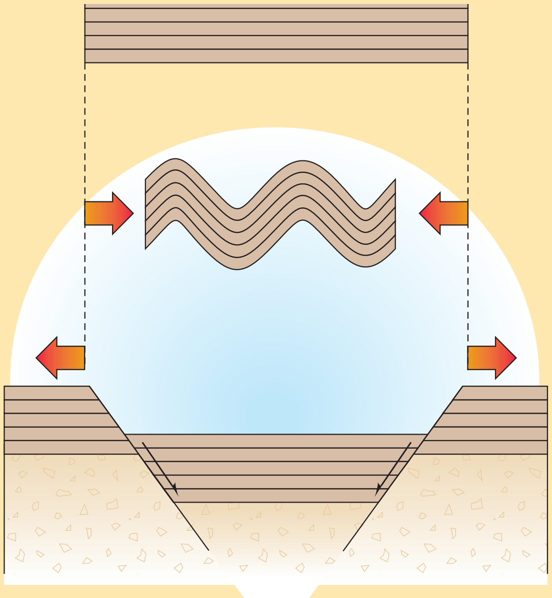
6. The theory describing the motions and changes through time of the continents and ocean basins, and the processes that fracture and fuse them, is called _______________.
   a. continental drift
   b. Earth dynamics
   c. plate tectonics
   d. the Wilson cycle

7. The _______________ is a soft, plastic layer that underlies the lithosphere.
   a. mantle
   b. outer core
   c. inner core
   d. asthenosphere

8. All time older than 570 million years before the present is _______________ time.
   a. Cambrian
   b. Mesozoic
   c. Triassic
   d. Precambrian

9. Extrapolating geologic time to a single 24-hour day, then the proliferation of life on planet Earth began only _______________ before midnight.
   a. 18 minutes
   b. 2 hours and 14 minutes
   c. 45 minutes
   d. 1 hour

10. The diagram shows two basic forms of tectonic activity. Identify and describe both processes. Which would we expect to see between separating oceanic plates? Which occurs between converging plate boundaries?



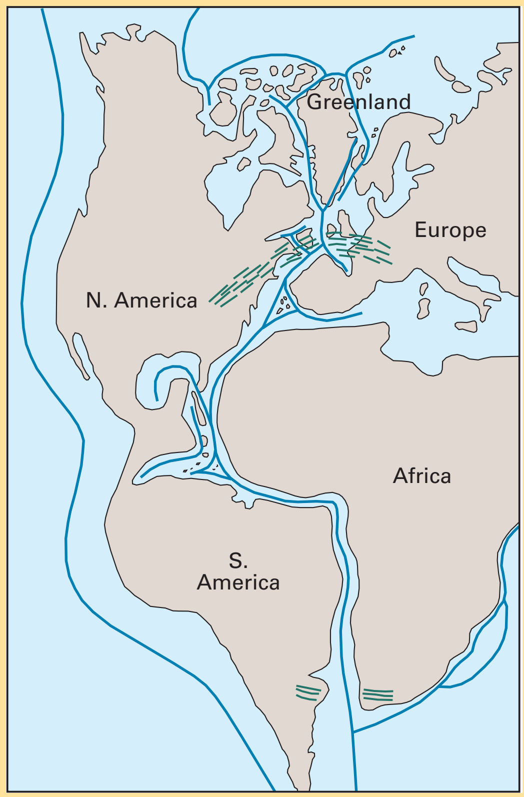
11. Ocean basins are characterized by a central _______________ consisting of submarine hills that rise gradually to a rugged central zone delineated by a narrow, trench-like feature called a(n) _______________.
   a. cordillera, rift
   b. midocean ridge, rift
   c. midocean ridge, axial rift
   d. ridge, axial rift

12. Some continental margins are _______________ and accumulate thick deposits of continental sediments while other continental margins are _______________ and have trenches marking the location at which ocean crust is sliding beneath continental crust.
   a. passive; active
   b. active; passive
   c. passive; tectonic
   d. submerging, emerging

13. The process in which one plate is carried beneath another is called _______________.
   a. advection
   b. convection
   c. liposuction
   d. subduction

14. _______________ plate boundaries with _______________ in progress are zones of intense tectonic and volcanic activity.
   a. Transform, subduction
   b. Subduction, orogeny
   c. Converging, subduction
   d. Spreading, axial motion

15. Alfred Wegener, a German meteorologist and geophysicist, suggested in 1915 that the continents had once been adjoined as a supercontinent, which he named _______________.
   a. Wegener Land
   b. Gondwanaland
   c. Pangea
   d. Laurasia



Volcanic and Tectonic Landforms 9

It was one of the worst natural disasters in the history of the United States. At 5 a.m., on April 18, 1906, the ground shook beneath San Francisco. The earthquake was felt as far as central Nevada, and along with the firestorm that followed, it killed around 3000 people and left 225,000 people homeless.

The earthquake was one of the first natural disasters to be documented through photographs. Although San Francisco was able to rebuild relatively quickly, repercussions from the earthquake are still felt today as the disaster had a serious impact on the development of California. At the start of the twentieth century, San Francisco was the largest city on the West Coast, with a population of about 410,000. Known as the "gateway to the Pacific," it also had the West Coast's busiest port and was its financial, trade, and cultural center. But the earthquake and fire destroyed over 80 percent of the city. The overall cost of the damage from the earthquake was estimated at the time to be around $400 million. Trade and industry were diverted to Los Angeles, which became the largest and most important urban area in the West.

The 1906 quake resulted from slippage along the San Andreas fault. The fault also passes about 60 km (about 40 mi) inland of Los Angeles, placing the densely populated metropolitan Los Angeles region in great jeopardy.

Devastating earthquakes around the world provide a dramatic example of the Earth's forces at work. These awesome forces are also responsible for building volcanoes, for triggering tsunamis, and for shaping a rich variety of landscapes.

San Franciscans survey the ruins of the city following the earthquake of 1906.

NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

- Volcanic Landforms p. 260

- Tectonic Landforms p. 270

- Earthquakes p. 277

- Landforms and Rock Structure p. 284

Volcanic Landforms

Learning Objectives

Define volcano.

Explain how stratovolcanoes and shield volcanoes form.

Describe the landforms associated with different types of volcanoes.

Continental landscapes reflect a tug-of-war between two opposing processes. Volcanic and tectonic activity brings 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 to endogenic processes, *exogenic processes* work at the Earth's surface. They lower continental surfaces by removing and transporting mineral matter through running water, waves and currents, glacial ice, and wind. Exogenic processes wear down initial landforms to create *sequential landforms*. Figure 9.1 shows how an initial landform, produced by crustal activity, is then carved into sequential landforms by erosion.

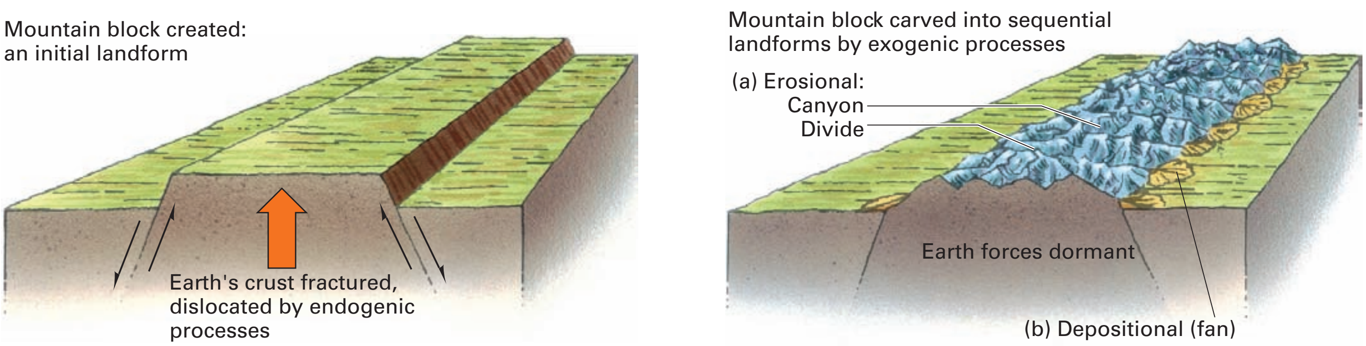
Where does the power to lift molten rock and rigid crustal masses from within the Earth to the surface come from? Natural radioactivity in rock in the crust and mantle creates heat energy. This is the fundamental energy source for the motion of lithospheric plates. Because the internal Earth forces act repeatedly and violently, 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

Volcano Conical, circular structure built by accumulation of lava flows and tephra (volcanic ash).

What exactly is a volcano? A **volcano** is a conical or dome-shaped initial landform. It is built from lava that emerges through constricted vents in the Earth's surface (Figure 9.2).

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, thousands of lives were snuffed out in seconds. The destruction associated with volcanoes is wreaked by a number of related effects. Sweeping clouds of incandescent gases descend the volcano slopes like great avalanches. Relentless lava flows



A This figure shows a mountain block uplifted by crustal activity.

B The initial landform is then sculpted by exogenic processes into sequential landforms.

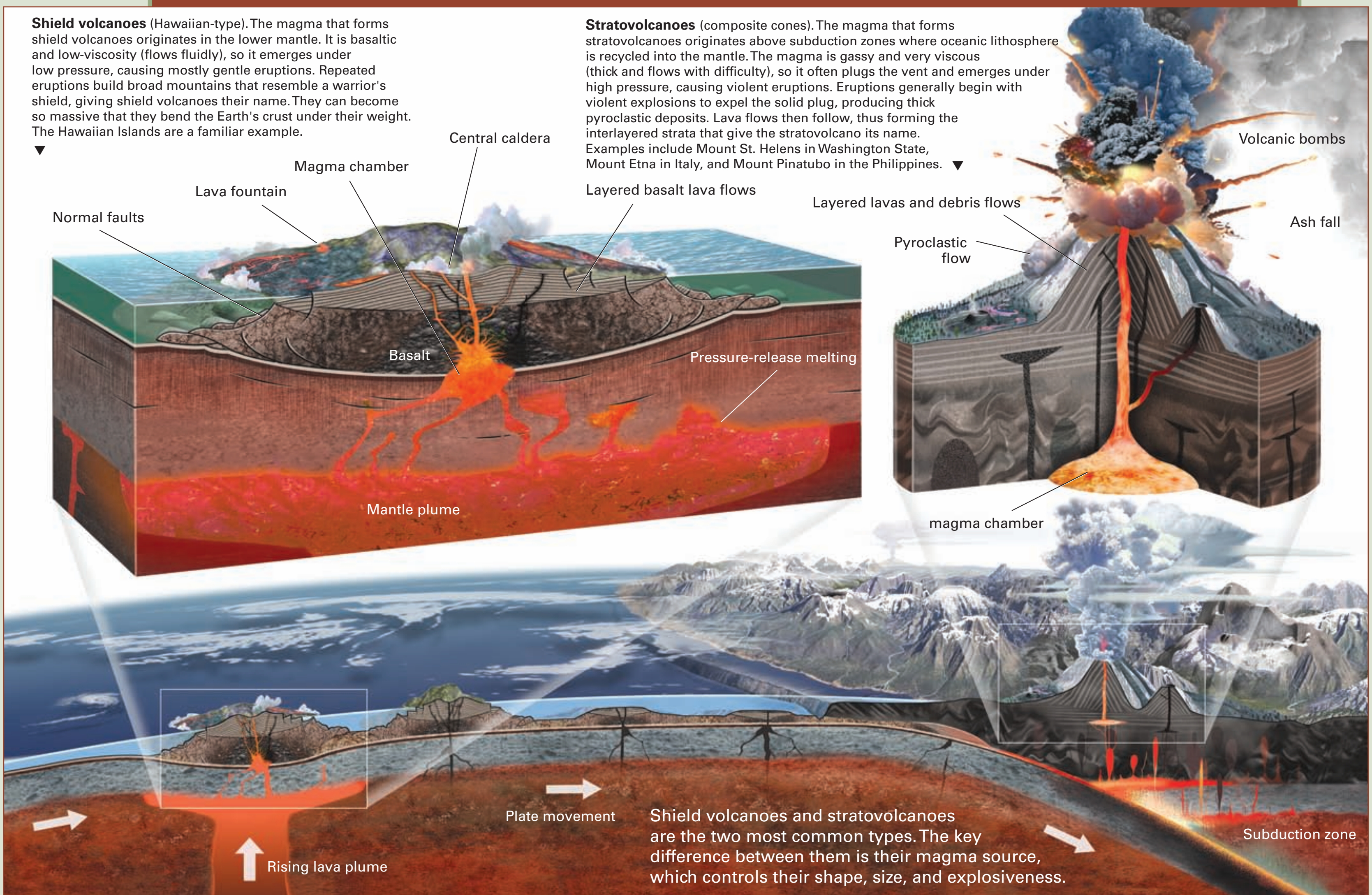
Initial and sequential landforms Figure 9.1

Initial landforms are produced directly by volcanic and tectonic activity.

can engulf whole cities. And showers of ash, cinders, and volcanic bombs (solidified masses of lava), all cause terrible devastation. Violent earthquakes are also associated with volcanic activity. And finally, for habitations along low-lying coasts, there is the peril of great seismic sea waves—similar to the Indian Ocean tsunami of 2004—generated by undersea or island volcanoes.

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.

Volcanoes: The inside story FIGURE 9.2



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Volcanic activity of the Earth FIGURE 9.3

A 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.

If you study FIGURE 9.3, you can see by comparing the maps that many volcanoes are located on subduction boundaries or crustal rifts.

Despite their harmful potential, volcanoes have created many sites of natural beauty. *Volcanism*, or volcanic activity, constructs imposing mountain ranges. Extruding magma, brought up to the Earth's surface, builds landforms that can accumulate in a single area both as volcanoes and as thick lava flows.

STRATOVOLCANOES

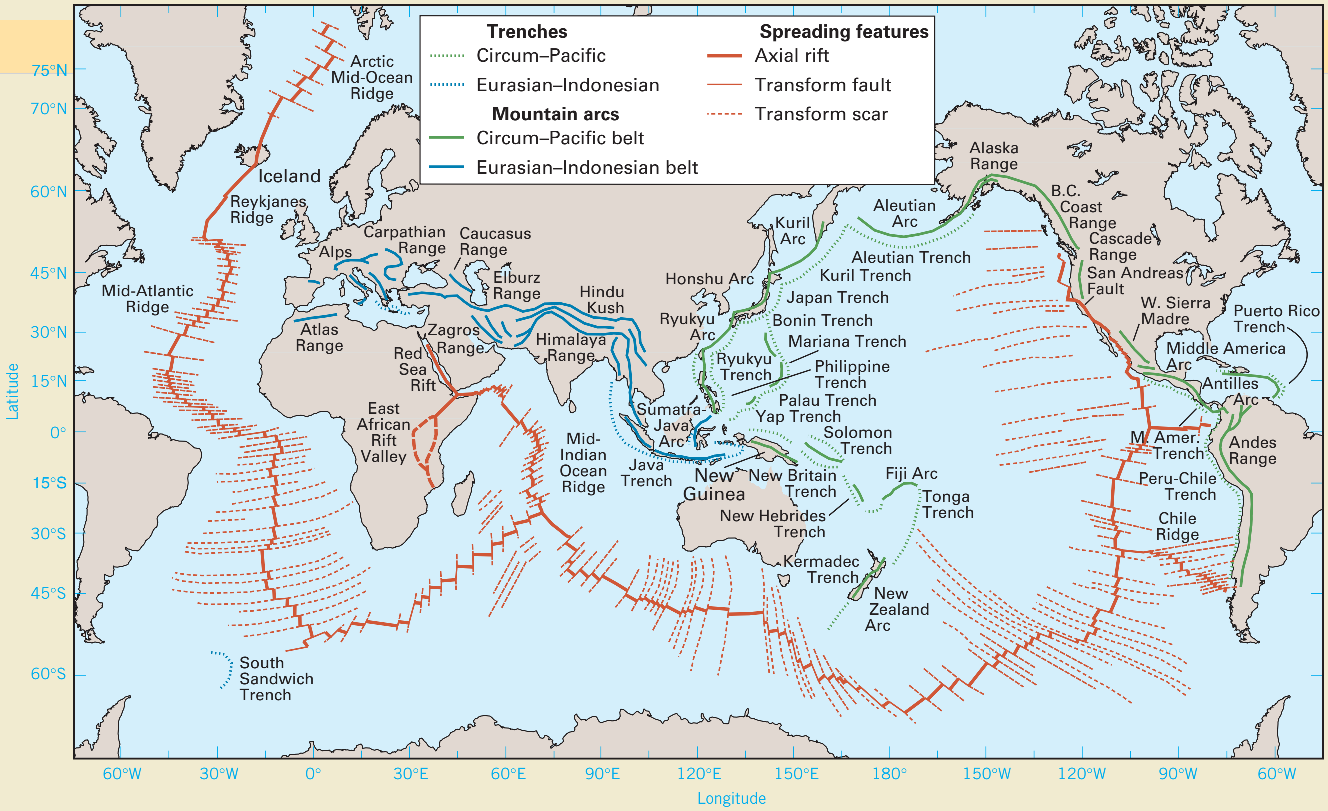
Volcanic eruptions can be explosive. But they can also be quiet. The nature of the eruption depends on the type of magma involved. There are two main types of igneous rocks: felsic and mafic. The felsic lavas (rhyolite and andesite) are very thick and gummy, resisting flow. So, felsic lava doesn't usually flow very far from the volcano's vent, 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 felsic-lava streams and tephra produce a **stratovolcano**. This tall cone steepens toward the summit, where you find the crater—a bowl-shaped depression. The crater is the principal volcano vent.

Stratovolcano Volcano constructed of multiple layers of lava and tephra (volcanic ash).

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.

Felsic lavas from stratovolcanoes hold large amounts of gas under high pressure, so they can produce explosive eruptions (FIGURE 9.4A). Sometimes the volcanic explosion is so violent that it actually de-



B This map shows the principal tectonic features of the world such as midoceanic ridges, trenches, and subduction boundaries. You can see that 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.

stroys the entire central 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* (**FIGURE 9.4B**). Although some of the upper part of the volcano is

Exploding volcanoes FIGURE 9.4

A 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).

B 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.

Ash cloud FIGURE 9.5

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 flooded with hot ash and debris, causing extensive fires that devastated the evacuated city. The southern two-thirds of the small island were left uninhabitable.

Hawaiian shield volcanoes FIGURE 9.6

On the distant skyline is the summit of Mauna Loa volcano. The shield volcanoes of the Hawaiian Islands have gently rising, smooth slopes that flatten near the top, producing a broad-topped volcano. Their domes rise to about 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.

blown outward in fragments, most of it settles back into the cavity formed beneath the former volcano by the explosion.

Explosive stratovolcanoes also emit "glowing avalanches," such as the Soufrière Hills eruption of 1997 (FIGURE 9.5). 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 Mount Pelée eruption issued without warning, sweeping down on the city of St. Pierre and killing all but two of its 30,000 inhabitants.

Over time, exogenic processes erode stratovolcanoes, creating new landscapes. The process diagram "Erosion of stratovolcanoes" shows the stages of this erosion.

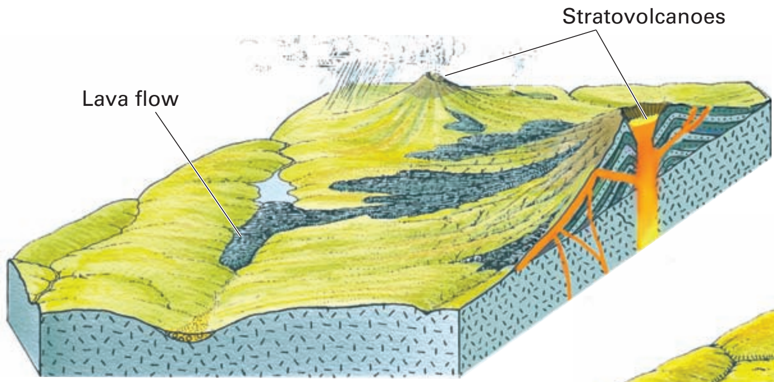
SHIELD VOLCANOES

In contrast to thick, gassy felsic lava that forms stratovolcanoes, mafic lava (basalt) is not very viscous and holds little gas. As you might expect, this means that eruptions of basaltic lava are usually quiet, and the lava can travel long distances to spread out in thin layers. Typically, then, large basaltic volcanoes are broadly rounded domes with gentle slopes (FIGURE 9.6). They are called **shield volcanoes**. Most of the lava flows from fissures (long, gaping cracks) on the flanks of the volcano.

Shield volcano Low, often large, dome-like accumulation of basalt lava flows emerging from long, radial fissures on flanks.

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. Crustal motion over a hotspot produces a long trail of islands and sunken islands, called *guyots*. The Hawaiian trail is shown in FIGURE 9.7.

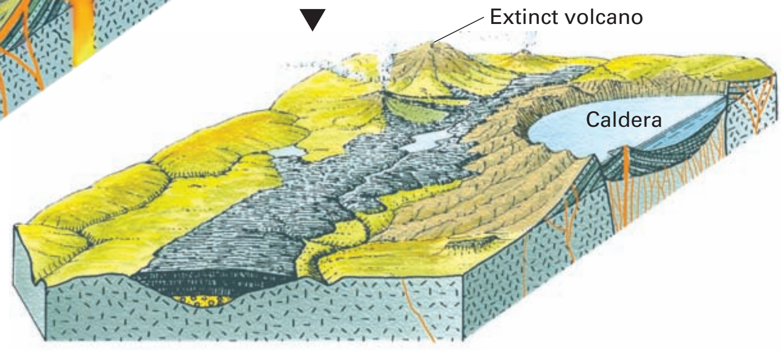
Erosion of stratovolcanoes



▲ **A 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 the lava dam.

B Waning volcanic activity After some time, the largest volcano has been destroyed in an explosive eruption, leaving behind a caldera. A lake occupies the caldera, and a small cone has been built inside. The other volcano shown in block (B) has now become extinct. It has been dissected by streams and has lost its smooth conical form.

▼



C 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. ▶

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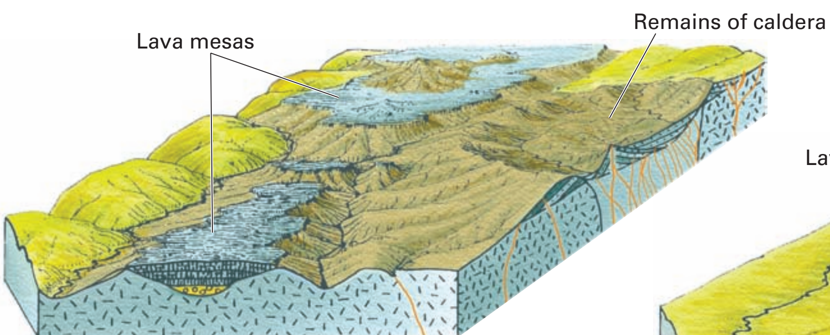
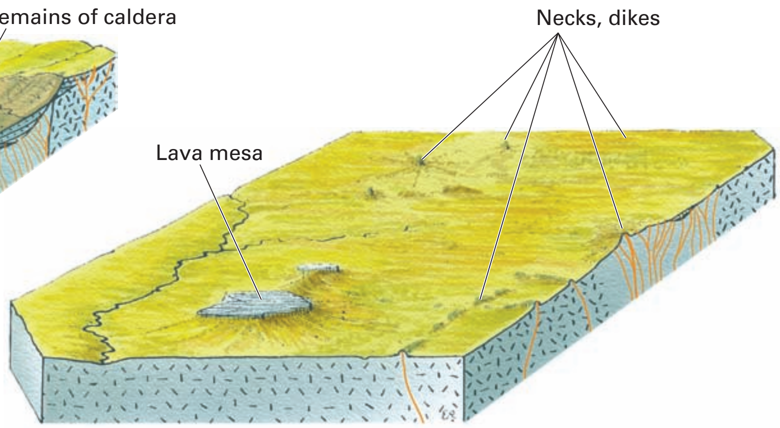




▲ **D Deeply eroded volcanoes** All volcanoes are now extinct and have been deeply eroded. The caldera lake has been drained, and the rim has been worn to a low, circular ridge. The lava flows have resisted erosion far better than therock of the surrounding area. They now stand high above the general level of the region, as mesas.

▲ **E Advanced erosion** All that remains now of each volcano is a small, sharp peak, called a *volcanic neck*. This is the remains of lava that solidified in the pipe of the volcano. Perhaps the finest illustration of a volcanic neck with radial dikes is Ship Rock, New Mexico.

◀ **F Ship Rock,** New Mexico, 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 tle left, you can see wall-like dikes extending far out from the central peak.

Hawaiian seamount chain FIGURE 9.7

The Hawaiian seamount chain in the northwest Pacific Ocean Basin is 2400 km (about 1500 mi) long and trends northwestward. 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 base of the volcano at the ocean floor.

Vestmannaeyjar after the Heimaey volcanic eruption FIGURE 9.8

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 cone that reached 100 m (about 300 ft) above sea level. Christened Eldfell, the cone appears on the right surrounded by lava flows extending into the ocean. Eldfell'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.

Several other long trails of volcanic seamounts cross the Pacific Ocean Basin following parallel paths that reveal the plate motion. The process diagram, "Hotspot Volcano Chain" shows how this happens.

A few basaltic volcanoes also occur along the midoceanic ridge, where seafloor spreading is in progress. Iceland, in the North Atlantic Ocean, provides an outstanding example (FIGURE 9.8). 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.

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 9.9).

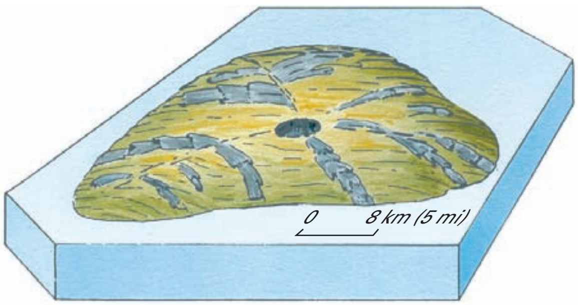
Flood basalts FIGURE 9.9

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.

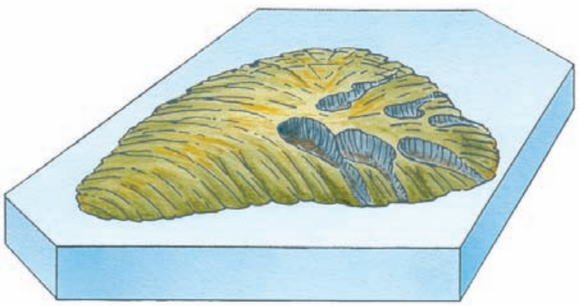
Cinder cones are small volcanoes that form when frothy basalt magma is ejected under high pressure from a narrow vent, producing tephra. The rain of tephra accumulates around the vent to form a roughly circular hill with a central crater. Cinder cones rarely grow more than a few hundred meters high. An exceptionally fine example of a cinder cone is Wizard Island, which was built on the floor of Crater Lake long after the caldera was formed.

Shield volcanoes show erosion features that are quite different from those of stratovolcanoes (**Figure 9.10**).

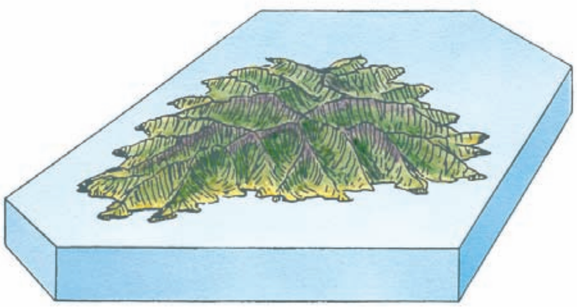
Erosion of shield volcanoes **Figure 9.10**



A The active volcano and its central depression are initial landforms.

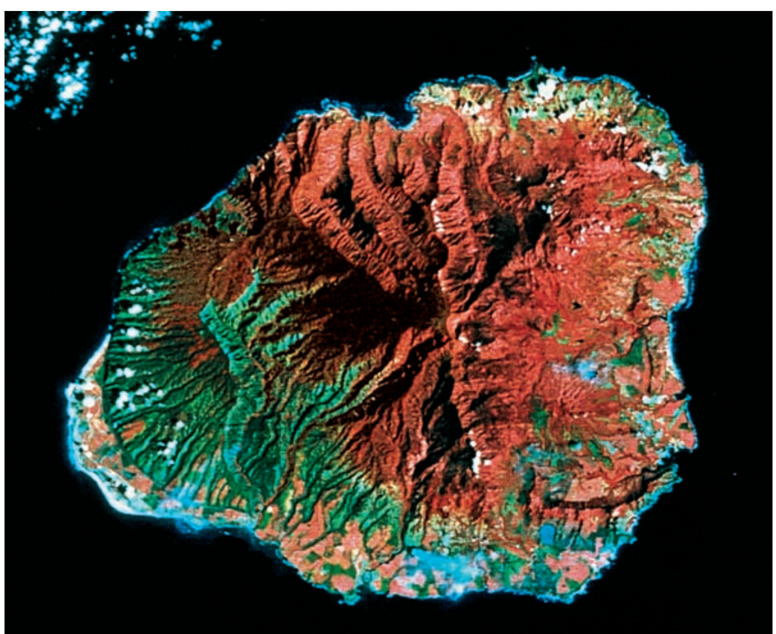


B In the early stage of erosion, radial streams cut deep canyons into the flanks of the extinct shield volcano. These canyons are opened out into deep, steep-walled amphitheaters.



C In the last stages, the original surface of the shield volcano is entirely obliterated, leaving a rugged mountain mass made up of sharp-crested divides and deep canyons.

D 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.



Process Diagram

Hotspot volcano chain

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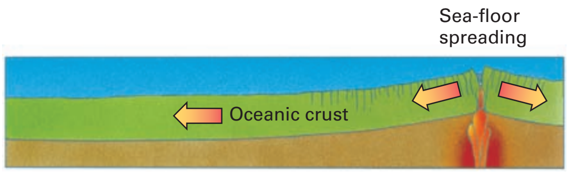
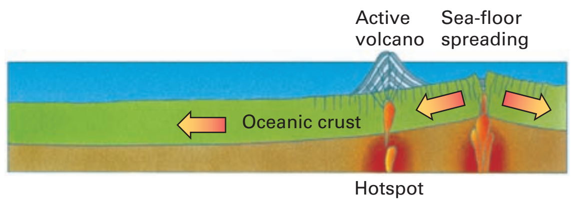
As two oceanic plates are pulled apart by tectonic activity, they create a conveyor belt of oceanic crust. The crust very slowly moves over a hotspot (at most a few meters per year), creating a chain of volcanoes and sunken islands over time. Images A–E show how a new volcano forms over the hotspot and is conveyed away, eventually to become a guyot.

A The setting: seafloor spreading As the oceanic plates are pulled apart, hot magma rises to plug the gap, continually creating new crust.

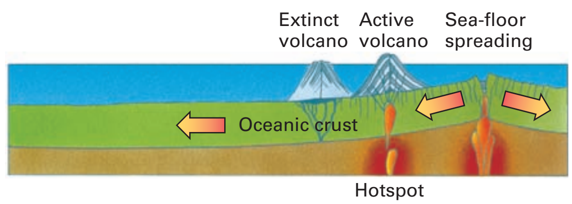


B Over a hotspot, a volcano forms At a hotspot, a plume of upwelling basaltic magma melts its way upward through the lithosphere, reaching the seafloor. Each major pulse of this magma plume sets off a cycle of volcano formation. An active volcano is produced over the hotspot.

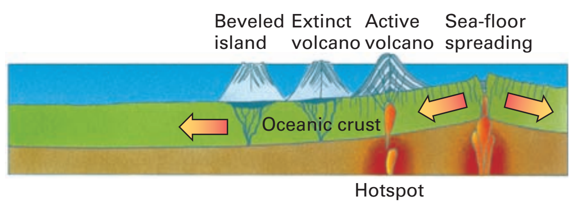


Tiny Nihoa Island (about 1 square kilometer) is part of the Hawaiian Island chain, northwest of the main islands. It formed as an active hotspot volcano about 7.5 million years ago, but today has migrated well beyond the hotspot. In time Nihoa will become a submerged guyot.

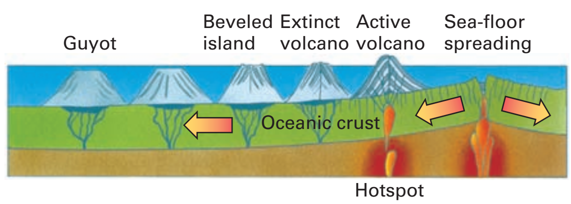
C Extinct volcano Over time, seafloor spreading moves the ocean lithosphere, carrying the volcano away from its origin above the deep plume, as though it were on a conveyor belt. Now away from the hotspot—its source of magma—the volcano grows inactive and extinct. Meanwhile, a new volcano forms over the hotspot.



D Beveled island As the extinct volcano is conveyed farther and farther from the hotspot, erosion and wave attack wears it away, eventually reducing it to a low island. Continual attack by waves further reduces it to a coral-covered platform.



E Guyot Eventually, only a sunken island exists-—a guyot.The hotspot continues to create new volcanoes. Over millions of years, this process of crustal motion over a hotspot can produce a trail of islands and guyots stretching for thousands of kilometers.



GEOTHERMAL ENERGY SOURCES

We've already mentioned that natural radioactivity in the Earth is the power source for creating awe-inspiring landforms. It provides the energy needed to raise magma from deep within the Earth, creating volcanoes, as we've seen. But is there any way for us to harness this immense power locked inside the Earth's hot rock as *geothermal energy*?

Scientists examining deep mines and bore holes have found that the temperature of rock increases steadily with depth. In the upper mantle, the rock is close to its melting point. The radioactive decay processes that produce this heat diminish so slowly that we can regard this heat as a basically limitless energy resource.

How do we tap into this energy? Could we drill deep holes into the crust and inject water? Then the hot rock would turn the water to steam, which we can use to generate electricity. Unfortunately, things aren't that simple. If we tried to drill to the required depths, the crust would slowly flow, closing up the cavity or preventing holes from being drilled in the first place. That means we must look for special geothermal locations where the hot rock lies within striking distance of conventional drilling techniques.

The first places to look are regions where we find hot springs and geysers. Here the ground water has been heated to near its boiling point by hot rock. We drill wells that tap the hot water, which flashes into steam when it's brought into the atmosphere, driving turbines (FIGURE 9.11).

Geothermal power plant FIGURE 9.11

The geothermal power plant at Svartsengi, Iceland, heats seven towns, 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.

CONCEPT CHECK STOP

What is the difference between an endogenic and an exogenic process? Give examples of both.

What is a stratovolcano? Name some landforms that you would associate with a stratovolcano.

What is a shield volcano?

Tectonic Landforms

Learning Objectives

Describe fold belts and the ridge-and-valley landscape.

Discuss normal, reverse, transcurrent, and overthrust faults.

Understand how landforms can be created by faults.

Explain the East African Rift Valley system.

FOLD BELTS

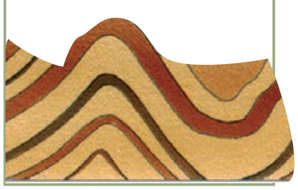
There are two basic forms of tectonic activity: compression and extension. Compression occurs when lithospheric plates are squeezed together along converging lithospheric plate boundaries, whereas extension happens along continental and oceanic rifting, where plates are being pulled apart.

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 9.12, are an example of relatively young—geologically speaking—open folds. The folds create a set of alternating **anticlines**, or upbends, and troughs, called **synclines**. We usually find broadly rounded mountain ridges at the anticlines, while synclines create open valleys.

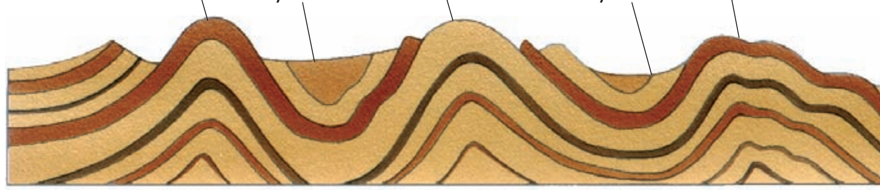
When fold belts are eroded they create a ridge-and-valley landscape. These folds are continuous and even-crested, producing almost parallel ridges. But in other fold regions, the fold crests "plunge," rising up in places and dipping down in others. FIGURE 9.13 explains this process.

Folds Corrugations of strata caused by crustal compression.

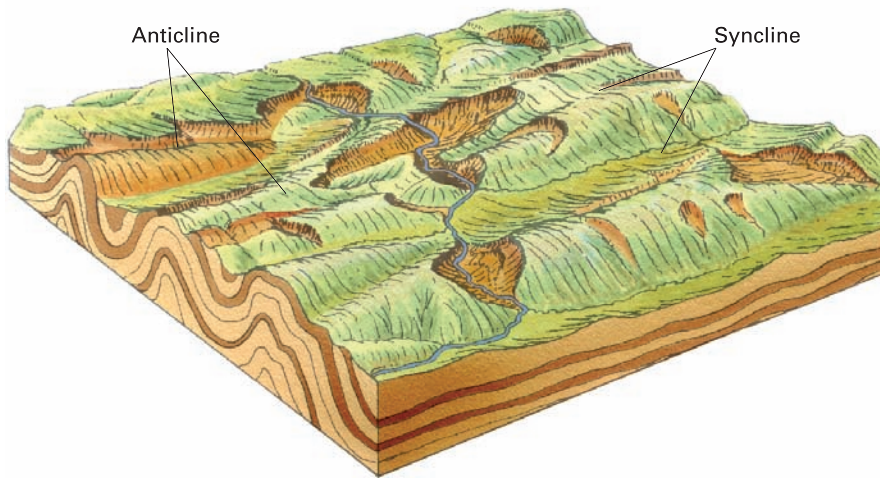
Anticline and **Syncline** An alternating set of bends in the Earth's crust.



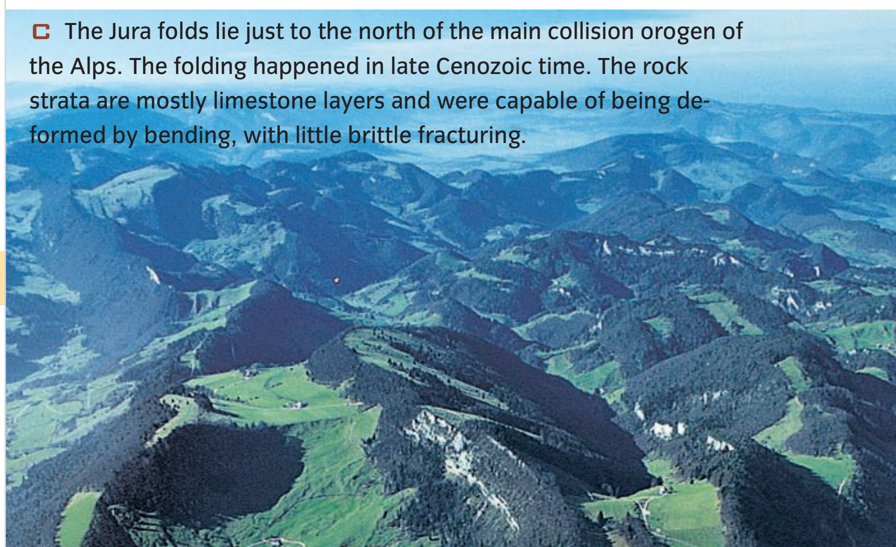
Fold belts FIGURE 9.12



A 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 elongate, open valley.



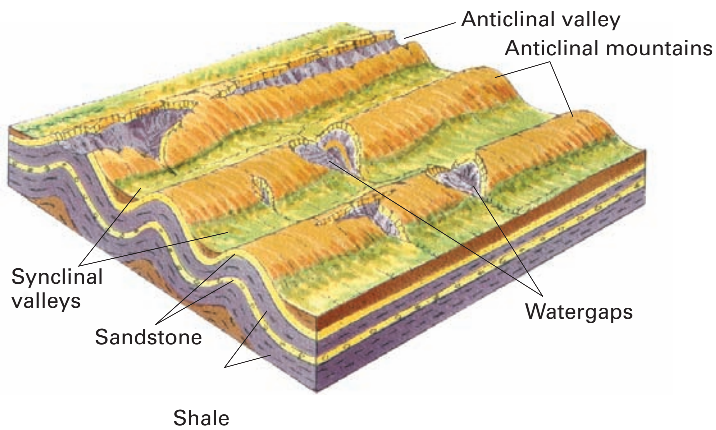
B Erosion process Some of the anticlinal arches have been partially removed by erosion processes. The rock structure can be seen clearly in the walls of the winding gorge of a major river that crosses the area.



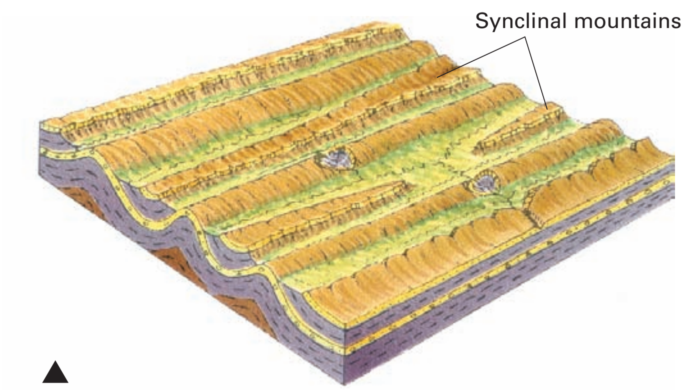
C The Jura folds lie just to the north of the main collision orogen of the Alps. The folding happened in late Cenozoic time. The rock strata are mostly limestone layers and were capable of being deformed by bending, with little brittle fracturing.

Stages in the erosional development of folded strata FIGURE 9.13

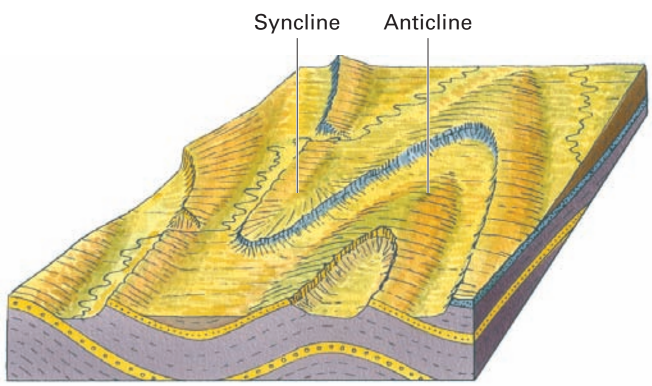
Deep erosion of simple, open folds produces a ridge-and-valley landscape. We see these landscapes along the eastern side of the Appalachian Mountains from Pennsylvania to Alabama. Folds that dip downward produce zigzag ridges following erosion.



A First, weaker formations such as shale and limestone are eroded away, leaving long, narrow ridges of hard strata, such as sandstone or quartzite. Sometimes, the resistant rock at the center of the anticline is eroded through to reveal softer rocks underneath, creating an anticlinal valley.

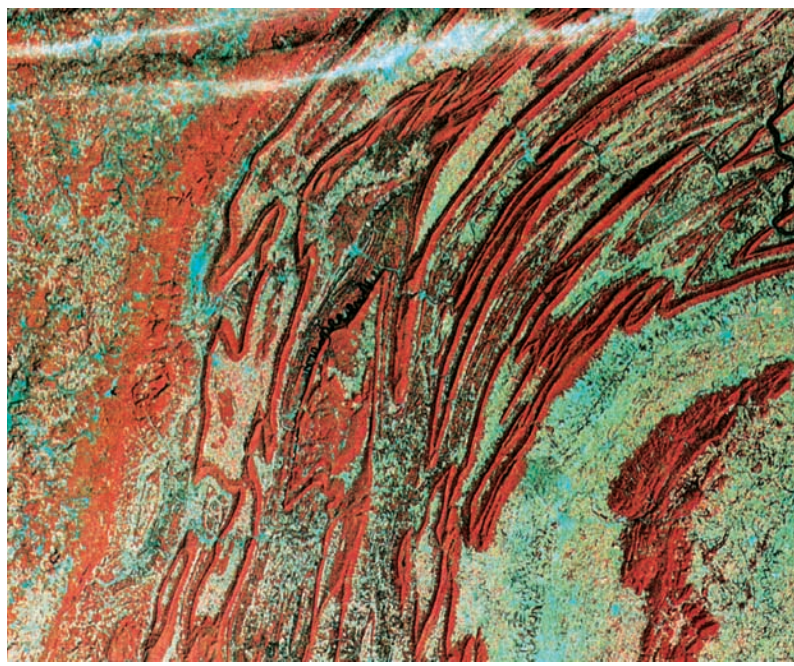


B Synclinal mountains can also be formed after continued erosion, when resistant rock at the center of a syncline is exposed, standing up as a ridge.



C Plunging folds that have been eroded lead to zigzag ridges.

D 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.



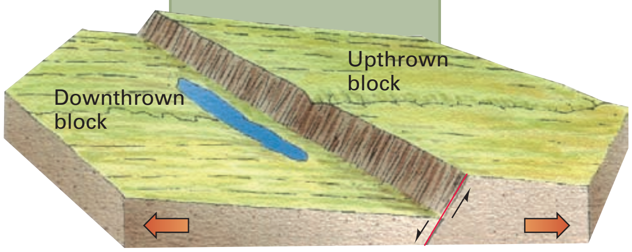
FAULTS AND FAULT LANDFORMS

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 9.14). These movements can happen many years or decades apart, 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.

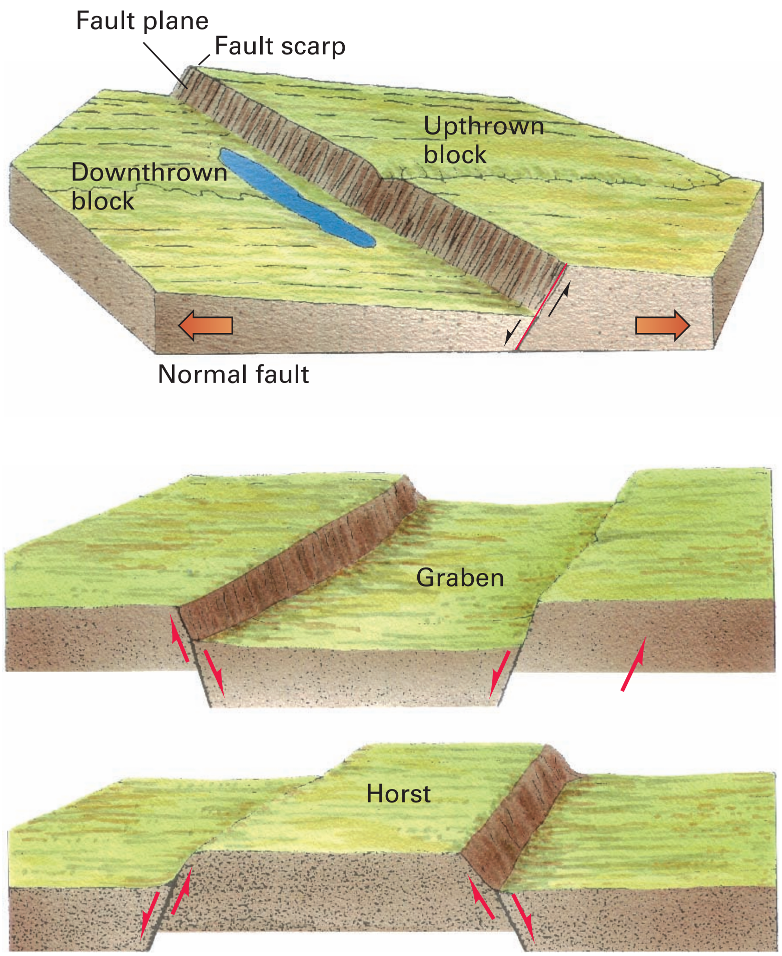
Normal faults are a common type of fault produced by crustal rifting (FIGURE 9.15). They usually occur as a set of parallel faults, giving rise to distinct landforms including *fault scarps*, *grabens*, and *horsts*. Where normal faulting occurs on a grand scale it produces mountain masses called *block mountains*.

Fault Sharp break in rock with a slippage of the crustal block on one side with respect to the block on the other.



Fault scarps FIGURE 9.14

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.



A **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.

B **Graben** A narrow block dropped down between two normal faults creates a *graben*—a trench with straight, parallel walls.

C **Horst** A narrow block elevated between two normal faults is a *horst*—making block-like plateaus or mountains, often with a flat top but steep, straight sides.

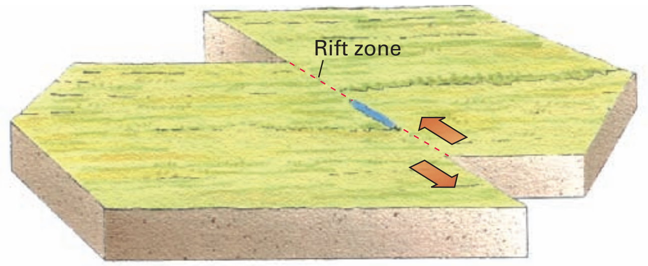
Faults and fault scarps FIGURE 9.15

When lithospheric plates slide past one another horizontally along major transform faults we refer to these faults as *transcurrent*, or *strike-slip*, *faults* (FIGURE 9.16). 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.

FIGURE 9.17 illustrates the *reverse fault* and the *overthrust fault*. Both are caused by compression. The San Fernando, California, earthquake of 1971 was generated by slippage on a reverse fault.

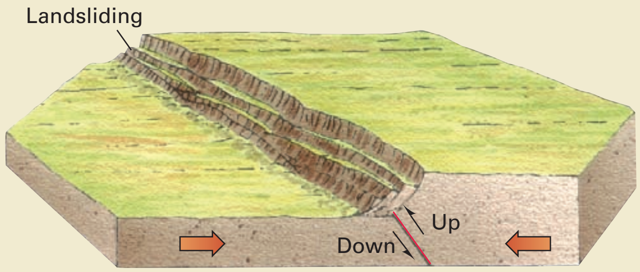
Repeated faulting can produce a great rock cliff hundreds of meters high. Because fault planes extend hundreds of meters down into the bedrock, their landforms can persist even after several million years of erosion. FIGURE 9.18 diagrams the effect of erosion on a fault scarp.

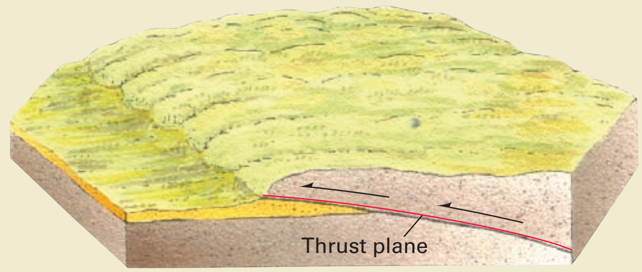
Transcurrent faults FIGURE 9.16



▲ **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.





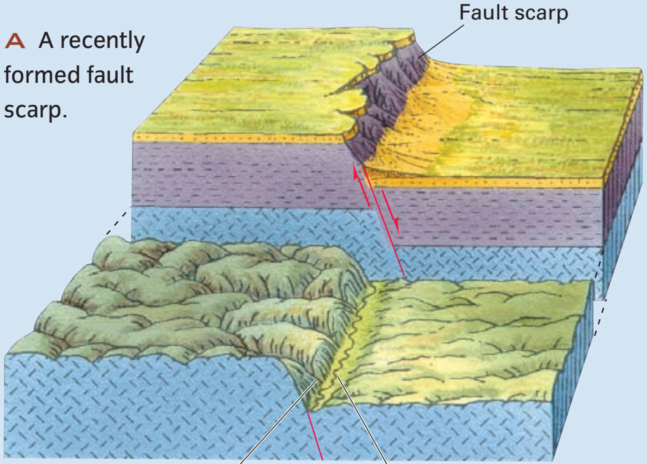
A Reverse fault The fault plane along a reverse fault is inclined such that one side rides up over the other. Reverse faults produce fault scarps similar to those of normal faults. But because the scarp tends to be overhanging there's a much greater risk of a landslide.

B 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.

Reverse and overthrust faults FIGURE 9.17

Reverse and overthrust faults are created when the crust is compressed.

A A recently formed fault scarp.



B 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.

C This dramatic photo shows a fault scarp in the southern Sierra Nevada Mountains in King's Canyon National Park. An enormous mountain block has been uplifted by many small movements over a few million years. Over time, erosion cut deeply into the rock face. The sheer slope was modified by glacial activity during the Ice Age, but it still retained its form.

Fault scarp evolution FIGURE 9.18

The Rift Valley system of East Africa

The East African Rift Valley system is a beautiful illustration of rifting—the very first stage in the splitting apart of a continent to form a new ocean basin. Extending from the Red Sea southward to the Zambezi River, the system is about 3000 km (1900 mi) long. The rift valleys are like keystone blocks of a masonry arch that have slipped down between neighboring blocks as the arch has spread apart. Each separate valley ranges in width from about 30 to 60 km (20 to 40 mi).

Geographers recognize that each rift valley is basically a graben. The sides of the rift valleys appear to be stepped, as shown in this photo, because they are made up of many fault scarps. These grabens have a complex history that includes volcano-building on the graben floor. Two great stratovolcanoes lie close to the Rift Valley east of Lake Victoria—Mount Kilimanjaro and Mount Kenya.

A geographer would also make note of the way local agriculture exploits the stepped landscape at the edge of the Rift Valley with cultivated fields laid out in the flat tops of terraces.

The flat faces of the slopes on the fault scarps between gullies are likely to be remnants of the original planes of motion.

CONCEPT CHECK STOP

What are folds? Give an example of a place that displays a fold-belt landscape.

Name the four types of fault. Which ones are created by compression of the crust?

What type of fault is the San Andreas fault?

Earthquakes

LEARNING OBJECTIVES

Explain how earthquakes arise.

Discuss the San Andreas fault.

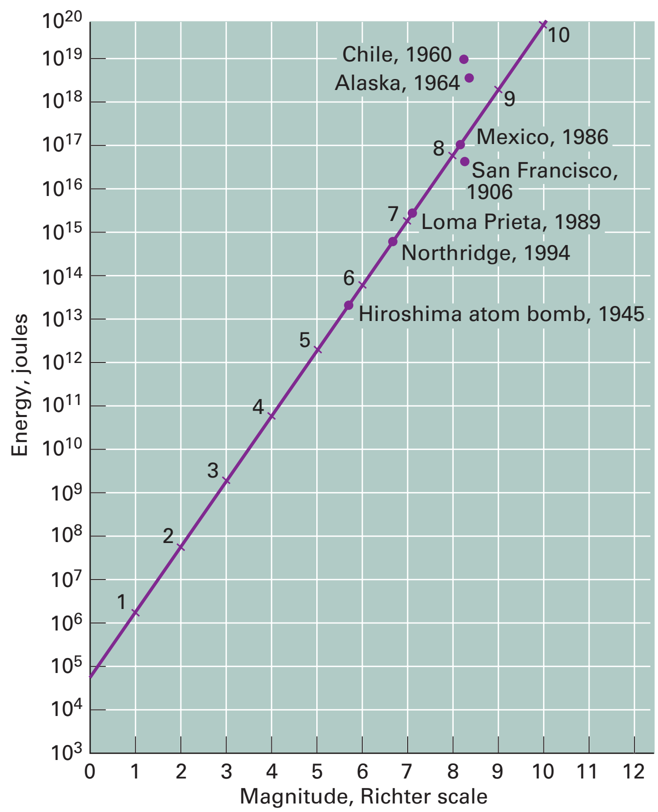
Describe tsunamis.

You've probably seen the destruction wreaked 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 waves. These *seismic waves* radiate out, 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.

Earthquake
A trembling or shaking of the ground produced by passing seismic waves.

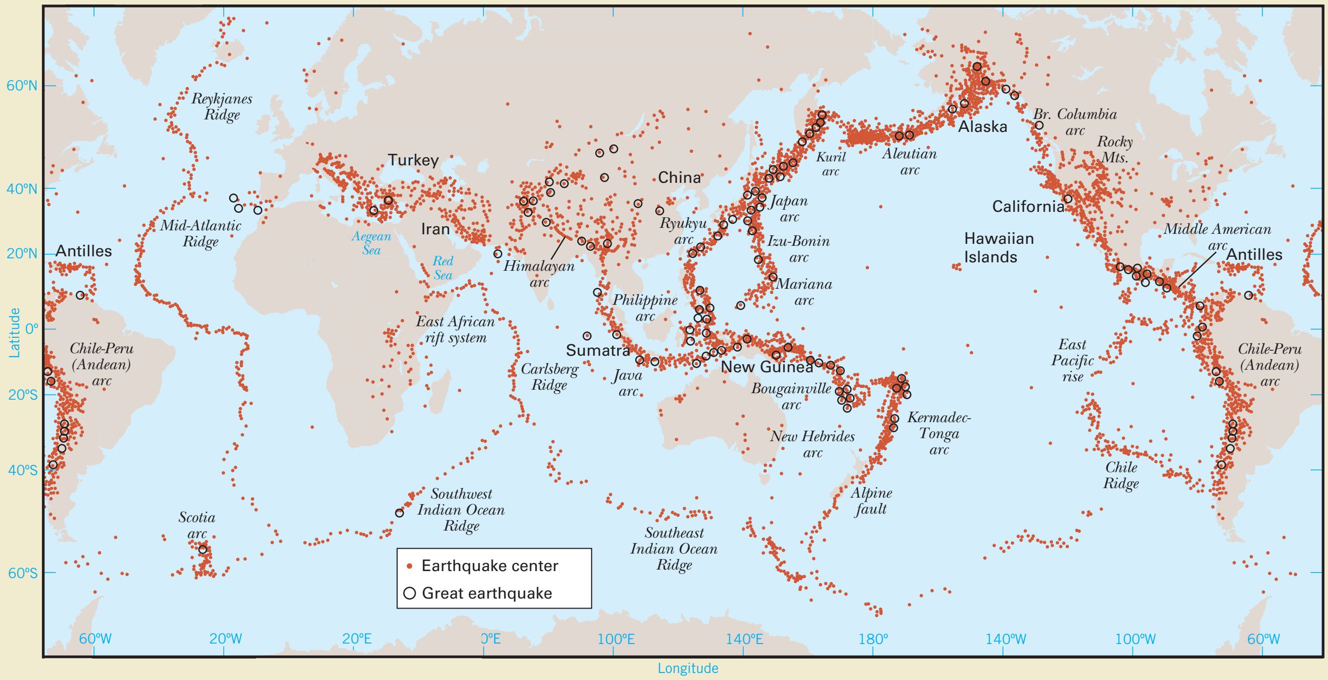
The distinguished seismologist Charles F. Richter devised the scale of earthquake magnitudes that bears his name in 1935. FIGURE 9.19 shows how the Richter scale relates to the energy released by earthquakes.



Great earthquakes on the Richter scale
FIGURE 9.19

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, with a value of 9.5. The great San Francisco earthquake of 1906 is now rated as magnitude 7.9.

Earthquake locations and plate boundaries FIGURE 9.20

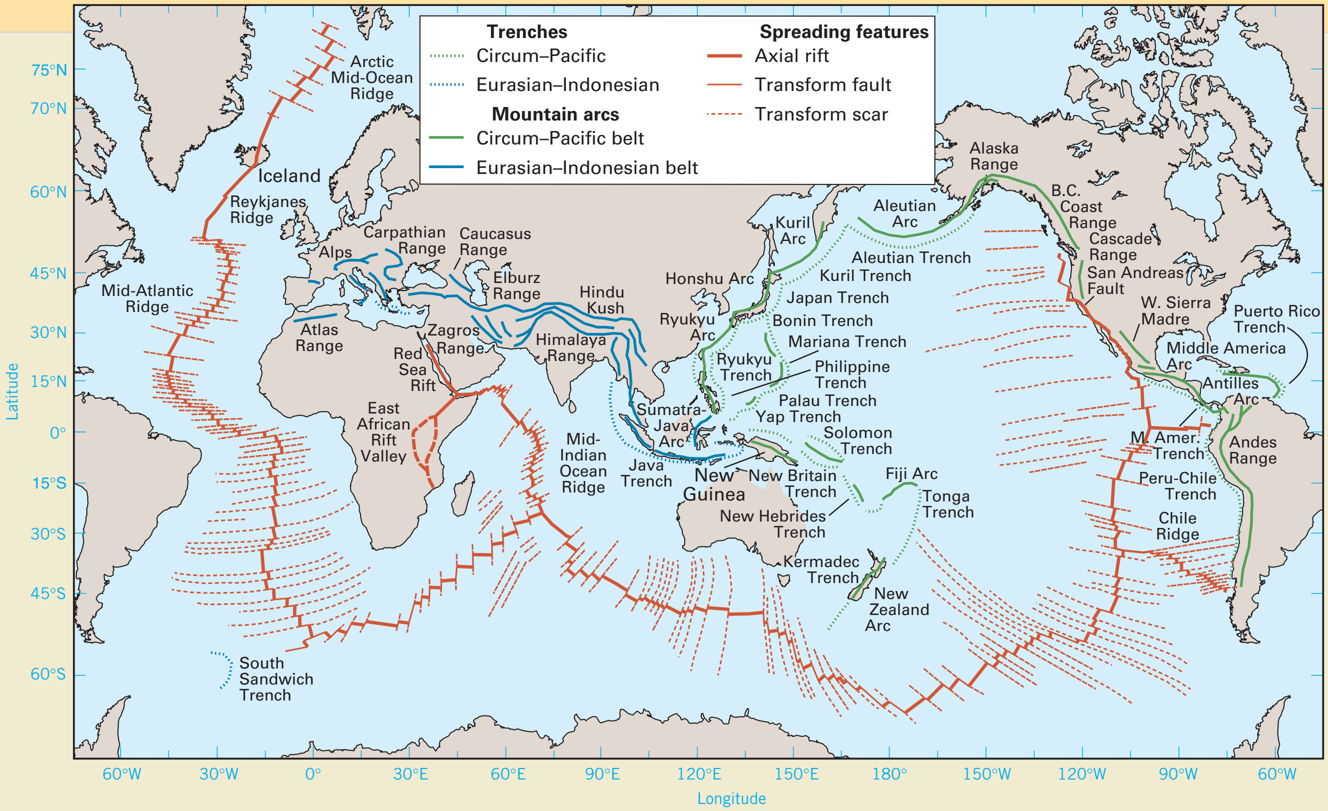


A Earthquake locations This world map plots earthquake center locations over a six-year period. Center locations of all earthquakes originating at depths of 0 to 100 km (62 mi) are shown by red dots. Each dot represents a single location or a cluster of centers. Black circles identify centers of earthquakes of Richter magnitude 8.0 or greater during an 80-year period.

FIGURE 9.20 is a map showing the centers of great earthquakes that occurred around the world in a six-year period. Strong pressures build up at the downward-slanting contact of colliding lithospheric plates, which are relieved by sudden fault slippages that generate earthquakes of large magnitude. This mechanism is responsible for the great earthquakes in Japan, Alaska, Central America, and Chile, and other narrow zones close to the trenches and volcanic arcs of the Pacific Ocean Basin.

On the Pacific coast of Mexico and Central America, the subduction boundary of the Cocos plate lies close to the shoreline. The great earthquake that devastated Mexico City in 1986 was centered in the deep trench offshore. Two great shocks in close succession, the first of magnitude 8.1 and the second of 7.5, damaged cities along the coasts of the Mexican states of Mĭchocoan and Guerrero. Although Mexico City lies inland about 300 km (about 185 mi) distant from the earthquake epicenters, it experienced intense ground shaking, killing some 10,000 people.

Transcurrent faults on transform boundaries that cut through the continental lithosphere cause moderate to strong earthquakes. The most familiar example of a transcurrent fault is the San Andreas fault, which we will look at in detail later. Another transcurrent fault often in the news is the North Anatolian fault in Turkey, where the Persian subplate is moving westward at its boundary with the European plate. A major earthquake occurred there on August 17, 1999, centered near the city of Izmit. It measured 7.4 on the Richter scale and killed more than 15,000 people. A few months later, a quake of magnitude 7.2 occurred not far away on the same fault, killing hundreds more. Central and south-



B 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.

east Turkey shook again on related faults in 2002 and 2003, with death tolls in the hundreds.

Spreading plate boundaries also produce seismic activity. Most of these boundaries are identified with the midoceanic ridge and its branches, and the earthquakes are moderate.

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. Large areas of land dropped and new lakes were formed.

EARTHQUAKES ALONG THE SAN ANDREAS FAULT

Just over a hundred years have passed since the great San Francisco earthquake of 1906, described in the chapter opener. That disaster was 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.

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 9.21). 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.

The displacement that caused the Loma Prieta earthquake occurred deep beneath the surface not far from the San Andreas fault, which has not slipped since the great San Francisco earthquake of 1906. The slippage on the Loma Prieta fault amounted to about 1.8 m (6 ft) horizontally and 1.2 m (4 ft) vertically, but did not break the ground surface above it. 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 San Andreas. 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.

We only need to look to Japan to see what the citizens of the San Francisco Bay area might face when a branch of the San Andreas fault lets go. The Hyogo-ken Nanbu earthquake that devastated the city of Kobe in January 1995 occurred on a short side branch of a major transcurrent fault quite similar tectonically to the San Andreas. Although Japan prides itself on being prepared for earthquakes, the Kobe catastrophe left 5000 dead and 300,000 homeless.

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. The second of these, the Landers earthquake, a powerful 7.5 on the Richter scale, occurred on a transcurrent fault trending north-

Earthquake damage in Oakland, California
FIGURE 9.21

This section of the double-decked Nimitz Freeway (Interstate 880) in Oakland, California, collapsed during the Loma Prieta earthquake, crushing at least 39 people in their cars.

northwest. It caused a 80-km (50-mi) rupture across the desert landscape. These three events have 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 close at hand. 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. Known as the Whittier Narrows earthquake, it was generated along a local fault system that had not previously shown significant seismic activity. 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. 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 local earthquakes, such as the Northridge or San Fernando earthquakes. On the other hand, the destructive effects of a San Andreas earthquake in downtown Los Angeles will be moderated by the greater travel distance. Although the intensity of ground shaking might not be much different from that of the San Fernando earthquake, for example, 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.

Tsunami Train of sea waves triggered by an earthquake (or other seafloor disturbance) traveling over the ocean surface.

SEISMIC SEA WAVES

Tsunamis, or seismic sea waves, are caused by major earthquakes centered on a subduction plate boundary. The sudden movement of the seafloor, near the earthquake source, generates a train of water waves. These waves travel over the ocean in ever-widening circles. We sometimes call seismic sea waves "tidal waves," but since they have nothing to do with tides, the name is quite misleading.

When a tsunami arrives at a distant 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 Sumatra. 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 9.22), killing thousands. As the wave moved down the Sumatran 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 nearby 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 water weighs about 1000 kg (65 lb/ft^3), the power of the water surge is enormous.

A Before the tsunami, Banda Aceh, Indonesia, seen from space on June 23, 2004, is a city of small buildings, parks, and trees.

B 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.

The Indian Ocean Tsunami of 2004 FIGURE 9.22

C This satellite image shows Kalutara Beach, Sri Lanka, seen before the Tsunami of 2004.

D 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.

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 to a 180-km (110-mi) stretch of the south coast of Java. The earthquake was detected by the Pacific Tsunami Warning Center in Hawaii, which issued a tsunami warning bulletin 24 minutes before the wave came ashore. But no local warning system was in place. About 1000 persons were killed or reported missing in the aftermath of the tsunami and earthquake.

CONCEPT CHECK **STOP**

What causes earthquakes?

What is a tsunami?

Landforms and Rock Structure

Learning Objectives

Explain how rock structure influences the shapes of landforms.

Describe the distinctive landforms of arid regions and coastal plains.

Explain how warped rock forms domes and hogbacks.

Define batholiths and monadnocks.

There is often a direct relationship between landforms and rock structure. Different types of rocks are worn down at different rates. Some are easily eroded, whereas others are much more resistant. For example, we usually find weak rocks under valleys, and strong rocks under hills, ridges, and uplands.

Over the world's vast land area, you'll see many types of rock and rock structures (Figure 9.23). Rock structure controls not only the locations of uplands and lowlands, but also the placement of streams and the shapes and heights of the intervening divides (Figure 9.24).

Landforms and rock structure Figure 9.23

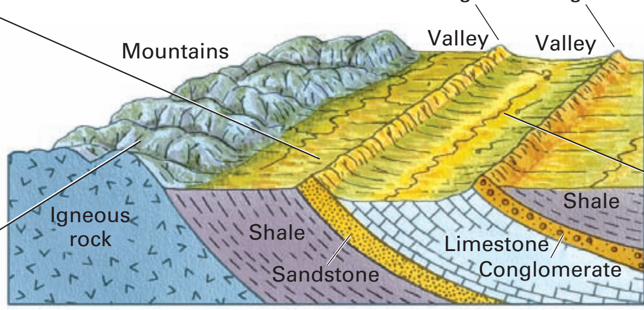
A Rapley monocline, Utah, shows an upwarp of rock layers with tilted beds cut in to flatiron shapes by erosion.

B 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.

C Sandstone formations of the Colorado front range are tilted upward and eroded to form hogback ridges.

Landforms and rock resistance FIGURE 9.24

Landforms evolve as weaker rock is slowly eroded, leaving the more resistant rock standing as ridges or mountains.



Shale is a weak rock that is easily eroded and forms the low valley floors of the region.

The igneous rocks are also resistant—typically forming uplands or mountains rising above adjacent areas of shale and limestone. Metamorphic rocks vary in resistance.

Limestone is dissolved by carbonic acid in rain and surface water, also forming valleys in humid climates. In arid climates, on the other hand, limestone is a resistant rock and usually stands high to form ridges and cliffs. Sandstone and conglomerate are typically resistant and form ridges or uplands.

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.

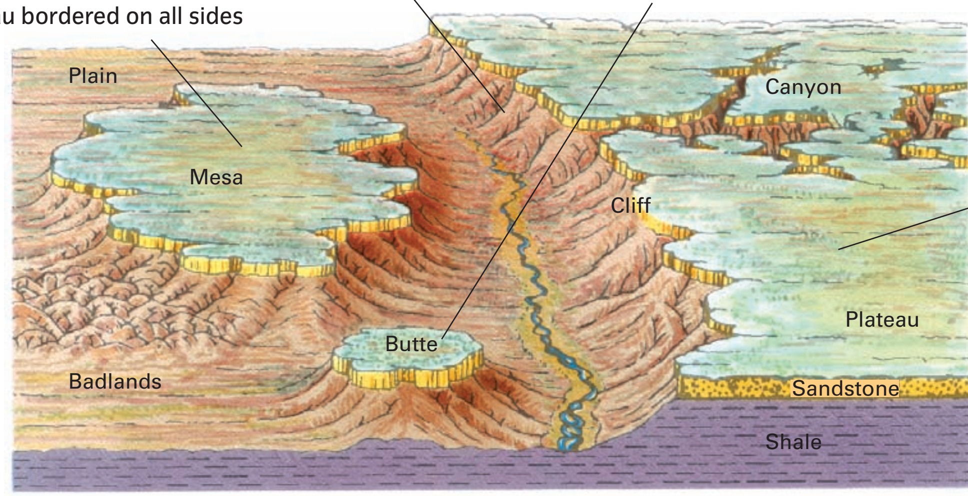
In arid climates, there isn't much vegetation to protect the ground, so overland flow is especially effective at sculpting landforms. FIGURE 9.25 describes how, over time, overland flow creates *plateaus*, *mesas*, and *buttes*.

Arid climate landforms FIGURE 9.25

When flat-lying rocks are eroted in an arid climate, we normally see a sheer rock wall, or cliff, at the edge of a resistant rock layer. At the base of the cliff is an inclined slope, which flattens out into a plain beyond.

Now undermined, the rock in the upper cliff face repeatedly breaks away along vertical fractures. Cliff retreat produces a *mesa*—a table-topped plateau bordered on all sides by cliffs.

As a mesa is reduced in area by retreat of the rimming cliffs, it maintains its flat top. Eventually, it becomes a small steep-sided hill known as a *butte*. Further erosion may produce a single, tall column before the landform is totally consumed.



Erosion strips away successive rock layers, leaving behind a broad platform, or *plateau*, capped by hard rock layers. As the weak clay or shale formations exposed at the cliff base are washed away, the cliffs retreat.

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. **FIGURE 9.26** shows how *consequent* and *subsequent streams* and *cuestas* develop on coastal plains over time. 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.

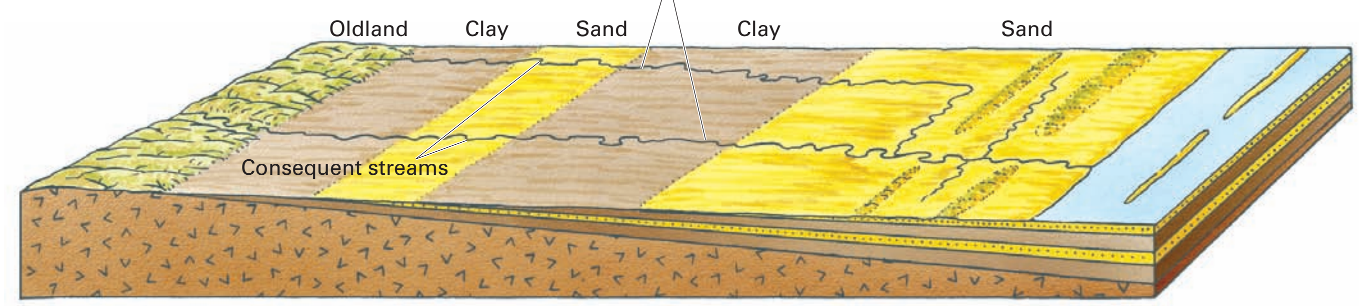
LANDFORMS OF WARPED ROCK LAYERS

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 had been crumpled and folded, forming anticlines and synclines.

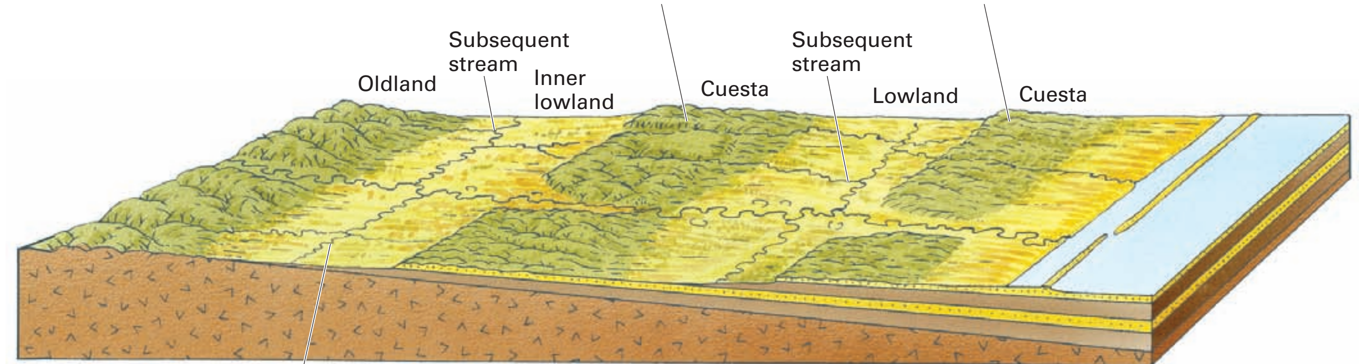
Development of a broad coastal plain FIGURE 9.26

The diagram shows a coastal zone that has recently emerged from beneath the sea, with layers of sediments.

A 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.



B 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.

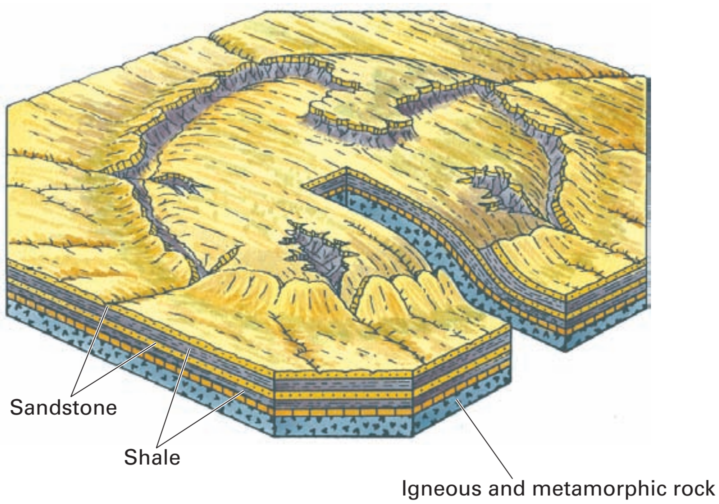


C *Subsequent streams* develop along the lowlands, parallel with the shoreline. They take their position along any belt or zone of weak rock and closely follow the pattern of rock exposure.

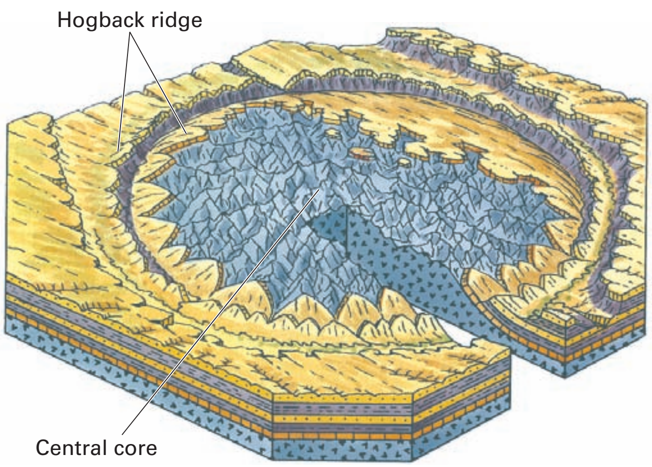
Another distinctive land-mass type is created when strata are forced upward into a dome. *Sedimentary domes* can be found in various places within the covered shield areas of the continents. We aren't sure what mechanism is responsible for each dome. Some may have been uplifted by intrusions of igneous rocks at great depths, whereas others may have been thrust upward on deep faults. FIGURE 9.27 shows how such domes are eroded over time to create *hogbacks*.

A classic example of a large and rather complex sedimentary dome is the Black Hills dome of western South Dakota and eastern Wyoming (FIGURE 9.27C). The eastern central part of the Black Hills is a mountainous core of intrusive and metamorphic rocks. 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

Dome erosion FIGURE 9.27

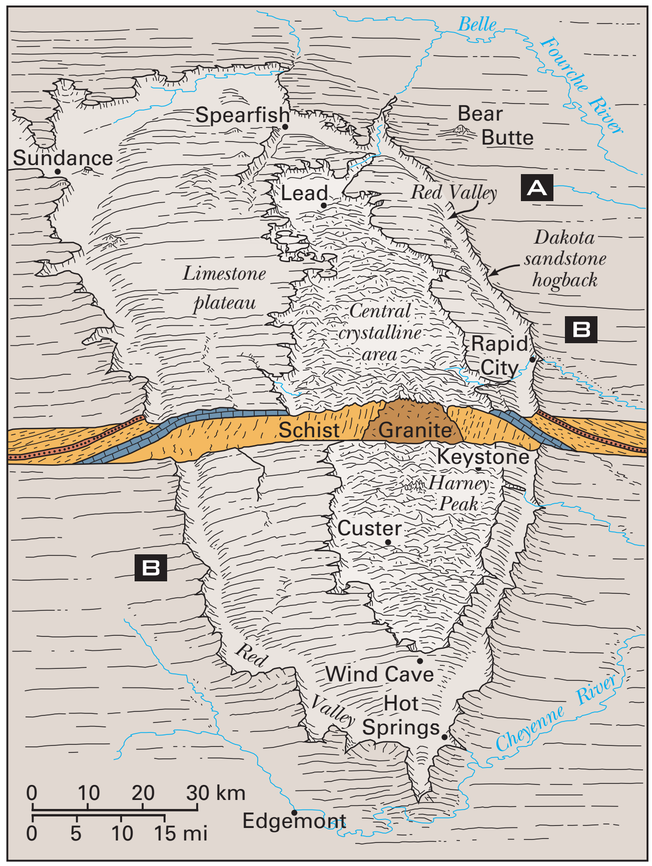


▲ The strata are partially eroded from the summit region of the dome, exposing older strata beneath. Eroded edges of steeply dipping strata form sharp-crested sawtooth ridges called hogbacks.



▲ When the last of the strata have been removed, the ancient shield rock is exposed in the central core of the dome, which then 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.

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.

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 continental collision, we'll still get a landscape with a strong grain of ridges and valleys. But these features won't be as sharp or as straight as the ridges and valleys produced in belts of open folds. Even so, the same principle that governs the development of ridges and valleys in open folds applies to metamorphic landscapes as well—namely, that resistant rocks form highlands and ridges, while weak rocks form lowlands and valleys. FIGURE 9.28 shows typical erosional forms associated with parallel belts of metamorphic rocks, such as schist, slate, quartzite, and marble.

Parts of New England, particularly the Taconic and Green Mountains of New Hampshire 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.

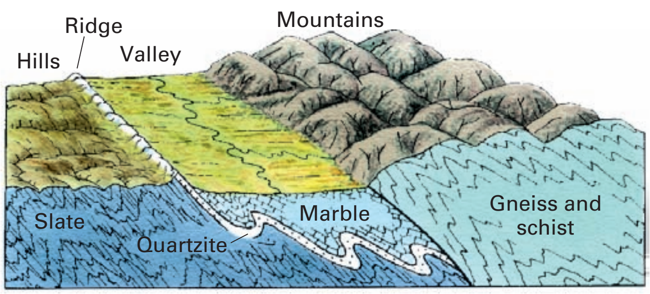
EXPOSED BATHOLITHS AND MONADNOCKS

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 lies below the ground. Such granite projections are often found surrounded by ancient metamorphic rocks into which the granite was intruded.

FIGURE 9.29 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.

Monadnock A mountain that rises out of a surrounding plain and that develops because it consists of more resistant rock than the bedrock of the surrounding region.



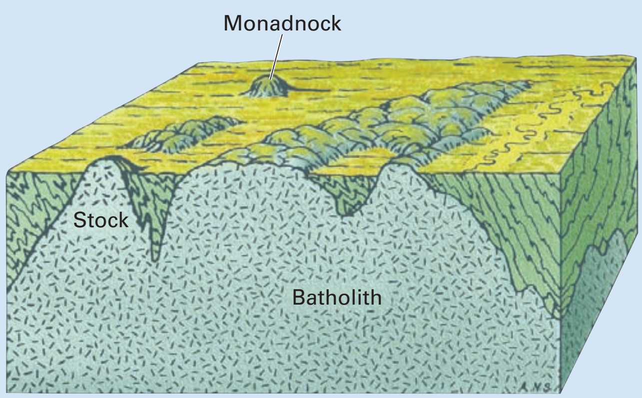
Metamorphic belts FIGURE 9.28

Marble forms valleys, while slate and schist make hill belts. Quartzite stands out boldly and may produce conspicuous narrow hogbacks. Areas of gneiss form highlands.

Batholiths and monadnocks FIGURE 9.29

A Sugar Loaf Mountain The monolithic rock dome of Sugar Loaf graces the harbor of Rio de Janiero, Brazil.

B Mount Monadnock The beautiful New Hampshire mountain for which all monadnocks are named.



C 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.

CONCEPT CHECK STOP

What landforms would you expect to see in an arid region?

What landforms might you expect to develop on a coastal plain?

With what types of features would you associate hogbacks?

What is a monadnock?

LANDFORM TYPES

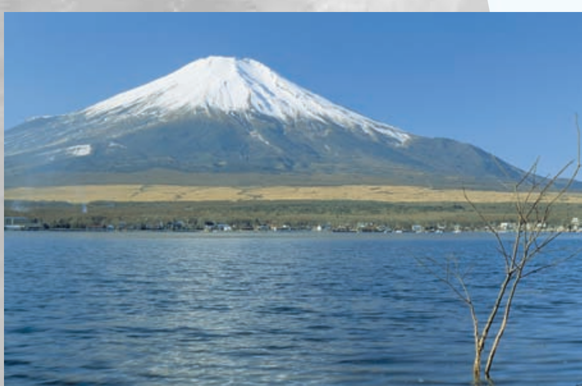
At the global scale, there are six major types of continental landforms. Plate collisions create mountain belts. Crustal uplift creates high plateaus and spreading creates widely spaced mountains. Crustal subsidence creates depressions. In stable regions, long–continued erosion yields low plateaus, hills, and plains. The global pattern of landforms is largely related to plate tectonic activity.

WIDELY SPACED MOUNTAINS Ranges of block mountains separated by wide valleys filled with mountain sediment. Found in regions of crustal uplift and stretching. Example: the Great Basin.

HIGH PLATEAUS Regions that are distinctly elevated above surrounding land. Slopes are gentle atop the plateau, although through–flowing rivers may carve steep canyons in high plateaus. Found in regions of crustal uplift. Example: the Colorado Plateau. The global pattern of landforms is largely related to plate tectonic activity.

PLAINS Gently sloping regions that have been eroded over long geologic time. Found in stable continental regions. Example: Great Plains and Coastal Plain.

MOUNTAINS Rocks lifted above the surrounding land by tectonic activity. Associated with active or former collisions of tectonic plates. Example: Andes Range.

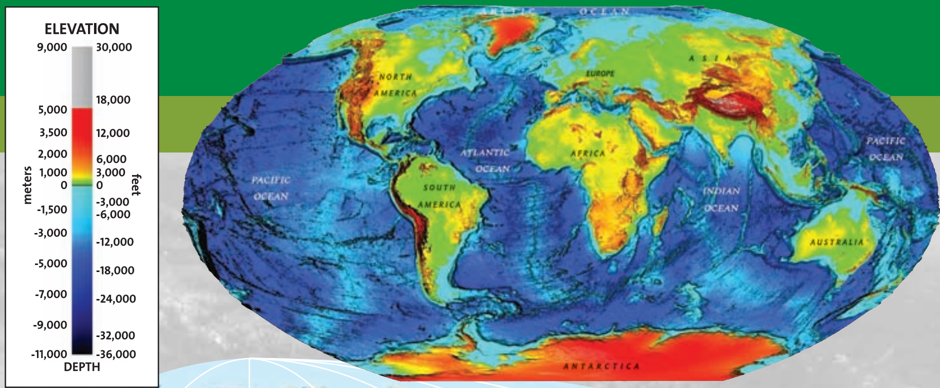


▲ **MOUNT FUJI** This famous stratovolcano, not far from Tokyo, Japan, is actually a composite of three separate cones. Volcanic activity is usually not far from a plate tectonic boundary.

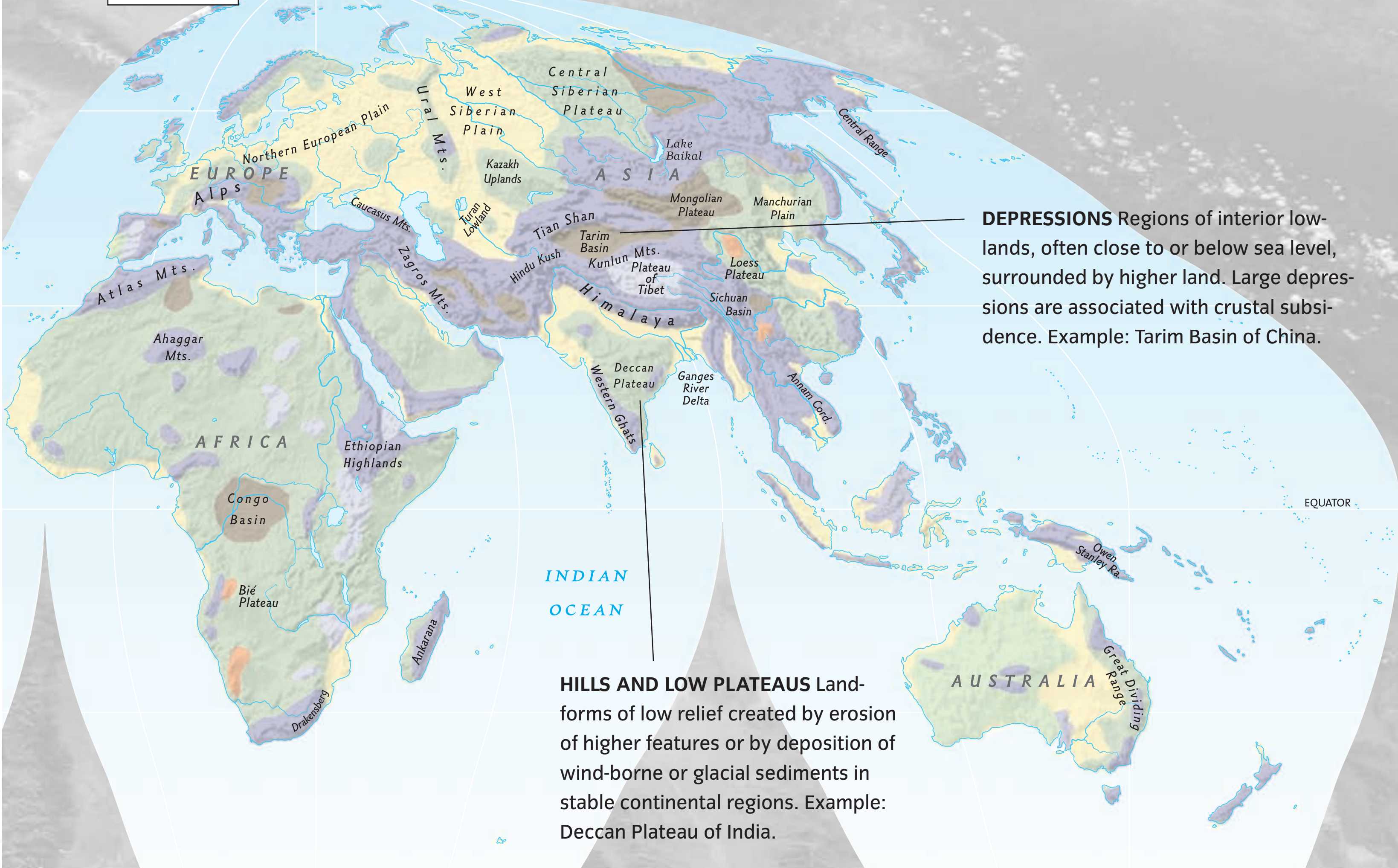
▲ **BASIN AND RANGE** The basin and range region of Utah and Nevada is marked by uplifted mountain blocks and intervening desert basins. Here the crust is arching up and spreading apart.

NATIONAL GEOGRAPHIC

Visualizing
Global Landforms

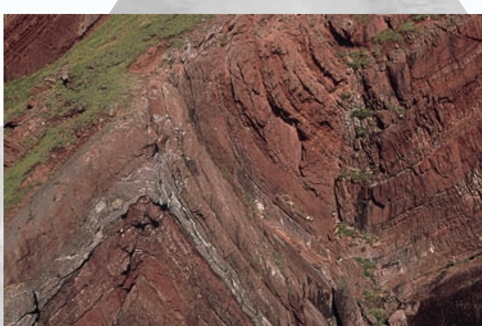


◀ **EARTH'S HIGHS AND LOWS** Continental crust stands out above ocean basins in this image of the Earth's topography. The broad pattern of mountain chains reflects the collision of tectonic plates. Continental interiors, subject to erosion over geologic time, are relatively flat.

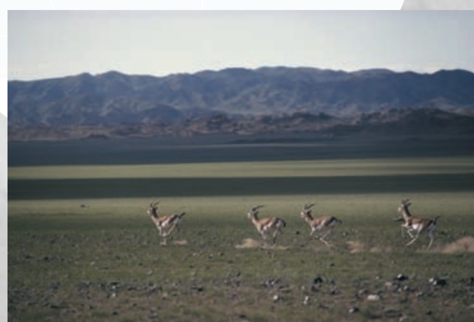


DEPRESSIONS Regions of interior lowlands, often close to or below sea level, surrounded by higher land. Large depressions are associated with crustal subsidence. Example: Tarim Basin of China.

HILLS AND LOW PLATEAUS Landforms of low relief created by erosion of higher features or by deposition of wind-borne or glacial sediments in stable continental regions. Example: Deccan Plateau of India.



▲ **ANTICLINE** This large up-arching bend of sedimentary rocks was formed in an ancient continent–continent collision.



▲ **TARIM BASIN** Tectonic activity has lowered this arid basin well below neighboring mountains and plateaus.

What is happening in this picture ?

- Few scenes in natural history are as awesome as the fire fountain of a volcanic eruption. Just imagine what it would be like to take this photo. As you near the fire fountain, you hear a deep rumbling. The heat gets stronger and stronger and the noise gets louder and louder. Donning your heat suit, helmet, and respirator, you inch toward the pyrotechnical display, your trusty camera in your heavily gloved hand. After a few quick snaps, a shower of heavy rocks lands nearby and you beat a hasty retreat. That was a lot more dangerous than you thought!
- This photo of turbulent magma on Mount Etna was taken by Carsten Peter, the famous National Geographic photographer. His volcano pictures, taken in locations all over the world, capture nature in its fiercest form.

VISUAL SUMMARY

1 Volcanic Landforms

1. 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.

2. Volcanoes are landforms marking the eruption of lava at the Earth's surface.

3. Stratovolcanoes have steep slopes and tend toward explosive eruptions that can form calderas. Most active stratovolcanoes lie along the Pacific Rim, where there's plate subduction. Stratovolcanoes produce lava flows that initially follow valleys but are highly resistant to erosion.

4. Hotspots form broadly rounded shield volcanoes. Hotspots beneath continental crust can also create flood basalts. Hawaiian shield volcanoes are eroded by streams that form deeply carved valleys with steeply sloping heads. Eventually, these merge to produce a landscape of steep slopes and knife-like ridges.

2 Tectonic Landforms

1. Compression occurs at lithospheric plate collisions. At first, the compression produces folding—anticlines (upfolds) and synclines (downfolds). If compression continues, folds may be overturned, creating overthrust faults.

2. Extension occurs where lithospheric plates are spreading apart, generating normal faults. Transcurrent faults occur where two rock masses move horizontally past each other.

3 Earthquakes

1. Earthquakes occur when rock layers, bent by tectonic activity, suddenly fracture and move. Most severe earthquakes occur near plate collision boundaries.

2. The San Andreas fault is a major transcurrent fault.

4 Landforms and Rock Structure

1. Because the various kinds of rocks differ in resistance to erosion, they influence the shapes of landforms.

2. In arid regions of horizontal strata, resistant rock layers produce vertical cliffs, plateaus, mesas, and buttes. On coastal plains, the more resistant rock layers stand out as cuestas.

3. Sedimentary domes and hogbacks are produced from warped rock layers.

4. Exposed batholiths are often composed of uniform, resistant igneous rock. Monadnocks of igneous rock stand up above a plain of weaker rocks.

KEY TERMS

- **volcano** p. 260
- **stratovolcano** p. 262
- **shield volcano** p. 264
- **folds** p. 270
- **anticline** p. 270
- **syncline** p. 270
- **fault** p. 272
- **earthquake** p. 277
- **tsunami** p. 281
- **monadnock** p. 288

CRITICAL AND CREATIVE THINKING QUESTIONS

1. What is the difference between initial and sequential landforms? How do they represent the balance of power between endogenic and exogenic processes?

2. What is a stratovolcano? What is its characteristic shape, and why does it have that shape? Where do stratovolcanoes generally occur and why?

3. How is a shield volcano distinguished from a stratovolcano? Describe the stages in the life cycle of a basaltic shield volcano of the Hawaiian type.

4. How does a transcurrent fault differ from a normal fault? What landforms are expected along a transcurrent fault? How are transcurrent faults related to plate tectonic movements?

5. What is an earthquake, and how does it arise? How are the locations of earthquakes related to plate tectonics?

6. Describe the tsunami, including its origin and effects.

7. Why is there often a direct relationship between landforms and rock structure? Which of the following types of rocks—shale, limestone, sandstone, conglomerate, igneous rocks, schist, slate, quartzite, marble, gneiss—tend to form lowlands? Uplands?

8. 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.

SELF-TEST

1. The ______________ of the magma present within a volcano primarily determines whether the volcano will erupt explosively or quietly.

a. temperature c. pressure
b. viscosity d. chemistry

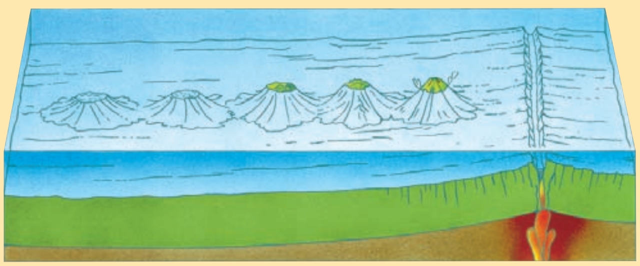
2. Occasionally, stratovolcanoes erupt so violently that the entire central portion of the volcano collapses into its empty magma chamber to form a large depression called a ______________.

a. caldera c. cinder cone
b. guyot d. batholith

3. Rapid mixing of volcanic ash and the water produced by the flash melting of ice and snow that has accumulated at the tops of erupting stratovolcanoes produces a deadly mud avalanche known as a ______________.

a. debris flow c. lahar
b. rock fall d. mudslide

4. The diagram shows a chain of Hawaiian volcanoes. Label the following features: (a) an active volcano, (b) a beveled island, (c) an extinct volcano, and (d) a guyot.



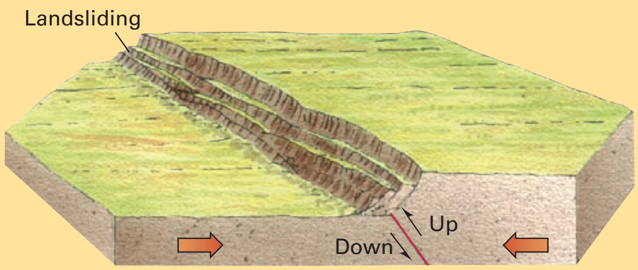
5. There are basically two different forms of tectonic activity. These are ______________.

a. compressional and extensional
b. stressful and decompressional
c. decompression and extensional
d. compressional and stressful

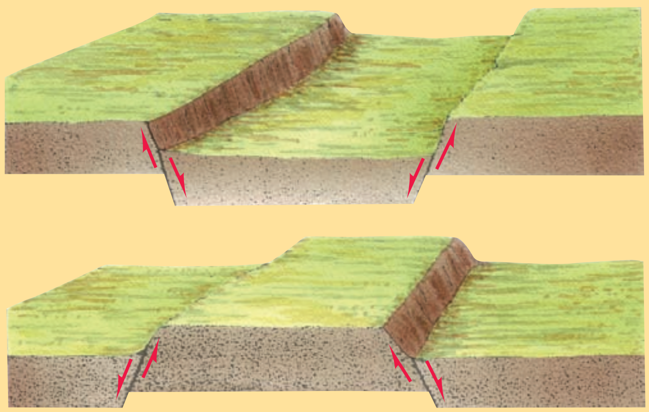
6. Compression leads to the folding of the crust, which results in the formation of ______________.

a. anticlines and synclines c. upfolds and troughs
b. synclines and troughs d. troughs and anticlines

7. Identify the type of fault shown in this diagram.



8. The diagram shows two initial landforms that can be created by normal faults. Identify each type.



9. ______________ faults result in crustal shortening produced by compression of the crust.

a. Normal c. Strike-slip
b. Transcurrent d. Reverse

10. The emanation point of the seismic waves released during an earthquake is called the ______________.

a. epicenter c. seismic front
b. fault surface d. focus

11. Cliff retreat produces a _______________, which is a table-topped plateau bordered on all sides by cliffs.

a. butte
b. promontory
c. plateau
d. mesa

12. A stream that flows directly seaward over a newly formed land surface is referred to as a _______________.

a. consequent stream
b. trellised stream
c. subsequent stream
d. braided stream

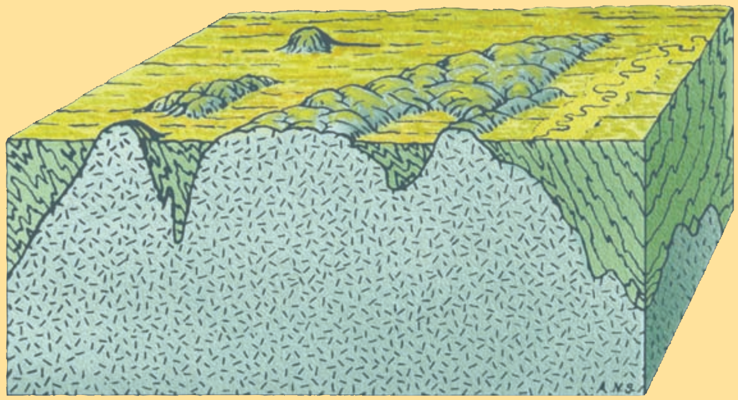
13. During an advanced stage of coastal-plain development, rapid denudation of weak strata like shale isolates broad belts of hills called _______________.

a. buttes
b. mesas
c. cuestas
d. plateaus

14. Which of the following descriptions best fits the sedimentary dome?

a. a circular structure in which strata have been forced upward
b. an oval structure in which strata have been tilted vertically
c. a circular-shaped structure with interleaving layers of shale and sandstone
d. an oval-shaped landform that inclines greatly from horizontal

15. The diagram shows a land surface feature that appears when sedimentary strata are eroded, exposing weather-resistant granite rock that lies underneath. Label the following features: (a) batholith, (b) monadnock, and (c) stock.



Weathering and Mass Wasting

10

For some 200 vacationers, including two female school teachers, a camping holiday in a deep canyon just downstream from Hebgen Lake, near Yellowstone National Park, on August 17, 1959, turned into the stuff of nightmares. That night not just one but four terrifying natural disasters were unleashed—earthquake, landslide, hurricane-force wind, and raging flood.

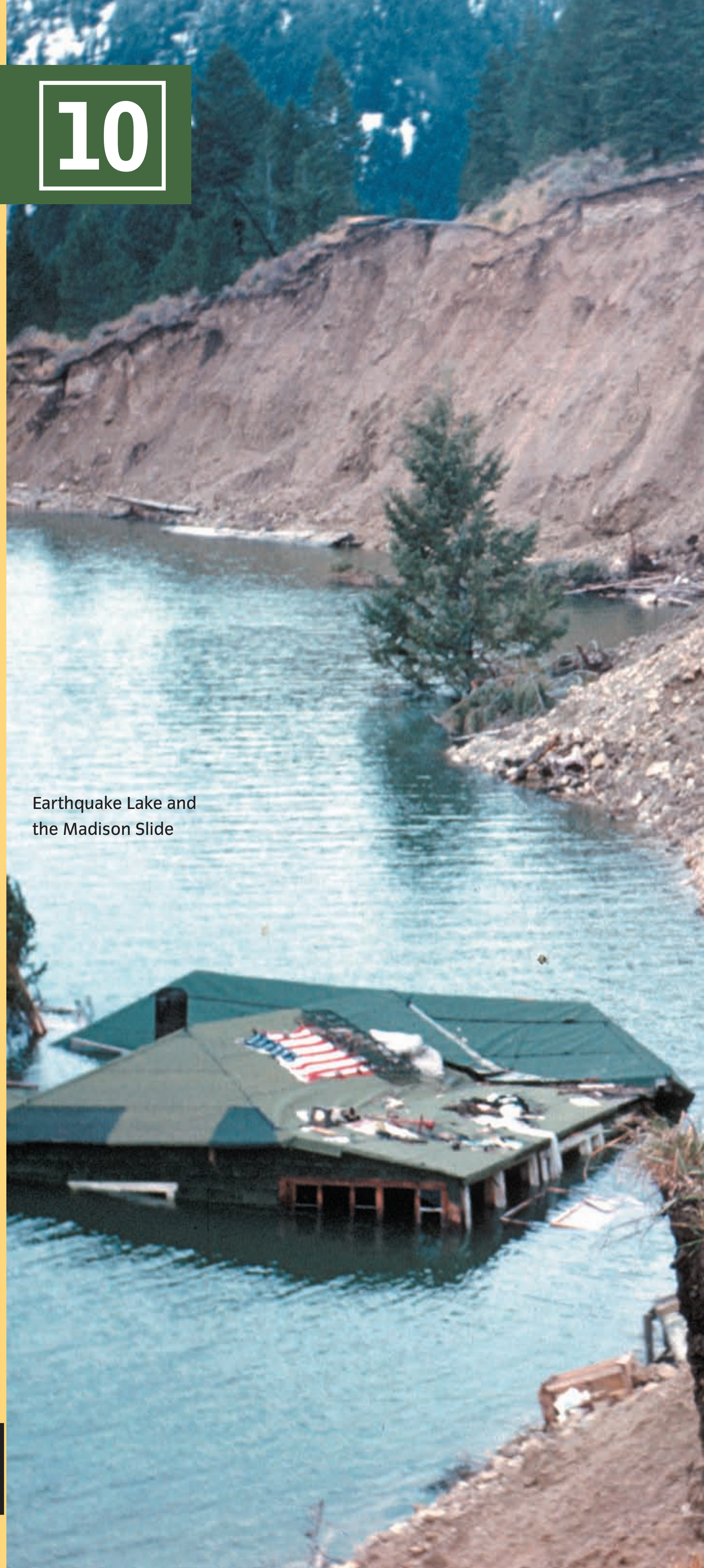
The catastrophe began with an earthquake, measuring 7.1 on the Richter scale. The schoolteachers, asleep in their car, described being awakened by violent shaking. Frightened, they started the engine and headed for higher ground.

The quake triggered a landslide. Other vacationers reported that the mountain seemed to move across the canyon, trees flying from its surface like toothpicks. This moving mountain pushed a vicious blast of wind that tumbled travel trailers.

As the landslide mass hit the river, it generated a wall of water. The schoolteachers heard a great roar from the mountainside above and behind them, and an instant later, their car was engulfed by a surging wall that then quickly drained back. As the two women struggled to drive the car to safe ground, other campers were drowning. At least 26 people died beneath the Madison Slide.

The huge earth movement consisted of 28 million m^3 (37 million yd^3) of rock, over 600 m (about 2000 ft) in length and 300 m (about 1000 ft) in thickness. It descended at 160 km (100 mi) per hour. The slide acted as a huge dam, creating a new lake, nearly 100 m (330 ft) deep. Today it is called Earthquake Lake.

Huge mass movements, such as this, begin with weathering processes that break rocks apart or alter their mineral composition. Mass wasting can also create distinctive landforms in less dramatic ways.



Earthquake Lake and the Madison Slide

CHAPTER OUTLINE

■ Weathering p. 298

■ Mass Wasting p. 304

■ Processes and Landforms of Arctic and Alpine Tundra p. 314

Weathering

LEARNING OBJECTIVES

Define weathering.

Explain the difference between physical and chemical weathering.

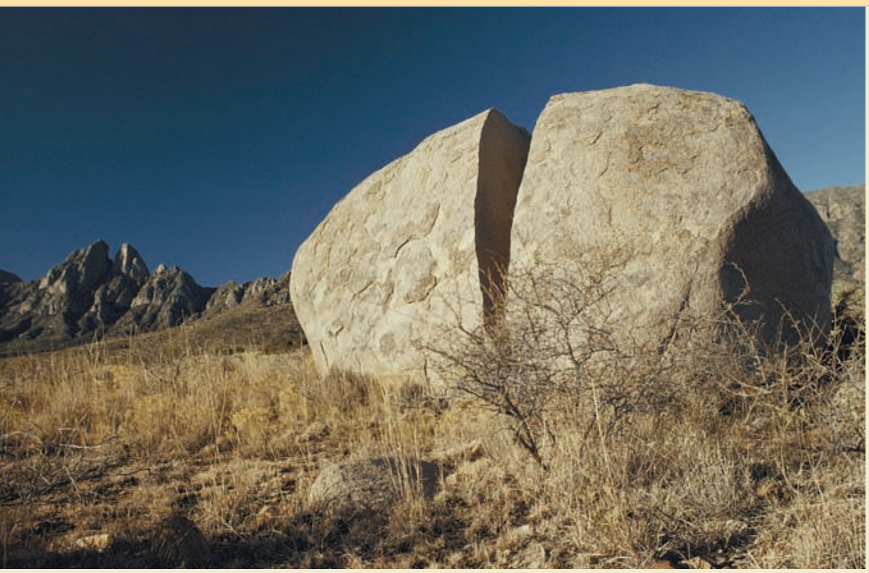
Describe examples of weathering.

So far we've been looking at the Earth's crust—its mineral composition, its lithospheric plates, and its landforms. Now let's examine the shallow surface layer in which life exists. We'll look first at weathering—how rocks are softened and how they break up. Later, we'll see how the resulting particles move downhill under the force of gravity, in a process called mass wasting.

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 miner-

Weathering All the processes that physically disrupt or chemically decompose a rock at or near the Earth's surface.

Frost action FIGURE 10.1



A Frost cracking Repeated growth of ice crystals in cracks during freeze-thaw cycles can crack open rocks. This frost-riven boulder is in the San Andres Mountains of New Mexico.

B 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.

Regolith Layer of mineral particles that lies above bedrock.

als are transformed from types that were stable when the rocks were formed to types that are now stable at surface temperatures and pressures. Weathering produces **regolith**—a surface layer of weathered rock particles that lies above solid, unaltered rock—and also creates a number of distinctive landforms.

PHYSICAL WEATHERING

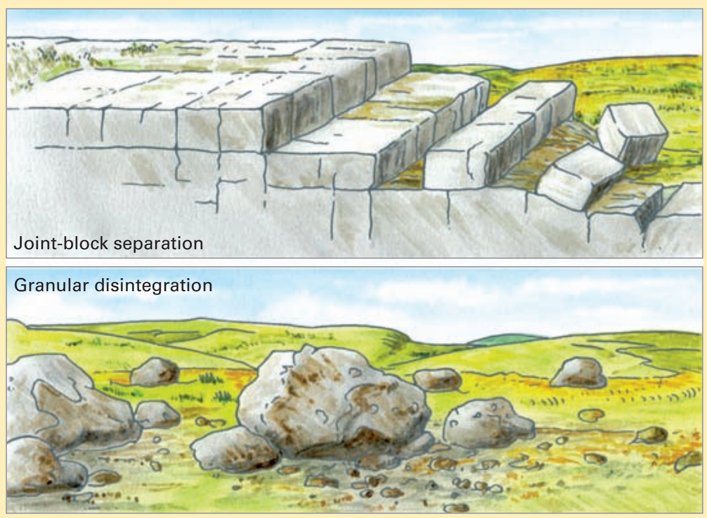
Physical weathering Breakup of massive rock (bedrock) by physical forces at or near the Earth's surface.

Physical weathering, or mechanical weathering, fractures rock, producing regolith. One of the most important physical weathering processes in cold climates is *frost action* (FIGURE 10.1). 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 firsthand. This expansion can fragment even extremely hard rocks, as water left in the pore spaces of soil and rocks freezes and thaws repeatedly.

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 weak surfaces (FIGURE 10.2). Water also invades sedimentary rocks along their stratification planes, or bedding planes. Joints often cut bedding planes at right angles, and relatively weak stresses will separate 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 a cycle of freezing and thawing show the effects of frost action. Frost action is a dominant process in arctic and high-mountain tundra environments.

C Talus slopes In high mountains, frost action on cliffs detaches fragments of rock that fall to the cliff base. These loose fragments are called *talus*. Fresh talus slopes are unstable. Walking across the slope or dropping a large rock fragment from the cliff above will disturb the cone and trigger the surface layer fragments to slide or roll down. Bow Lake, Banff National Park, Alberta, Canada.



Bedrock disintegration FIGURE 10.2

Joint-block separation and granular disintegration are two common forms of bedrock disintegration.

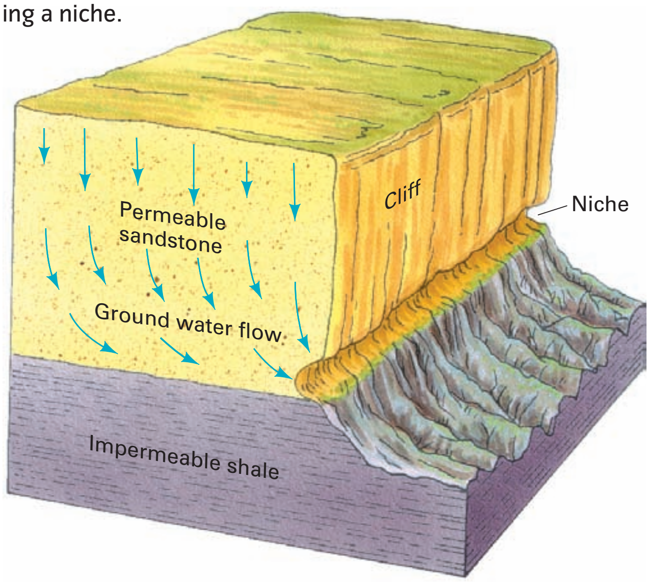
A similar weathering process occurs in dry climates. *Salt-crystal growth* in rock pores can disintegrate rock, and this process carves out many of the niches, shallow caves, rock arches, and pits seen in sandstones of arid regions. During long drought periods, ground water moves to the rock surface 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 tiny salt crystals behind. Over time, the force of these growing crystals breaks the sandstone apart, grain by grain.

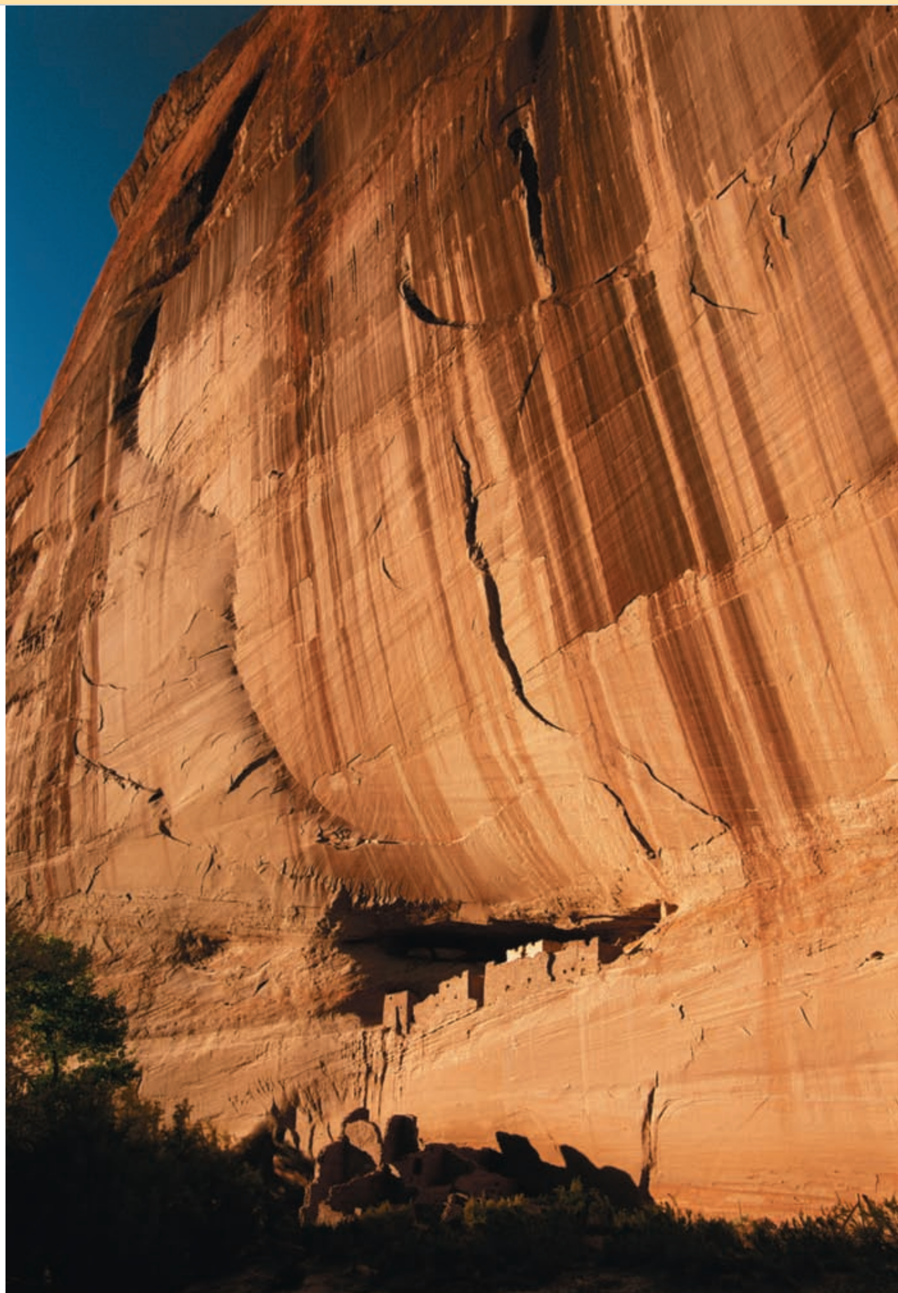
Rock at the base of cliffs is especially susceptible to salt-crystal growth (FIGURE 10.3). Salt crystallization also damages masonry buildings, concrete sidewalks, and streets. Salt-crystal growth occurs naturally in arid and semiarid regions, but in humid climates, rainfall dissolves salts and carries them downward to ground water.

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 that are more or less parallel to the surface, creating a type of jointing called *sheeting structure*. In massive rocks like granite or marble, thick curved layers or shells of rock peel free from the parent mass below, much like the layers of an onion (FIGURE 10.4).

Salt-crystal growth FIGURE 10.3

A 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.





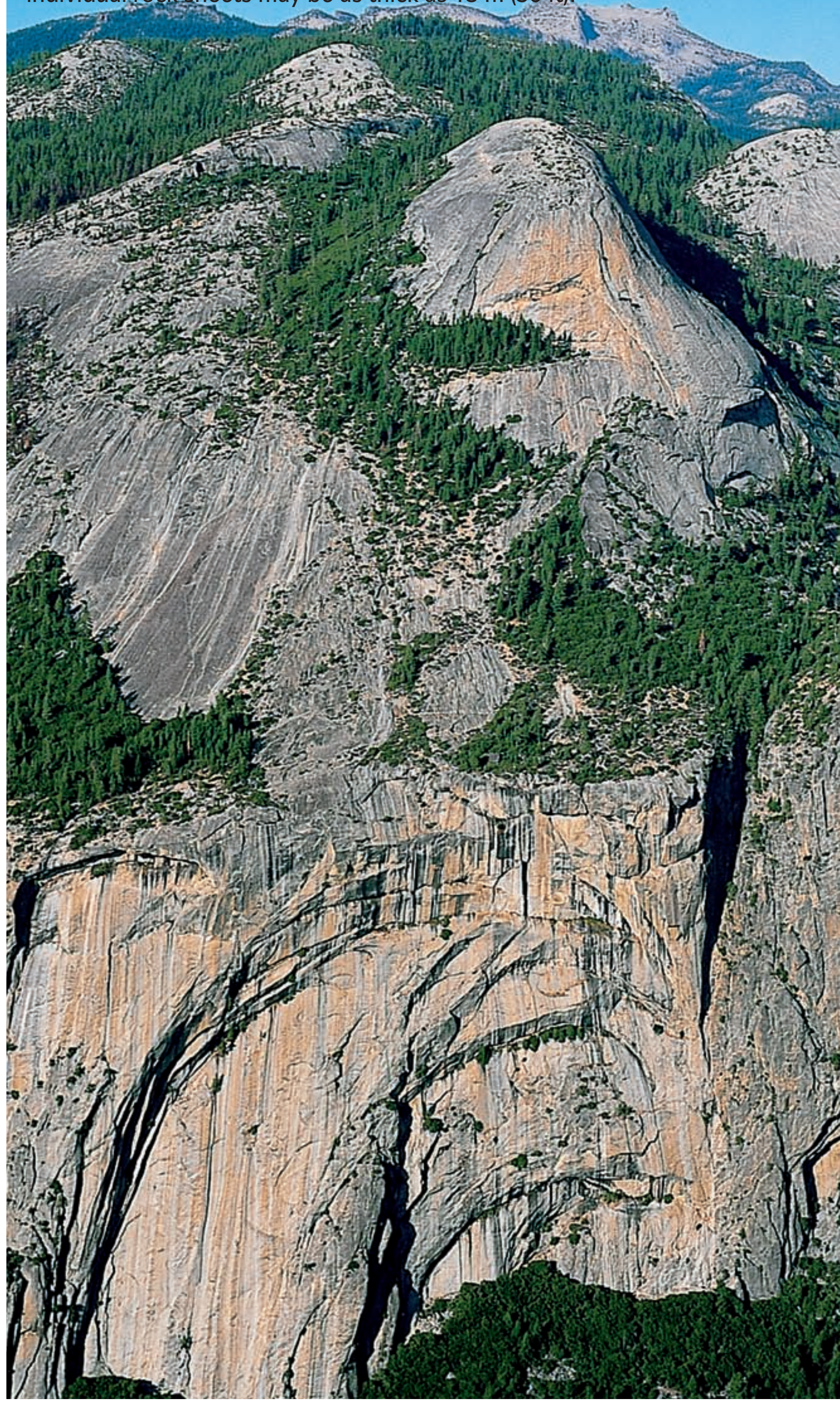
B Cliff dwellings Many of the deep niches or cavelike recesses formed in this way in the southwestern United States were occupied by Native Americans. Their cliff dwellings gave them protection from the elements and safety from armed attack. This is the White House Ruin, a large niche in sandstone in the lower wall of Canyon de Chelly, Arizona.

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 powerful 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.

C 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 apart the sand grains. This breaks off the rock close to the ground, leaving less-weathered rock above perched on an eroding pillar. Nubian sandstone, Karnasai Valley, Chad.

Exfoliation domes FIGURE 10.4

When sheeting structure forms over the top of a single large knob or hill of massive rock, an exfoliation dome is produced. The sheeting structure of these exfoliation domes is visible in the lower part of the photo of North Dome and Royal Arches in Yosemite National Park, California. Here successive shells of rock have fallen away. Domes are among the largest of the landforms shaped by weathering. In Yosemite Valley, where domes are spectacularly displayed, individual rock sheets may be as thick as 15 m (50 ft).



CHEMICAL WEATHERING AND ITS LANDFORMS

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.

Chemical reactions proceed more rapidly at warmer temperatures, so **chemical weathering** is most effective in 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 330 ft). The decayed rock material is soft, clay-rich, and easily eroded. In dry climates, hydrolysis weathers exposed granite, producing many interesting boulder and pinnacle forms (FIGURE 10.5).

Chemical weathering
Chemical change in rock minerals through exposure to the atmosphere and water.

Carbonic acid—a weak acid that is formed when carbon dioxide dissolves in water—also weathers rocks. It is often found in rainwater, soil water, and stream water, and 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 10.6). Soil acids also rapidly dissolve basaltic lava in the wet low-latitude climates (see “What a Geographer Sees: Solution Weathering of Basalt”).

Granular disintegration of granite FIGURE 10.5

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 weathering of tombstones FIGURE 10.6

A These weathered tombstones are from a burying ground in Massachusetts. This marker is carved in marble. It has been strongly weathered, weakening the lettering.

B 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.

What a Geographer Sees

Solution weathering of basalt

This photograph from the Napali coast, Kauai, Hawaii, shows spectacular grooves, fins, and spires on the walls of deep alcoves in part of the Hawaiian Islands. A geographer would recognize that this is the handiwork of chemical weathering, which has eroded the rock. Soil acids in warm and humid climates rapidly dissolve mafic rock, particularly basaltic lava. Carbonic acid can produce similar features in limestone in moist midlatitude climates. What else would a geographer see?

CONCEPT CHECK STOP

Name three physical weathering processes.

What is chemical weathering?

Mass Wasting

Learning Objectives

Define mass wasting.

Describe soil creep, earthflow, mudflows, and landslides.

Explain induced 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. Bedrock is usually so strong and well supported that it remains fixed in place. But when a mountain slope becomes too steep, bedrock masses can break free and fall or slide to new positions of rest. 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

Processes and forms of mass wasting Figure 10.7

Mass wasting processes and the landforms they produce are extremely varied and grade one into another. We've selected only a few of the most important forms of mass wasting here, categorized according to the water content of the material and the speed of motion that occurs.

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form of **mass wasting**—the spontaneous downhill movement of soil, regolith, and rock caused by gravity.

Because soil, regolith, and many forms of sediment are poorly held together, they are much easier to move than hard, massive bedrock. On most slopes, gravity almost always makes at least a small amount of rock move downhill. This motion is slow and unnoticeable, but sometimes regolith slides or flows rapidly (FIGURE 10.7).

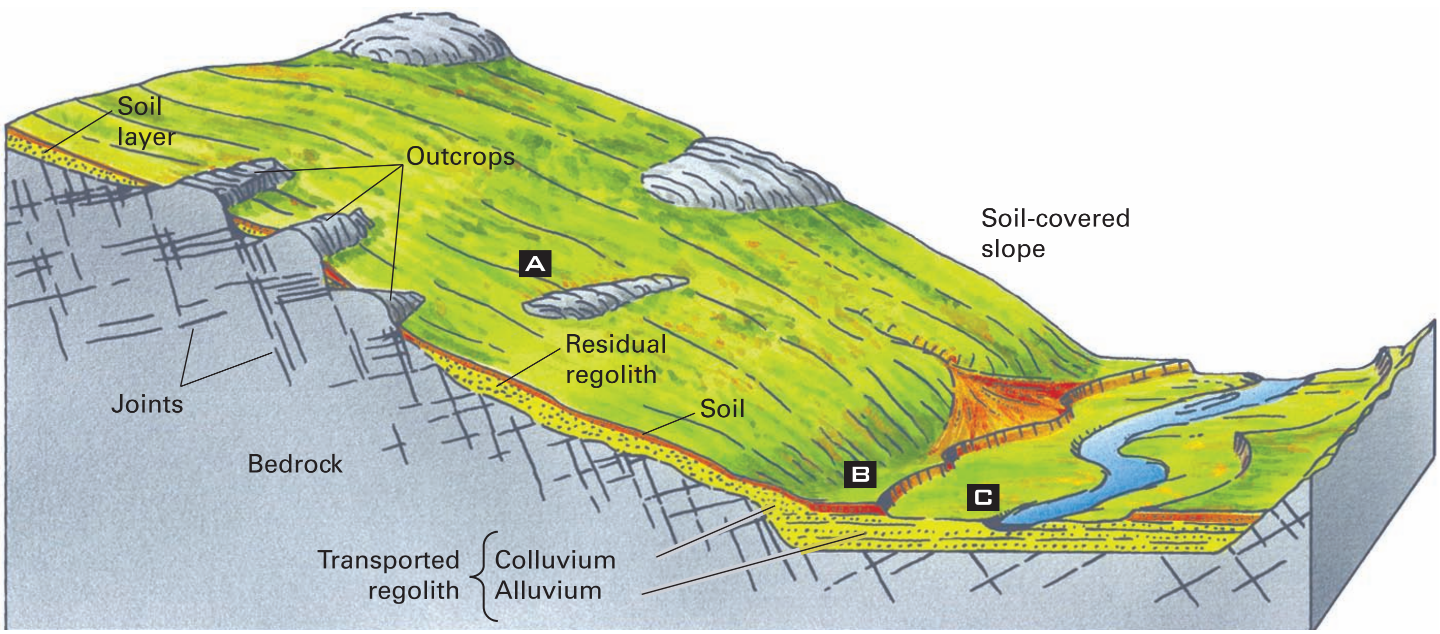
Mass wasting Spontaneous downhill movement of soil, regolith, and bedrock under the influence of gravity.

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. Regolith makes up that sediment, while the fluids can be water, air, or even glacial ice. Regolith and sediment are the parent materials of soil. FIGURE 10.8 shows a typical hill slope that forms one wall of the valley of a small stream.

Bedrock Solid rock layer under soil and regolith, which is relatively unchanged by weathering.



Soil, regolith, and outcrops on a hill slope FIGURE 10.8

A Soil and regolith blanket the bedrock, except in a few places where the bedrock is particularly hard and projects in the form of outcrops.

B Residual regolith, which broke off from the rock beneath, moves very slowly down the slope toward the stream and accumulates at the foot of a slope. This accumulation is called *colluvium*.

C Layers of sediment are also transported by the stream and lie beneath the valley bottom. This sediment, called *alluvium*, came from regolith on hill slopes many kilometers or miles upstream.

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 10.9).

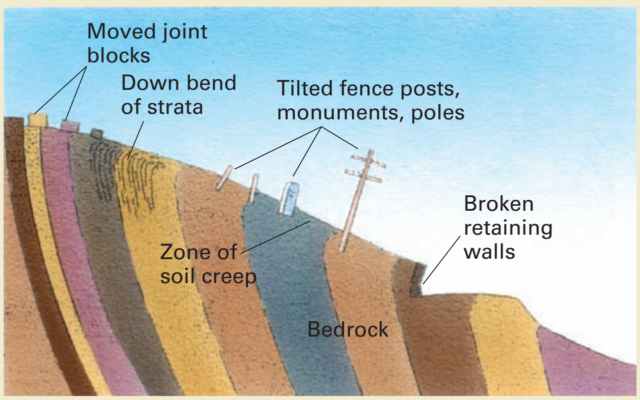
In humid climates, water-saturated soil, regolith, or weak shale can move down a steep slope in just a few hours. This is an **earthflow**, (FIGURE 10.10). It's common to see shallow earthflows, affecting only the soil and regolith, on sod-covered and forested slopes that have been saturated by heavy 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.

Soil creep Extremely slow downhill movement of soil and regolith.

Earthflow Moderately rapid downhill flow of water-saturated soil, regolith, or weak shale.

During heavy rains, earthflows can block highways and railroad lines. Flows aren't usually a threat to life because they move quite slowly, but they can often severely damage buildings, pavements, and utility lines that have been constructed on unstable slopes.

Soil creep FIGURE 10.9



▲ The slow, downhill creep of soil and regolith shows up in many ways on a hillside. Joint blocks of distinctive rock types are 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.

Earthflow FIGURE 10.10

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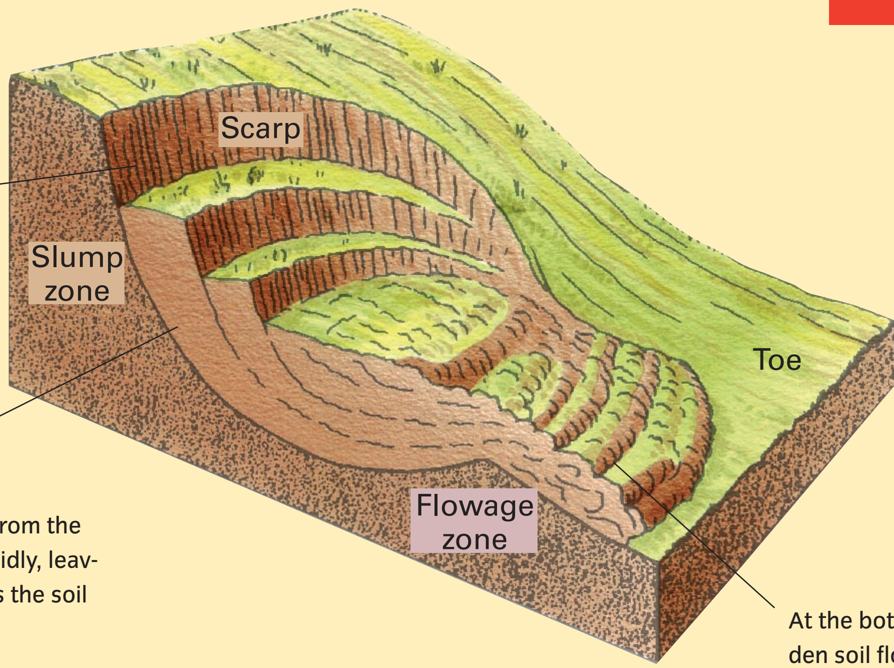


At the top, the material slumps away, leaving a curved, wall-like scarp.

Often the soil farther from the scarp moves more rapidly, leaving a series of steps as the soil mass slips downward.

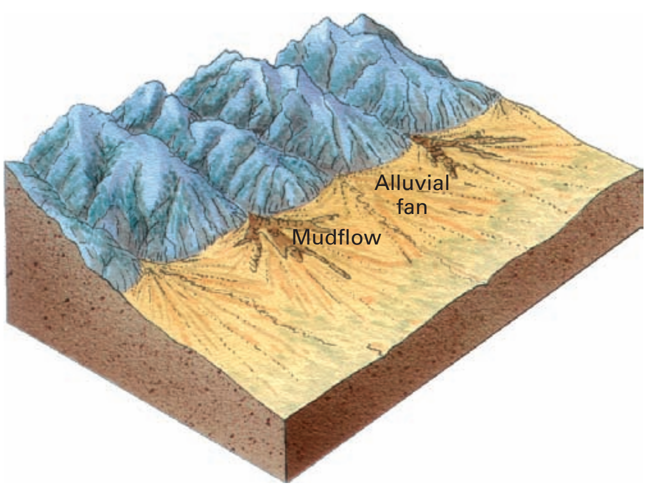
At the bottom, the sodden soil flows in a sluggish mass that piles up in ridges or lobes to form a bulging toe.

Nicolet earthflow An earthflow in Nicolet, Quebec, in 1955 carried much of the town into the Nicolet River. Fortunately, only three lives were lost, but the damage to buildings and a bridge ran into millions of dollars.

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 10.11). 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 on 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.

Mudflow Flowing mixture of water and soil or regolith that flows rapidly downhill.



Mudflows in an arid environment
FIGURE 10.11

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.

Mudflow FIGURE 10.12

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.

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 10.12). 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 10.13) 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 eastern United States often causes debris avalanches in the hollows and valleys of the Blue Ridge and Smoky Mountains.

Debris flow FIGURE 10.13

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.

LANDSLIDE

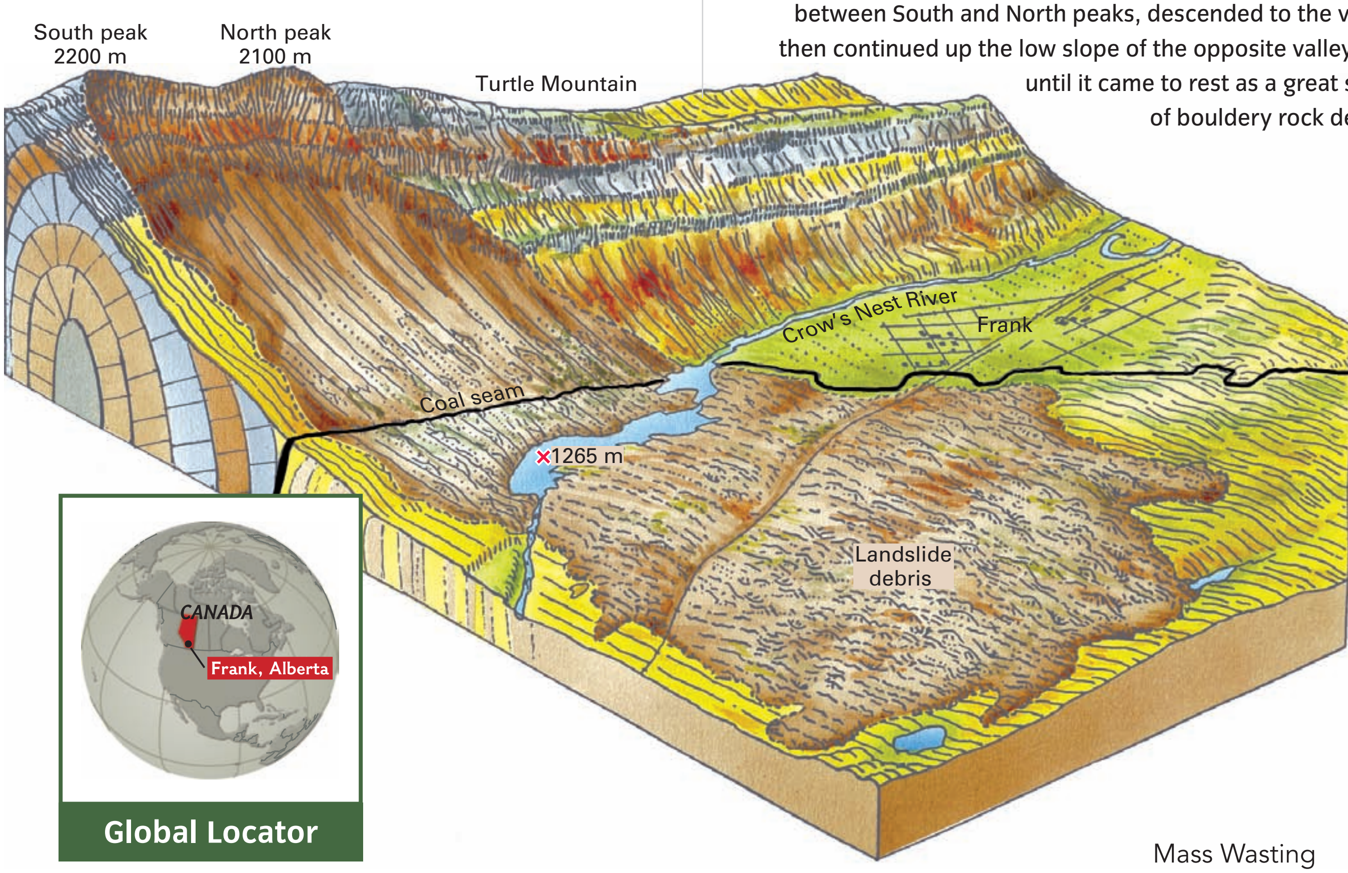
A large mass of bedrock or regolith sliding downhill is known as a **landslide**. Large, disastrous landslides are possible wherever mountain slopes are steep (FIGURE 10.14). In Switzerland, Norway, or the Canadian Rockies, for example, villages built on the floors of steep-sided valleys have been destroyed when millions of cubic meters of rock descended without warning.

Landslide Rapid sliding of large masses of bedrock on steep mountain slopes or from high cliffs.

Unlike mudflows and earthflows, which are triggered by heavy rain, landslides are set off by earthquakes or sudden rock failures. 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

The Turtle Mountain slide FIGURE 10.14

A classic example of an enormous, disastrous landslide is the Turtle Mountain slide, which took place near Frank, Alberta. 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.



which most of the bedrock remains more or less intact as it moves. 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 with the lower surface, so the rubble can move faster.

Severe earthquakes in mountainous regions are a major cause of landslides (FIGURE 10.15). Aside from occasional local catastrophes, landslides don't have much influence on the environment. They don't occur very often, and when they do, they usually affect thinly populated mountainous regions. Small slides can, however, repeatedly block or break important mountain highways or railway lines.

Santa Tecla landslide FIGURE 10.15

On January 13, 2001, an earthquake measuring 7.6 on the Richter scale triggered a landslide, 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 Santa Tecla, El Salvador. 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.

Global Locator

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 far down the canyon floors and spread out, burying streets and houses in mud and boulders. FIGURE 10.16 shows an example of induced mass wasting in the Palos Verdes Hills of Los Angeles, California.

Induced earthflow FIGURE 10.16

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 flow. Over 115,000 liters (about 30,000 gallons) of water were discharged per day from some 150 homes. This is thought to have weakened the clay layer enough to start and sustain the flowage.

Strip mining FIGURE 10.17

A 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.

B Earth-moving equipment Huge power shovels and trucks move coal and overburden. This giant truck is filled with coal at a Montana strip mine.

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 10.17 describes the problems 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.

CONCEPT CHECK STOP

What is soil creep?

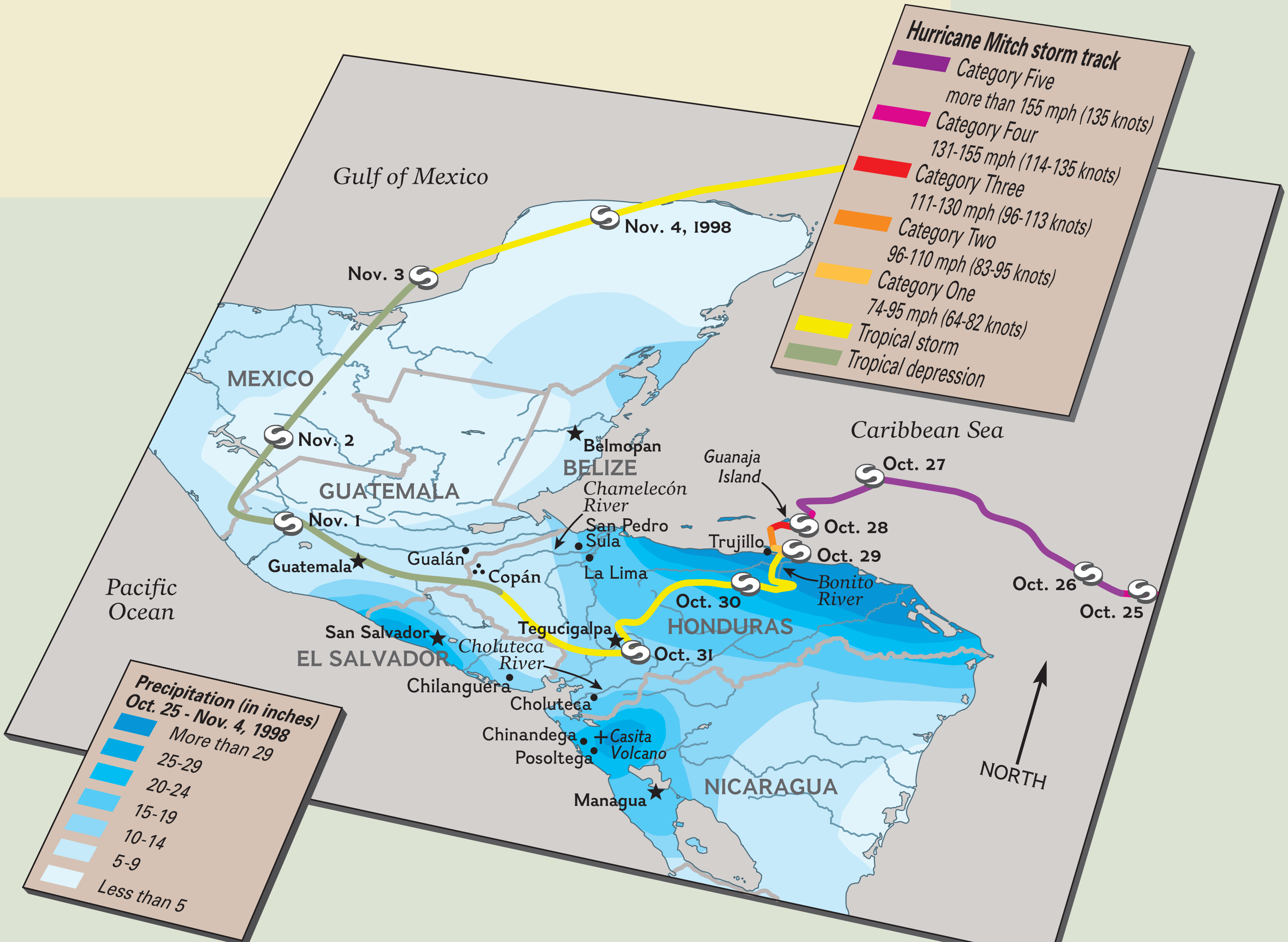
What is the difference between an earthflow and a mudflow?

What is a landslide?

Describe two ways in which human activity can induce mass wasting.

HURRICANE AFTERMATH: MASS WASTING

Rare but intense hurricanes can shed huge volumes of water on landscapes of weathered soils and rock, bringing debris avalanches and mudslides to upland and mountainous regions.



▲ **HURRICANE MITCH**

One of the strongest hurricanes ever recorded, Hurricane Mitch was a Category Five storm as it hit the northern coast of Honduras in October 1998. Slowing to a crawl, the storm spent the better part of a week wandering across the Central American peninsula, dumping huge amounts of rain on high-elevation slopes.

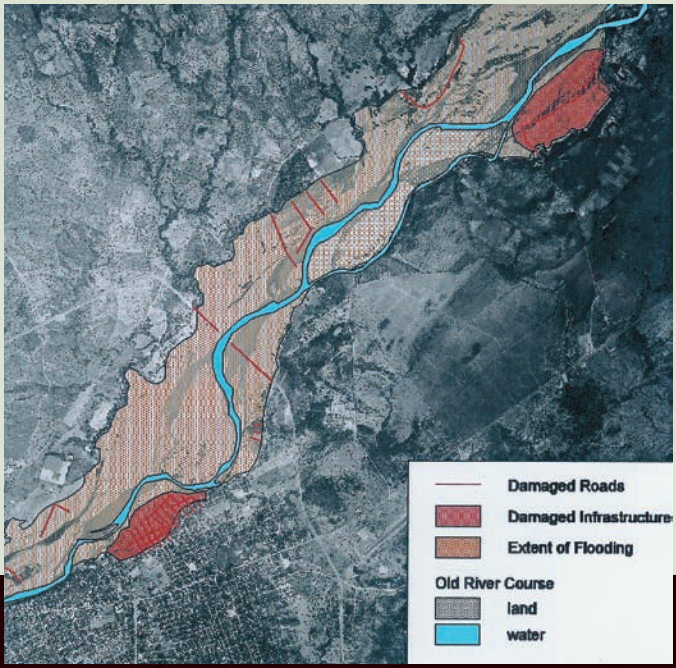
NATIONAL GEOGRAPHIC

Visualizing

Mass Wasting—After the Deluge

◀ **CASITA VOLCANO DEBRIS AVALANCE**
The worst single event of many to hit Honduras during Mitch was the Casita volcano debris avalanche. A huge section of the volcano's slope descended onto lowlands below in a matter of minutes, sending a wall of soil, rocks, trees, and water into the towns of Rolando Rogríguez and El Porvenir. In all, about 2000 people died.

▶ **EARTHFLOW IN TEGUCIGALPA**
Its soil saturated by Mitch's deluge, an entire neighborhood in Tegucigalpa flowed downhill, blocking the Choluteca River. Houses shattered and collapsed as they descended on a tide of mud and rocks.



◀ **CHOLUTECA RIVER SEDIMENT**
Filling its floodplain from bank to bank, the Choluteca River buried part of the city of Choluteca and much of its rich agricultural lands in sterile sand, mud, and stones. At some locations the river changed its course completely, leaving its bridges to cross new land instead of water.

Processes and Landforms of Arctic and Alpine Tundra

LEARNING OBJECTIVES

Define permafrost.

Describe ice wedges and pingos and explain how they form.

Discuss the environmental problems of permafrost.

Describe the causes of patterned ground and solifluction.

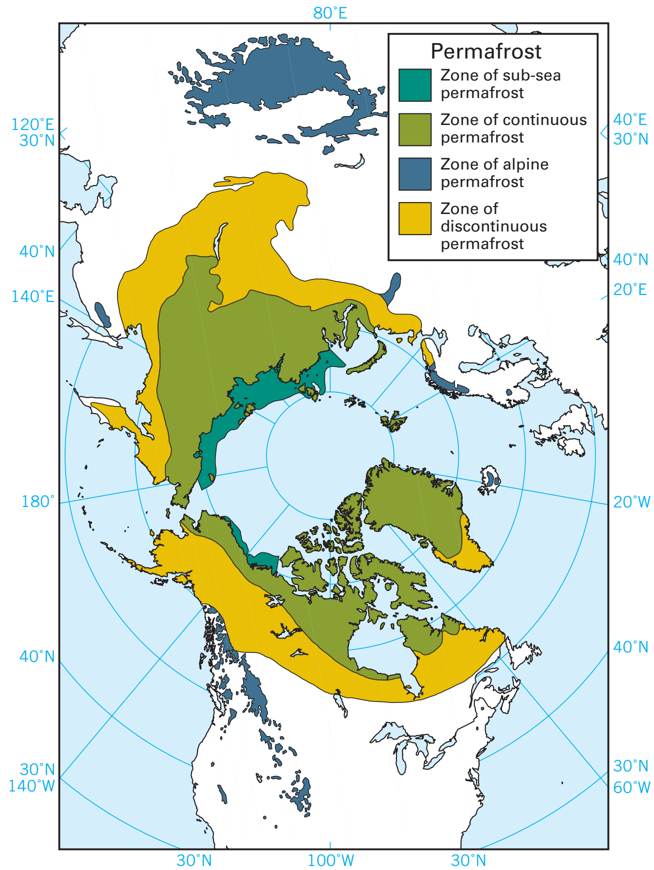
The treeless arctic and alpine tundra environment is severely cold in winter (**FIGURE 10.18**). In the tundra, soil water is solidly frozen for many months. During the short summer season, however, the surface thaws, leaving the soil saturated and vulnerable to mass wasting and water erosion. With the 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* (*peri*, meaning "near") location.

Permafrost
Soil, regolith, and bedrock at a temperature below 0°C (32°F), found in cold climates.

PERMAFROST

Ground and bedrock that lie below the freezing point of fresh water (0°C; 32°F) all year round are called **permafrost**. "Ground"



Permafrost map FIGURE 10.19

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. Sub-sea 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.

Permafrost tundra FIGURE 10.18

Musk oxen graze a landscape of tundra on Victoria Island, Nunavut, Canada, at sunset. The ground is permanently frozen beneath the grassy vegetation.

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*.

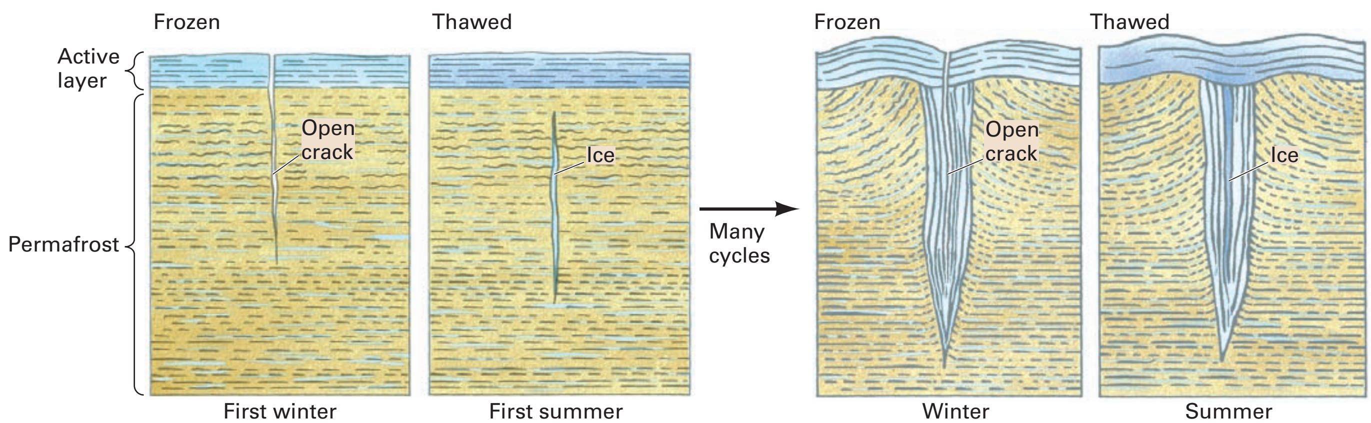
Permafrost terrains have a shallow surface layer, known as the *active layer*, which thaws with the changing seasons. The active layer ranges in thickness from about 15 cm (6 in) to about 4 m (13 ft), depending on the latitude and nature of the ground. Below the active layer is the *permafrost table*, marking the upper surface of the permanently frozen zone.

FIGURE 10.19 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 latitude 70° N. Much of this permanently frozen zone is inherited from the last Ice Age and will eventually thaw unless a glacial period returns.

The amount of ground ice present below the permafrost table varies greatly from place to place. Near the surface, it can take the form of a body of almost 100 percent ice. At increasing depth, the percentage of ice becomes lower, approaching zero at great depth. A common form of ground ice is the ice wedge (**FIGURE 10.20**). Ice wedges form as ice accumulates in vertical wedge-forms in deep cracks in the sediment. Ice wedges are typically interconnected into a system of polygons, called *ice-wedge polygons*.

Ice wedge FIGURE 10.20

A Exposed by river erosion, this great wedge of solid ice fills a vertical crack in organic-rich floodplain silt along the Yukon River, near Galena in western Alaska.



B **Formation of an ice wedge** Ice wedges are thought to originate in cracks that form when permafrost shrinks during extreme winter cold. Surface meltwater enters the crack during the spring freezes, widening the crack.

C 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 100 ft).

Process Diagram

Pingo formation

A pingo is formed when a tundra lake in sandy alluvium is drained, leaving an unfrozen pocket below, called a *talik*, to slowly freeze and expand.

This is Ibyuk pingo, on the Mackenzie River delta, Northwest Territories, Canada. It began to form about 1,200 years ago in a drained lake bed. Later, coastline retreat flooded the former lake basin, and today it is connected to Kugmallit Bay of the Beaufort Sea. The diagrams below show how a pingo forms.

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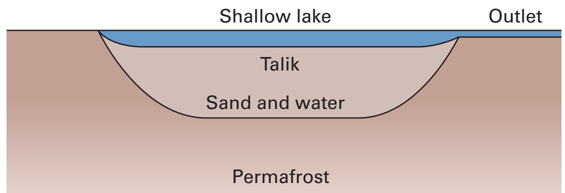
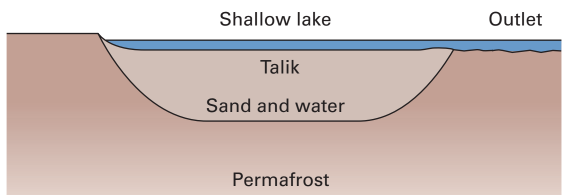
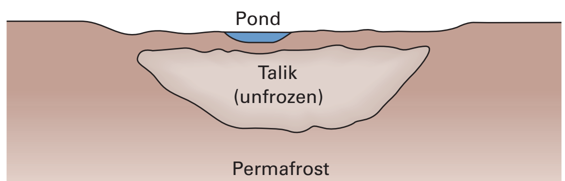
1 Shallow lake A shallow lake lies above a pocket of unfrozen ground, called a *talik*.



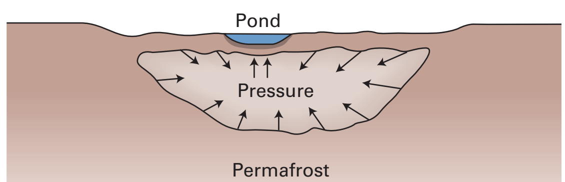
2 Draining Over time, the lake drains and grows shallower, perhaps because its outlet has eroded and become larger.



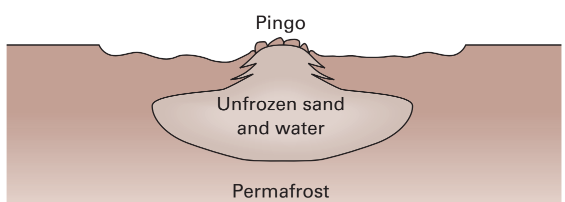
3 Freezing Eventually, the lake shrinks to a small pond. The unfrozen talik is made of highly porous sand, so it is rich in water. Without the protective cover of water from the lake, the lake bottom begins to freeze.



4 Pressure The lake bottom freezes downward. As water in the unfrozen region is converted to ice, its volume expands. This puts pressure on the remaining unfrozen talik.



5 Dome The pressure on the talik pushes water upward at a weak point in the permafrost layer, forming an ice dome. As permafrost slowly engulfs the talik, the pingo grows.



Another remarkable ice-formed feature of the arctic tundra is a conspicuous conical mound, called a *pingo*. In extreme cases, pingos reach heights of 50 m (164 ft), with a base diameter of 600 m (about 2000 ft). The process diagram, "Pingo formation" shows one way that pingos are formed.

ENVIRONMENTAL PROBLEMS OF PERMAFROST

Human activity is degrading the permafrost environment. People burn or scrape 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 ice bodies melt in the summer and waste downward. Meltwater mixes with silt and clay to form mud, which is then eroded and transported by water streams, leaving trench-like morasses. This total activity is called *thermal erosion*.

When natural surface cover is removed over a large expanse of nearly flat arctic tundra, the ground can subside, forming depressions. These depressions become larger as water erodes them, giving rise to numerous new lakes. We call the new terrain *thermokarst*. The serious consequences of thermal erosion were seen after World War II, when military bases, airfields, and highways were constructed hurriedly without regard for the maintenance of the natural protective surface insulation. In extreme cases, scraped areas turned into mud-filled depressions and even into small lakes that expanded with successive seasons of thaw, engulfing nearby buildings. We know now that buildings in such environments should be placed on piles with an insulating air space below or, alternatively, that a thick insulating pad of coarse gravel should be placed over the surface before construction. Steam and hot-water lines are now placed above ground to prevent thaw of the permafrost layer.

We learned the lessons of superimposing our technology on a highly sensitive natural environment the hard way—encountering surprising, costly, and undesirable effects. We're likely to learn more hard lessons as we continue to develop arctic regions.

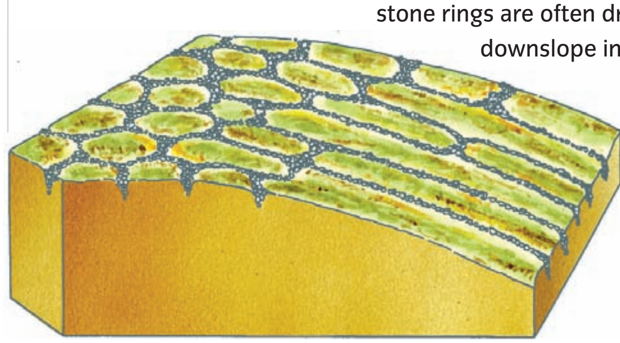
PATTERNED GROUND AND SOLIFLUCTION

Areas that contain coarse-textured regolith, consisting of rock particles 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 (FIGURE 10.21). On steep slopes, soil creep elongates these polygons in the downslope direction, turning them into parallel stone stripes. Stone polygons and ice-wedge polygons are examples of *patterned ground*.

Patterned ground FIGURE 10.21

▲ **Stone polygons** 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 are often drawn out downslope into stone stripes.



Solifluction
A type of earthflow found in arctic permafrost regions caused by soil that is saturated with water and then deformed into terraces.

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, this saturated soil is deformed into solifluction terraces and solifluction lobes that give the tundra slope a stepped appearance (FIGURE 10.22).

ALPINE TUNDRA

Most of the periglacial processes and forms we've discussed for the low arctic tundra are also found in the high alpine tundra throughout high mountains of the middle and high latitudes (FIGURE 10.23). 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, and 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?

First, the warm temperatures and increased precipitation, especially snow, 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 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 survive.

Solifluction FIGURE 10.22

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.

Alpine tundra FIGURE 10.23

Treeless tundra is found at high elevations, often with permafrost. These hikers are enjoying the views of the Selkirk Mountains in the Canadian Rockies.

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—further boosting warming. And 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.

CONCEPT CHECK STOP

What is permafrost?

What is a pingo?

What is an ice wedge? How does it form?

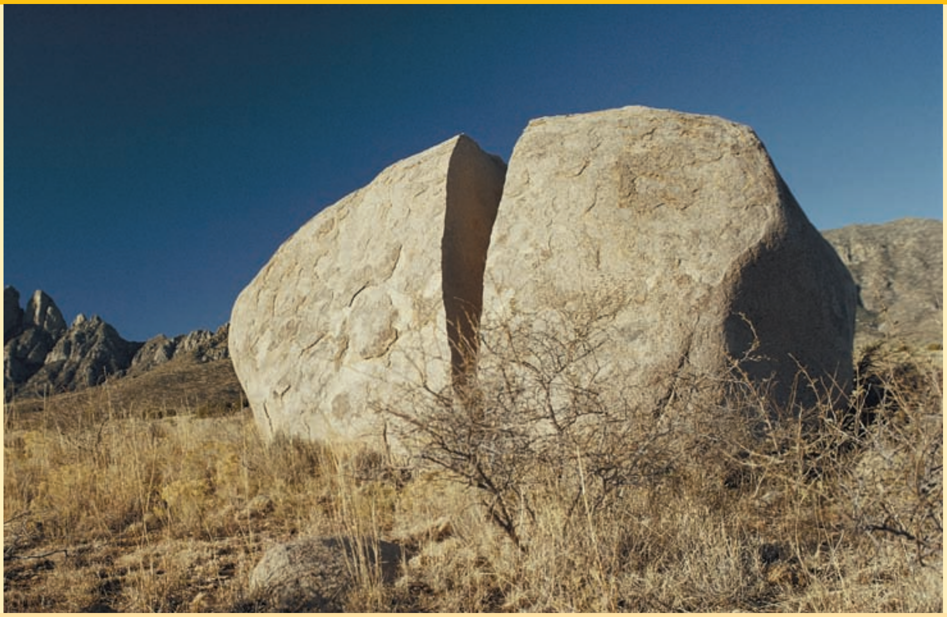
Describe solifluction.

What is happening in this picture ?

This photograph from Beacon Valley, eastern Antarctica, shows a curious pattern of interconnected cracks on the ground. The polygons are about 18 m (60 ft) in width. What climate region is shown here? What is the ground pattern called? Explain how it might have formed.

VISUAL SUMMARY

1 Weathering



1. Physical weathering breaks bedrock into pieces. Frost action breaks rock apart by the repeated growth and melting of ice crystals in rock fractures and joints and between mineral grains. Salt-crystal growth in dry climates breaks individual grains of rock free. Unloading of the weight of overlying rock layers produces exfoliation domes.

2. Chemical weathering results from mineral alteration. Hydrolysis and oxidation produce a regolith that is often rich in clay minerals. Carbonic acid action dissolves limestone.

2 Mass Wasting

1. Mass wasting is the spontaneous downhill motion of soil, regolith, or rock under gravity.

2. In soil creep, regolith moves down slopes almost imperceptibly. In an earthflow, water-saturated soil or regolith slowly flows downhill. A mudflow is much swifter than an earthflow. A landslide is a rapid sliding of large masses of bedrock, sometimes triggered by an earthquake.

3. Mass wasting can be induced by heaping up soil and regolith into unstable piles and by removing layers that naturally support soil and regolith.

3 Processes and Landforms of Arctic and Alpine Tundra

1. Pingos and ice wedges are forms of ground ice found in permafrost terrains.

2. Removing the surface layer in permafrost terrains thaws the upper permafrost, creating thermal erosion and thermokarst.

3. Patterned ground occurs when ice growth and melting in freeze-thaw cycles create stone polygons and ice-wedge polygons.

4. During the brief summer thaw, saturated soils flow to form solifluction terraces.

5. Climate warming will thaw vast areas of permafrost and produce more thermokarst lakes. The boreal forest will migrate poleward.

KEY TERMS

- **weathering** p. 298
- **regolith** p. 299
- **physical weathering** p. 299
- **chemical weathering** p. 302
- **mass wasting** p. 305
- **bedrock** p. 305
- **soil creep** p. 306
- **earthflow** p. 306
- **mudflow** p. 308
- **landslide** p. 309
- **permafrost** p. 314
- **solifluction** p. 318

CRITICAL AND CREATIVE THINKING QUESTIONS

1. What is meant by the term weathering? What are the types of weathering?

2. Sketch a cross section through a part of the landscape showing regolith, bedrock, sediment, and alluvium.

3. Name and describe three types of physical weathering. Name three types of chemical weathering. Describe how limestone is often altered by a chemical weathering process.

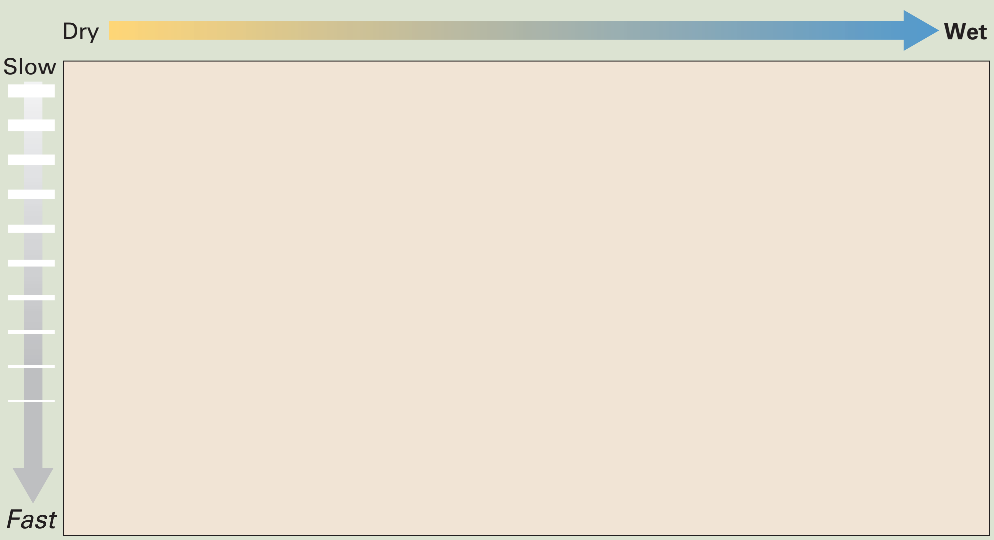
4. Define mass wasting. Using the empty version of Figure 10.7 below, identify and plot on the diagram the mass movement associated with each of the following locations: Turtle Mountain, Palos Verdes Hills, Madison River, and Herculaneum.

5. Define and describe induced mass wasting. Provide some examples.

6. Diagram the formation of a pingo, adding explanatory text as needed.

7. Identify and describe the unique processes of mass wasting that characterize arctic environments. What role does permafrost play? How has human activity affected the arctic environment in the past, and what impact is predicted for the future?

8. Imagine yourself as the newly appointed director of public safety and disaster planning for your state. 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.



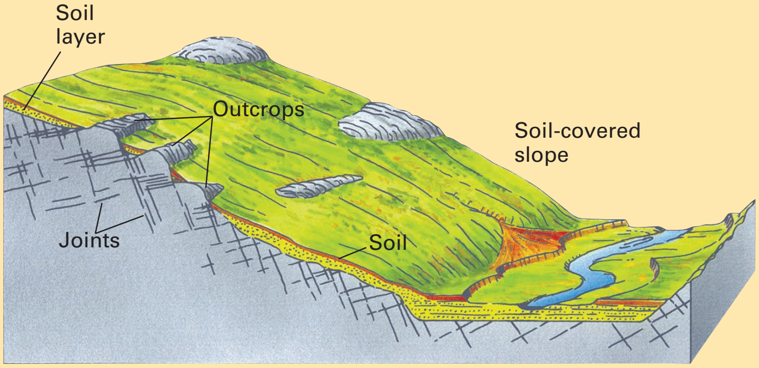
SELF-TEST

1. The process in which rocks are fractured, broken and/or transformed to softer and weaker forms is known as _______________.

a. erosion
b. mass wasting
c. weathering
d. soil creep

2. Label the following on the figure below:

a. bedrock
b. regolith
c. colluvium
d. alluvium



3. _______________ is the spontaneous movement of soil, regolith and rock under the influence of gravity.

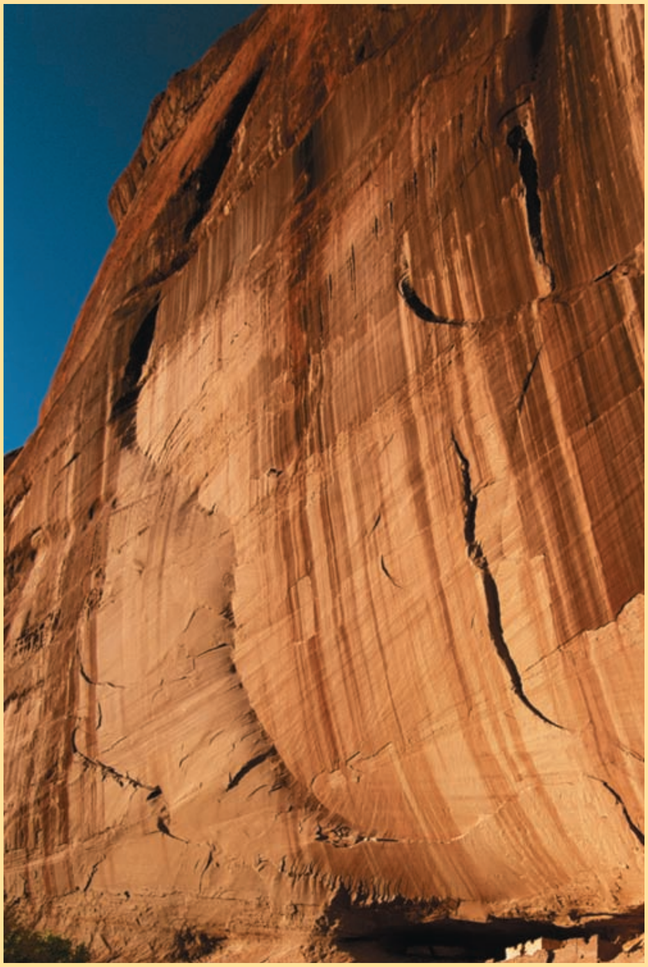
a. Erosion
b. Mass wasting
c. Weathering
d. Soil creep

4. _______________ is the source for sediment, which may be transformed into soil.

a. Bedrock
b. Granite rock
c. Alluvium
d. Regolith

5. What do we call the opening in the cliff pictured below, which occurs in arid climates?

a. rock arch
b. pit
c. niche
d. talus cone



6. When carbon dioxide naturally dissolves in rain, soil, and ground waters, it produces _______________, which can easily dissolve _______________.

a. carbonic acid, carbonate sedimentary rocks
b. carbonic acid, igneous rocks
c. carbonic acid, clastic sedimentary rocks
d. sodium bicarbonate, carbonate sedimentary rocks

7. A(n) _______________ is a mass of water-saturated soil that slowly moves downhill.
   a. earthflow c. landslide
   b. mudflow d. slump

8. A(n) _______________ is the rapid sliding of large masses of bedrock and is usually triggered by a(n) _______________.
   a. landslide, earthquake
   b. landslide, thunderstorm
   c. mudflow, thunderstorm
   d. earthflow, earthquake

9. Mudflows that occur on the flanks of erupting volcanoes are called _______________.
   a. pyroclastic flows c. lahars
   b. debris floods d. mudflows

10. A region in close proximity to active glaciers and ice sheets and typified by intense frost action is generally referred to as a(n) _______________ environment.
   a. subarctic c. periglacial
   b. glacial d. arctic

11. In permafrost regions, _______________ is commonly present in pore spaces or as free bodies or lenses in the ground.
   a. permafrost c. dirty ice
   b. ground ice d. tundra ice

12. The _______________ layer of permafrost terrains is due to seasonal thaws.
   a. continuous permafrost c. active
   b. permafrost d. discontinuous permafrost

13. The _______________ is the upper surface of the perennially frozen zone directly below the active layer.
   a. permafrost table
   b. continuous permafrost zone
   c. discontinuous permafrost zone
   d. permafrost zone

14. A system of interconnected ice wedges that often form in silty alluvium near the top of the permafrost table is known as _______________.
   a. ice-wedge polygons c. ice-wedge crystals
   b. ice-wedge hexagons d. ice lenses

15. A _______________ is formed when ground ice accumulates and slowly grows in height, forming a conical mound in the overlying sediment.
   a. talik c. solifluction zone
   b. pingo d. stone polygon

16. The removal of the natural surface cover in permafrost regions can lead to landscape subsidence and the subsequent formation of water-filled depressions called _______________.
   a. thermokarst lakes c. pingos
   b. water lenses d. ice lenses

Fresh Water of the Continents

11

Venice is sinking. January 2001 saw the worst sustained flooding in the city's history—lasting more than two weeks, with an eighth of the picturesque Italian city underwater. Venice could be permanently flooded within a century.

Famed for its canals, Venice was built in the eleventh century A.D. on low-lying islands in a coastal lagoon. The city is now dropping about one millimeter a year due to the natural movement of the lithospheric plates underneath. But Venice's plight was greatly exacerbated after World War II when industries began pumping ground water from below the city. That caused Venice to sink a foot in two decades, leaving St. Mark's Square, the center of Venetian social life, just two inches above the normal high-tide level.

We now depend on ground water to meet much of our demand for fresh water. But it takes thousands of years for this water to accumulate underground, and when it's rapidly removed the ground surface sinks. Although ground-water removal has now stopped in Venice, flooding is still a huge problem. The city's fate may now depend on the construction of floodgates on the barrier beach that lies between Venice and the open ocean. But Venice is not the only city in peril. Ground-water withdrawal affects the Thai city of Bangkok—now the world's most rapidly sinking city—and regions in California and Texas and Mexico City.

Ground water forms one part of the hydrologic, or water, cycle. Venice provides a dramatic reminder of the importance of understanding the processes that remove and replenish our water supply.

High water in Saint Mark's Square, Venice.

NATIONAL GEOGRAPHIC

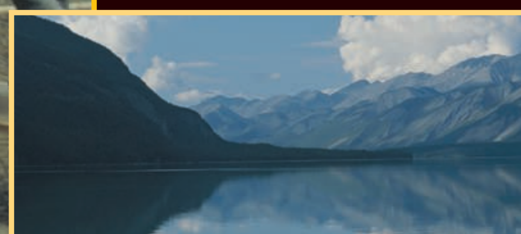
CHAPTER OUTLINE

- The Hydrologic Cycle Revisited p. 326

- Ground Water p. 330

- Surface Water p. 338

- Stream Flows and Floods p. 344



- Lakes p. 348

- Surface Water as a Natural Resource p. 352

The Hydrologic Cycle Revisited

Learning Objectives

Diagram and explain the hydrologic cycle.

Describe the paths of precipitation.

Water is essential to life. Nearly all organisms require a constant flux of water or at least a water-rich environment for survival (Figure 11.1). 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.

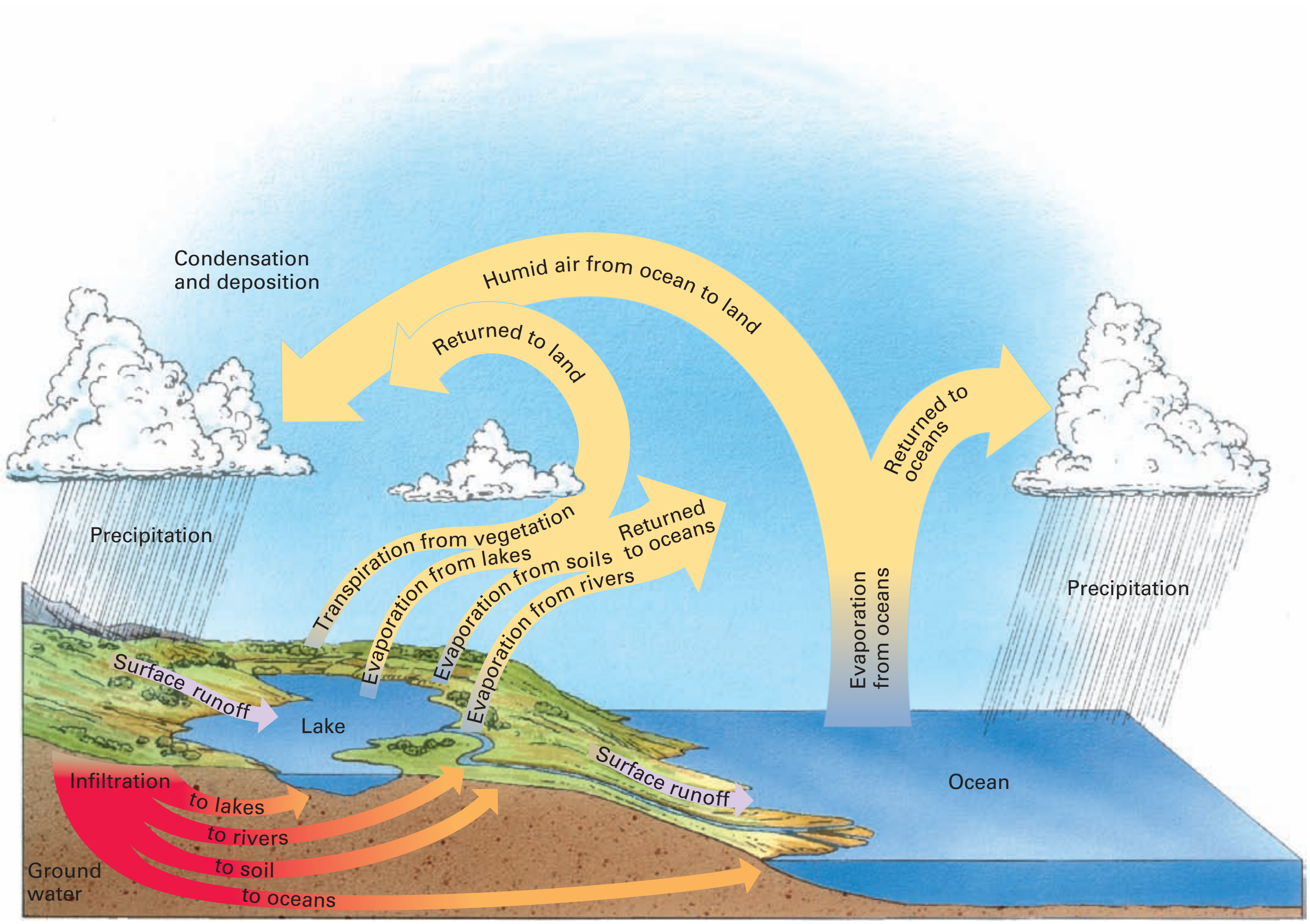
The hydrologic cycle involves atmospheric moisture and precipitation as well as surface and ground water. This cycle is illustrated in the process diagram "The hydrologic cycle."

Fresh water Figure 11.1

Humans require abundant amounts of fresh water. Rivers and streams are important sources of water for human uses.

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.



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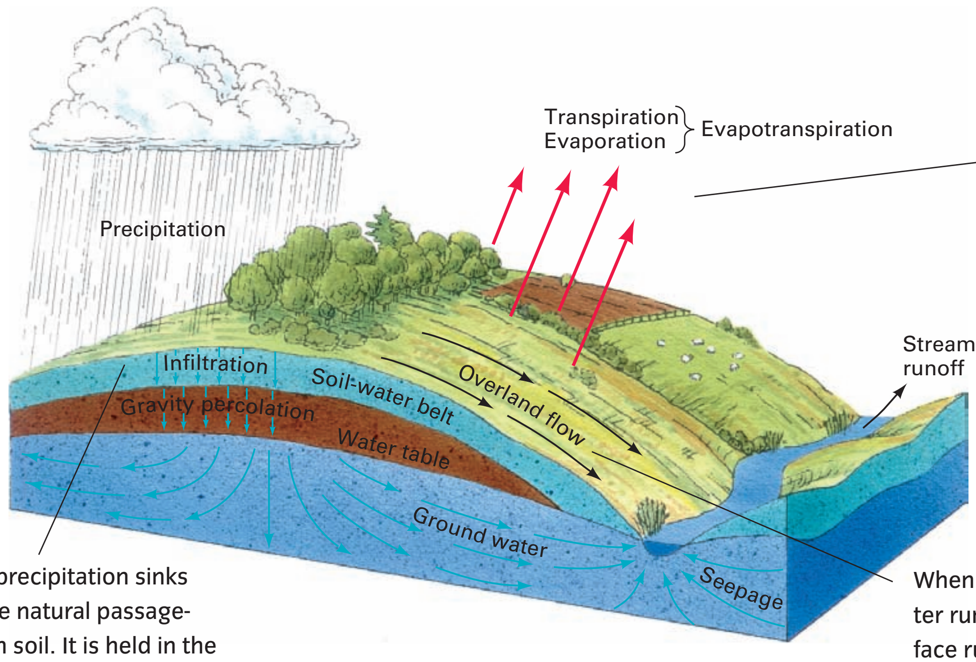
Process Diagram

Precipitation and distribution of the Earth's water FIGURE 11.2



Water in the belt can return to the atmosphere by evaporation or through transpiration by the vegetation. A portion of the infiltrating water passes through the soil-water belt into the ground-water zone.

Some precipitation sinks into the natural passageways in soil. It is held in the soil-water belt temporarily, where plants can reach it.

When rain falls rapidly, some water runs over the surface. This surface runoff is called overland flow. In periods of heavy, prolonged rain or rapid snowmelt, overland flow feeds directly to streams.

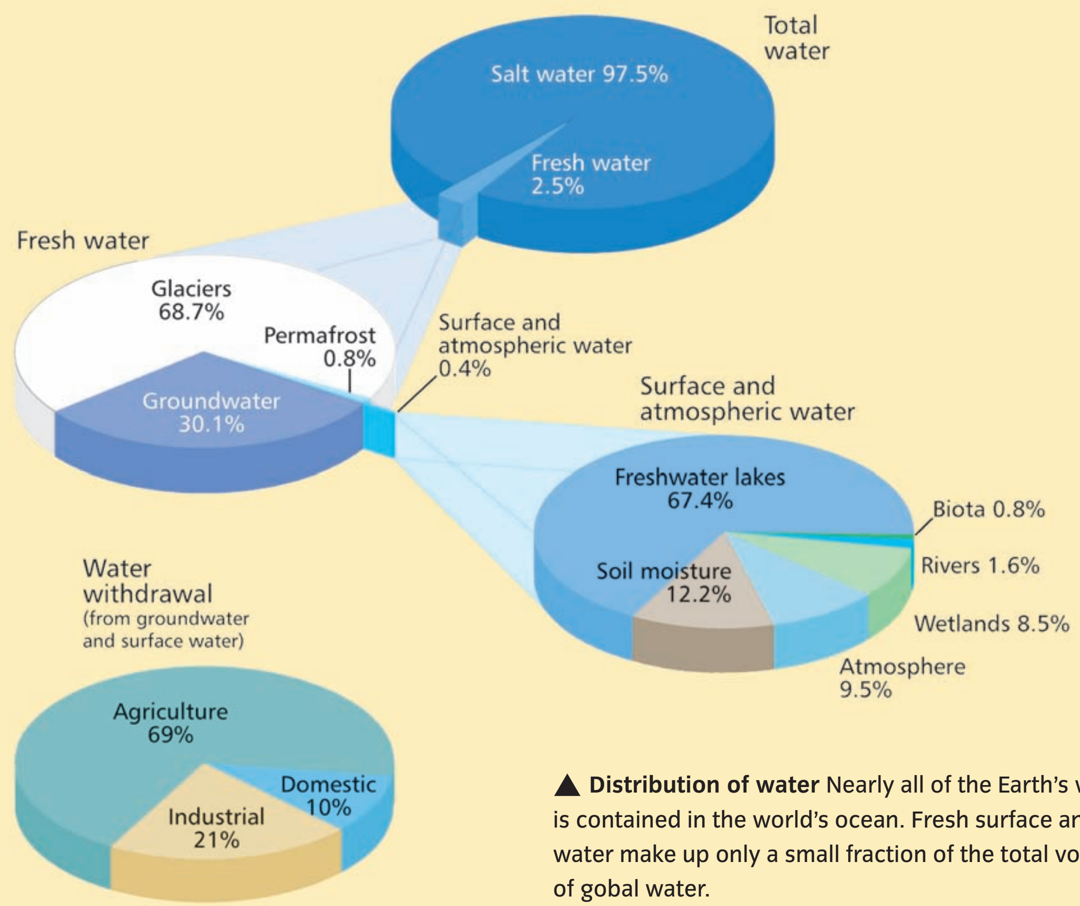
Infiltration Absorption and downward movement of precipitation into the soil and regolith.

Runoff Flow of water from continents to oceans through stream flow and ground-water flow.

Most natural soil surfaces can absorb rain water from light or moderate rain. FIGURE 11.2 shows what happens to water from precipitation as it first reaches the land surface, focusing on the processes of **infiltration**, surface **runoff**, and evapotranspiration.

Overland flow moves surface particles from hills to valleys, and by doing so it helps 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.

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.



▲ **Distribution of water** Nearly all of the Earth's water is contained in the world's ocean. Fresh surface and soil water make up only a small fraction of the total volume of gobal water.

CONCEPT CHECK STOP

Where do we find the Earth's fresh water?

What are the three primary paths that precipitation can take after hitting the soil layer?

Ground Water

Learning Objectives

Define ground water.

Describe karst landscapes.

Explain how ground water can become contaminated.

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 11.3). 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.

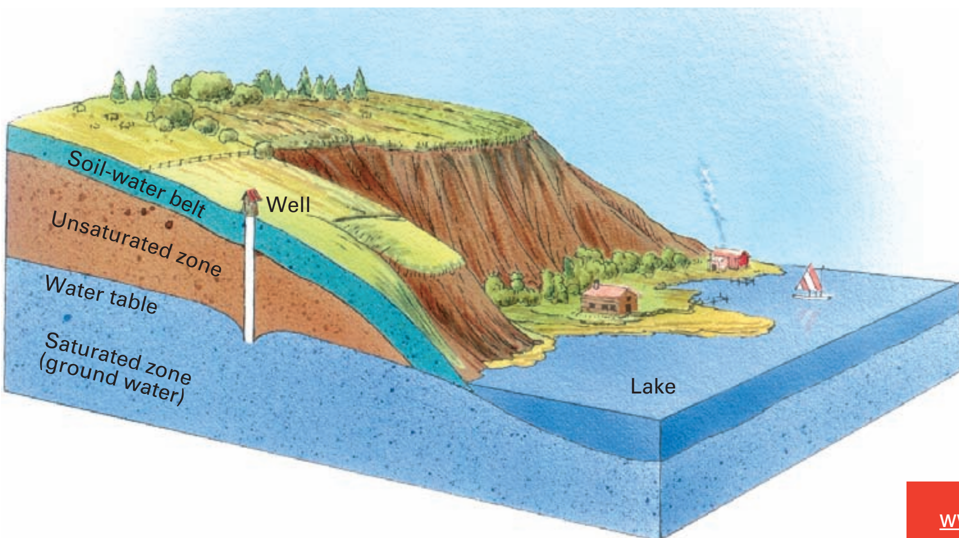
Ground water Subsurface water in the saturated zone that moves under the force of gravity.

Water table Upper limit of the body of ground water; marks the boundary between the saturated and unsaturated zones.

In the hydrologic cycle, ground water moves slowly along deep flow paths and eventually emerges by seepage into streams, ponds, lakes, and marshes (FIGURE 11.4). In these places the land surface dips below the water table. Ground water can also be dramatically ejected into the air in geysers as illustrated in "What a Geographer Sees: Hot Springs and Geysers."

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 11.5). 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.



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Zones of subsurface water FIGURE 11.3

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.

A Stream 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.

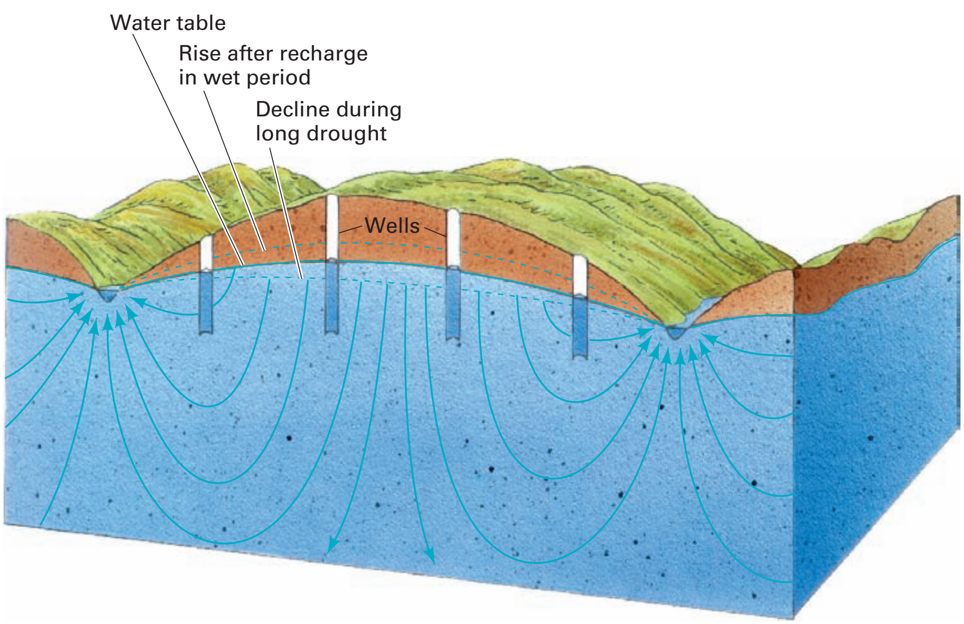
B Pond Ponds and lakes are fed by ground water, so their levels are determined by the water table. This pond is in Baxter State Park, Maine.

Surface waters FIGURE 11.4

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.

Clean, well-sorted sand—such as that found in beaches, dunes, or in stream deposits—can hold an amount of ground water equal to about one-third of its bulk volume. So, 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*.

Aquifer
Layer of rock or sediment that contains abundant freely flowing ground water.



Ground water and the water table FIGURE 11.5

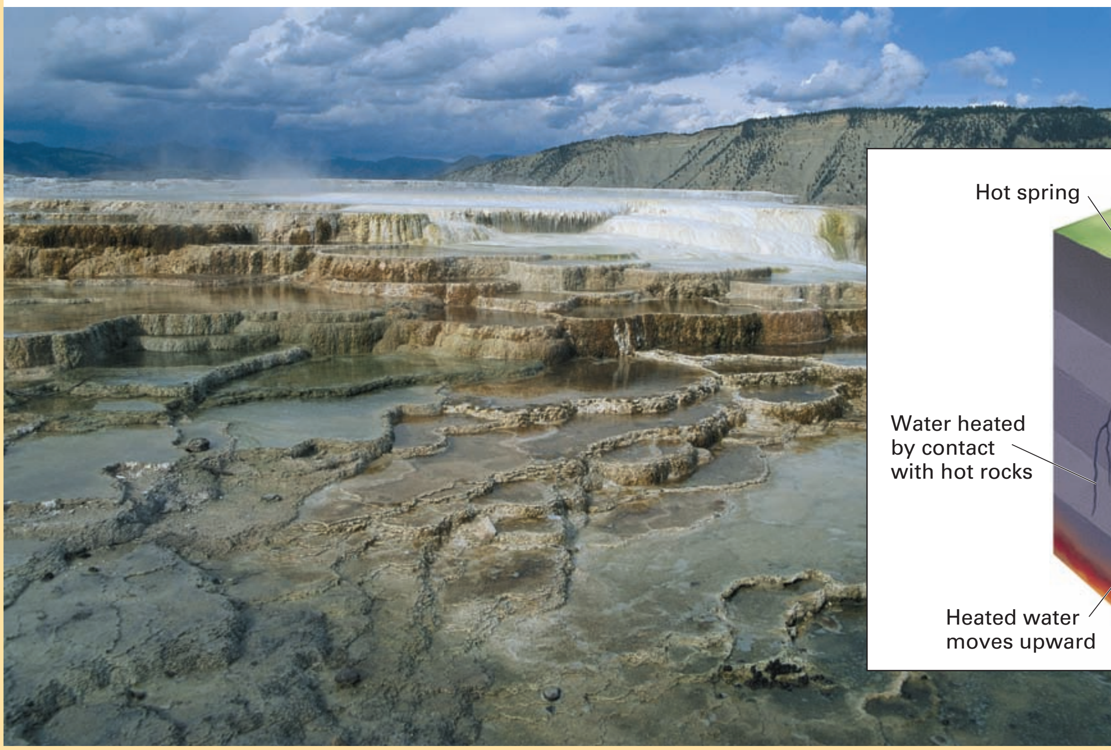
This figure shows paths of groundwater flow. It takes a long time for water to flow along the deeper paths, but flow near the surface is much faster. The most rapid flow is close to the stream, where the arrows converge.

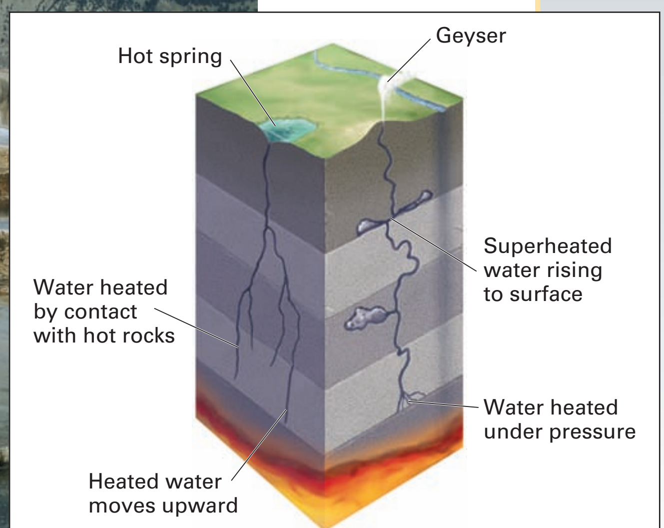
What a Geographer Sees

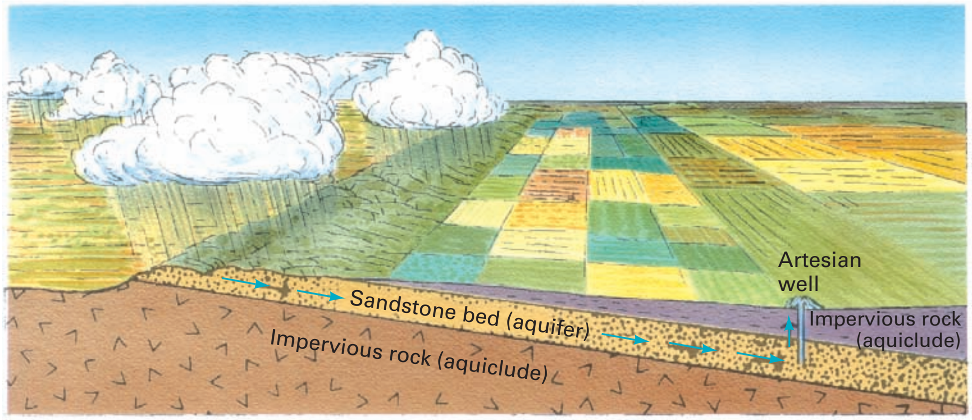
Hot springs and geysers

These dramatic pictures of the Mammoth Hot Springs and Old Faithful Geyser at Yellowstone National Park, Wyoming, show heated ground water emerging at the land surface. The features in the photographs were created because hot rock material near the Earth's surface heated the nearby ground water to high temperatures. When this heated ground water reaches the surface, it can emerge as hot springs, with temperatures not far below the boiling point of water. At Mammoth Hot Springs, shown below, steaming pools of hot water collect as the spring cascades down the slope. Jets of steam and hot water can also shoot from small vents—producing geysers like Old Faithful (right).

A geographer would notice the buildup of mineral deposits on the bottom and edges of the pools. It forms as the hot, mineral-rich water cools and evaporates, leaving the deposit behind.







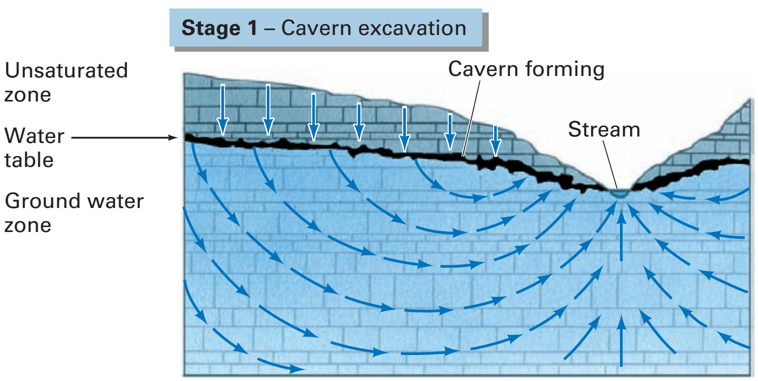
Artesian well FIGURE 11.6

A porous sandstone bed (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.

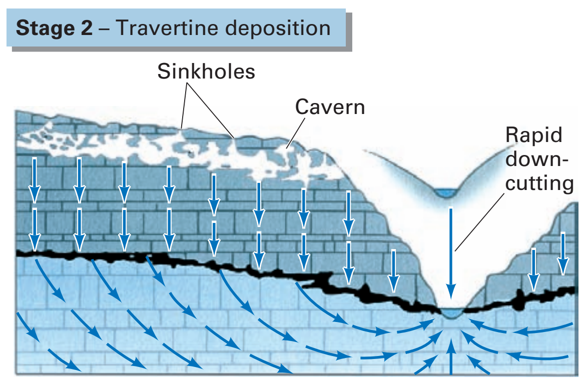
FIGURE 11.6 shows ground water flowing in an aquifer that is sandwiched between two aquicludes. Because it can't easily penetrate into the aquicludes, this ground water is under pressure, so it flows freely from a well. This type of self-flowing well is an *artesian well.*

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 the surface can be dissolved by ground water slowly flowing in the saturated zone, forming deep underground caverns. The caverns can then collapse, creating a unique type of landscape. Mammoth Cave in Kentucky and Carlsbad Caverns in New Mexico are examples of famous and spectacular caverns formed by solution. FIGURE 11.7 describes how caverns develop.



Stage 1 Carbonic acid action is concentrated in the saturated zone just below the water table. Limestone dissolves at the top of the groundwater 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.

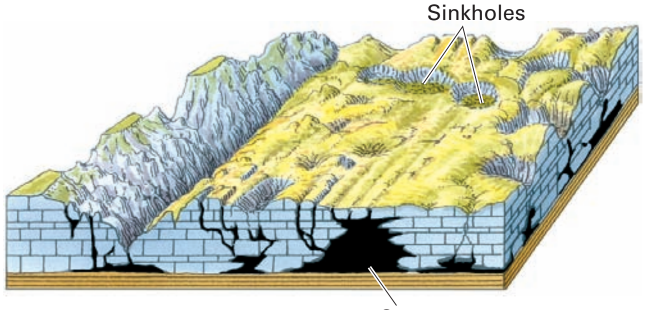
Cavern development FIGURE 11.7

Sinkhole FIGURE 11.8

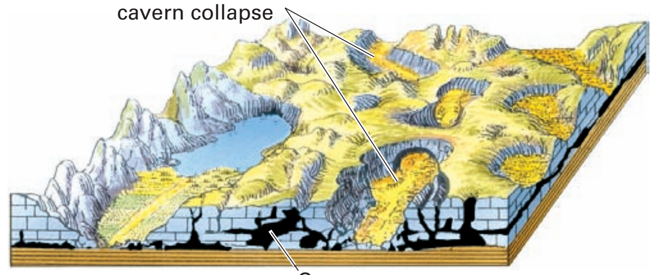
When underground caverns collapse, they can create sinkholes at the surface. This sinkhole, in Belize, is known as Nohoch Ch'en. Note the pure, white limestone outcropping on the far side of the sinkhole.

Sinkholes are surface depressions in a region of cavernous limestone (FIGURE 11.8). 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 11.9 shows how a karst landscape develops. Important regions of karst or karst-like 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 11.10).



A Over time, rain water dissolves limestone, producing caverns and sinkholes. In warm, humid climates, solution of pure limestone can form towers (left side of diagrams).



B 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.

Evolution of a karst landscape FIGURE 11.9

Tower karst FIGURE 11.10

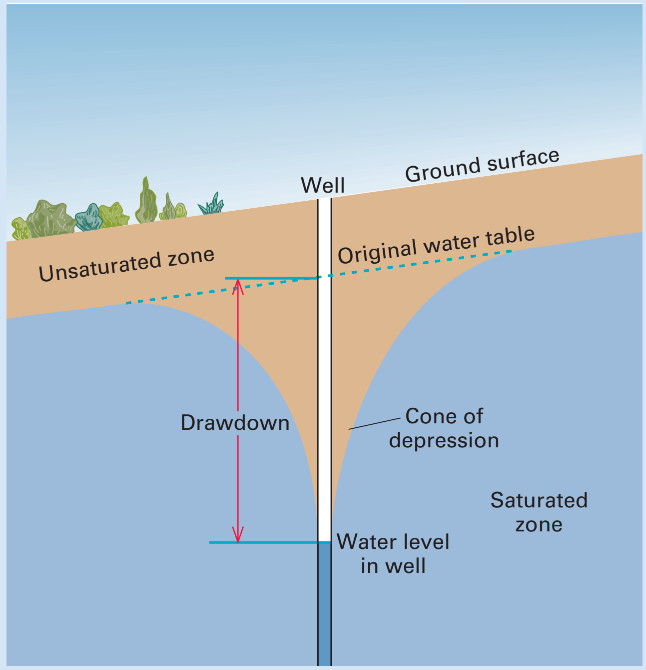
White limestone can been seen exposed in the nearly vertical sides of these towers, which are 100 to 500 m (about 300 to 1500 ft) high. The towers are often riddled with caverns and passageways. Near Guilin (Kweilin), Guanxi Province, southern China at latitude 25° N.

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 11.11).

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 11.12). 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. Subsidence—sinking of land—is another byproduct of water table depletion. Removing water from underlying sediments can make the land sink.

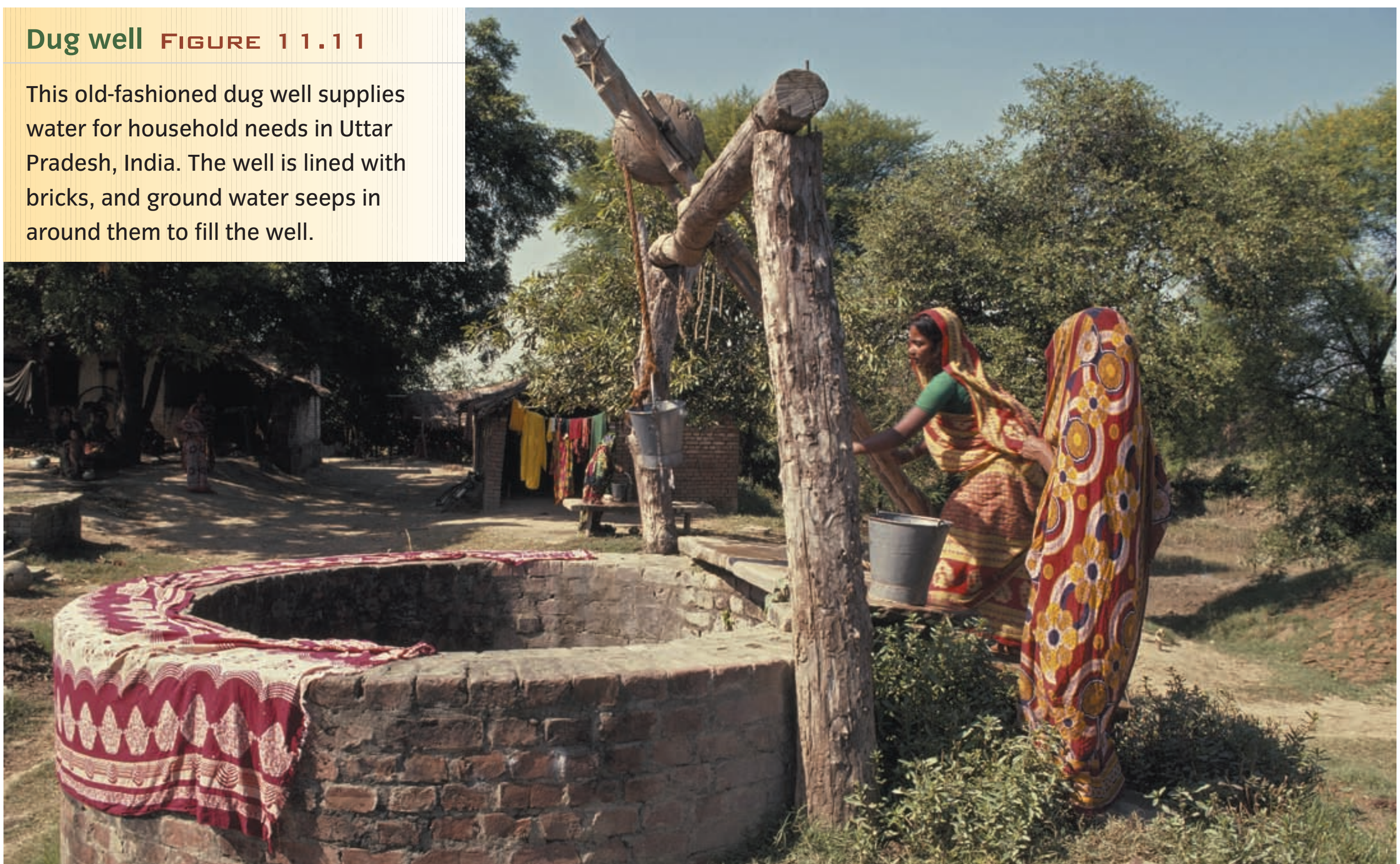


Drawdown in a pumped well
FIGURE 11.12

As the well draws water, the water table is depressed in a cone shape centered on the well. The cone of depression may extend out as far as 16 km (10 mi) or more from a well where heavy pumping is continued.

Dug well FIGURE 11.11

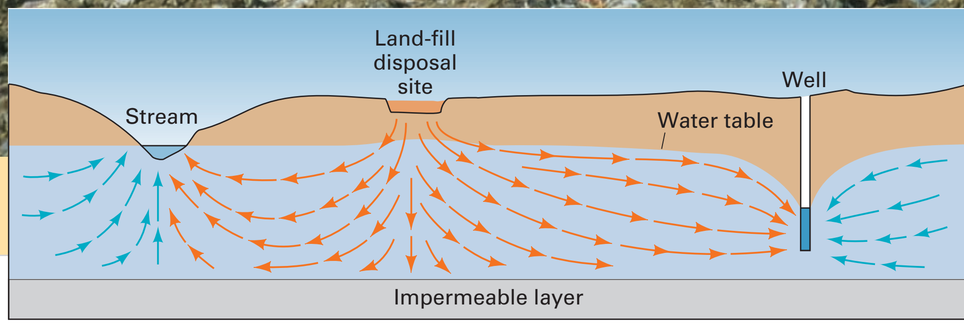
This old-fashioned dug well supplies water for household needs in Uttar Pradesh, India. The well is lined with bricks, and ground water seeps in around them to fill the well.



Ground-water contamination

FIGURE 11.13

A 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.



B Movement of polluted ground water Polluted water, leached from a waste disposal site, moves toward a supply well (right) and a stream (left).

Another major environmental problem is the contamination of wells by pollutants. Industrial economies such as the United States provide an endless source of garbage and trash. In recent decades, a major effort has been made to improve solid-waste disposal methods. One method is high-temperature incineration, but it often leads to air pollution. Another is the sanitary landfill method in which layers of waste are continually buried, usually by sand or clay available on the landfill site (FIGURE 11.13A). This waste is situated in the unsaturated zone, where it reacts with rainwater that infiltrates the ground surface. This water picks up a wide variety of chemical compounds from the waste and carries them down to the water table (FIGURE 11.13B).

Saltwater can also contaminate the water in coastal wells. Fresh water is less dense than saltwater, so a layer of saltwater from the ocean can lie below a coastal aquifer. When the aquifer is depleted, the level of saltwater rises and eventually reaches the well from below, making the well unusable.

CONCEPT CHECK STOP

- **What** is ground water?
- **What** are the key features of a karst landscape?
- **How** do wells affect the water table?
- **How** is ground water contaminated?

Surface Water

Learning Objectives

Describe overland and stream flow.

Diagram a drainage system and explain how it works.

OVERLAND FLOW AND STREAM FLOW

Runoff that flows down the slopes of the land in broadly distributed sheets is called *overland flow*. This is different from *stream flow*, 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 11.14). 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 progress on a sloping lawn. On heavily forested slopes, overland flow may be entirely concealed beneath a thick mat of decaying leaves.

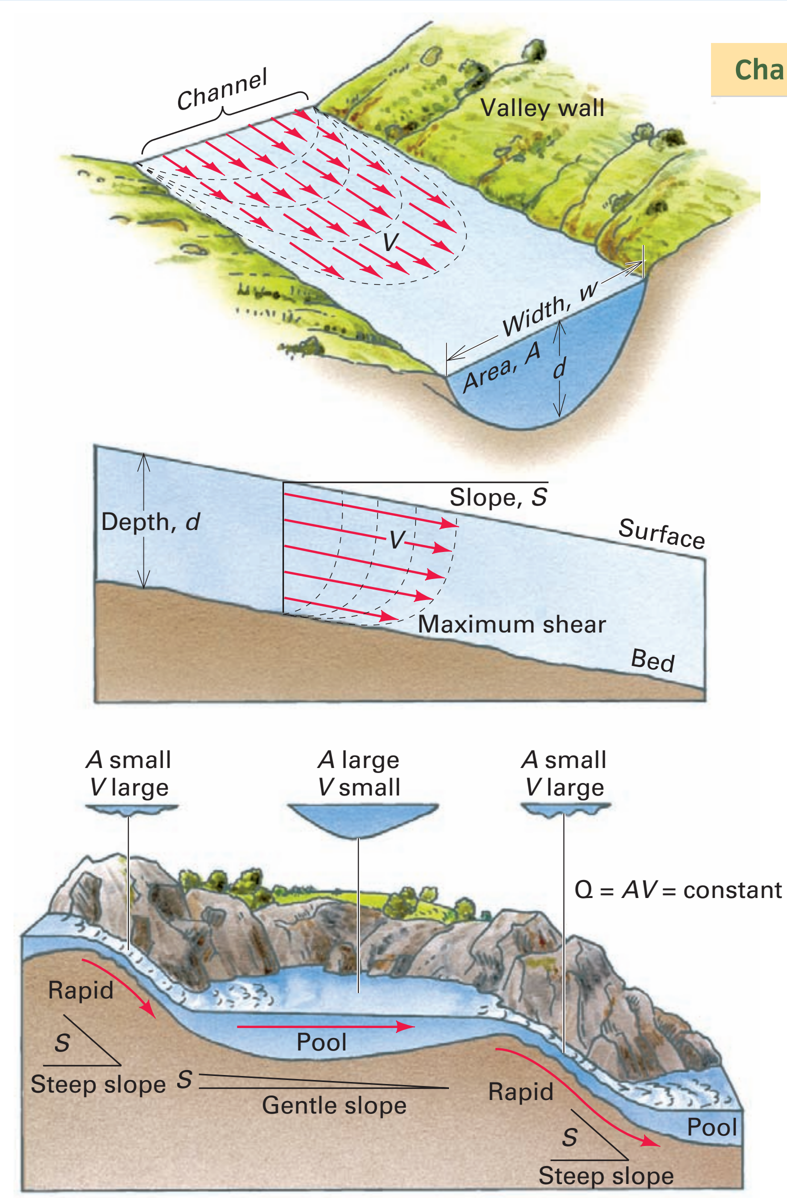
Overland flow eventually runs to a stream. We can define a **stream** as a long, narrow body of water flowing through a channel and moving to lower levels under the force of gravity. The *stream channel* is a narrow trough, shaped by the forces of flowing water (Figure 11.15). A channel may be so narrow 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.

Stream Long, narrow body of flowing water moving along a channel to lower levels under the force of gravity.

Overland flow Figure 11.14

Following a downpour, a thin sheet of water flows across this semiarid grassland near Holbrook, Arizona.

Characteristics of stream flow FIGURE 11.15



A The velocity of flow is greatest in the middle and at the top of the stream. Mean velocity (V), cross-sectional area (A), and slope (S) change in the pools and rapids of a stream section of uniform discharge.

B This figure shows how average velocity, cross-sectional area and slope 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*—remains constant. Discharge is measured in cubic meters (cubic feet) per second.

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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. 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 downstream.

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.

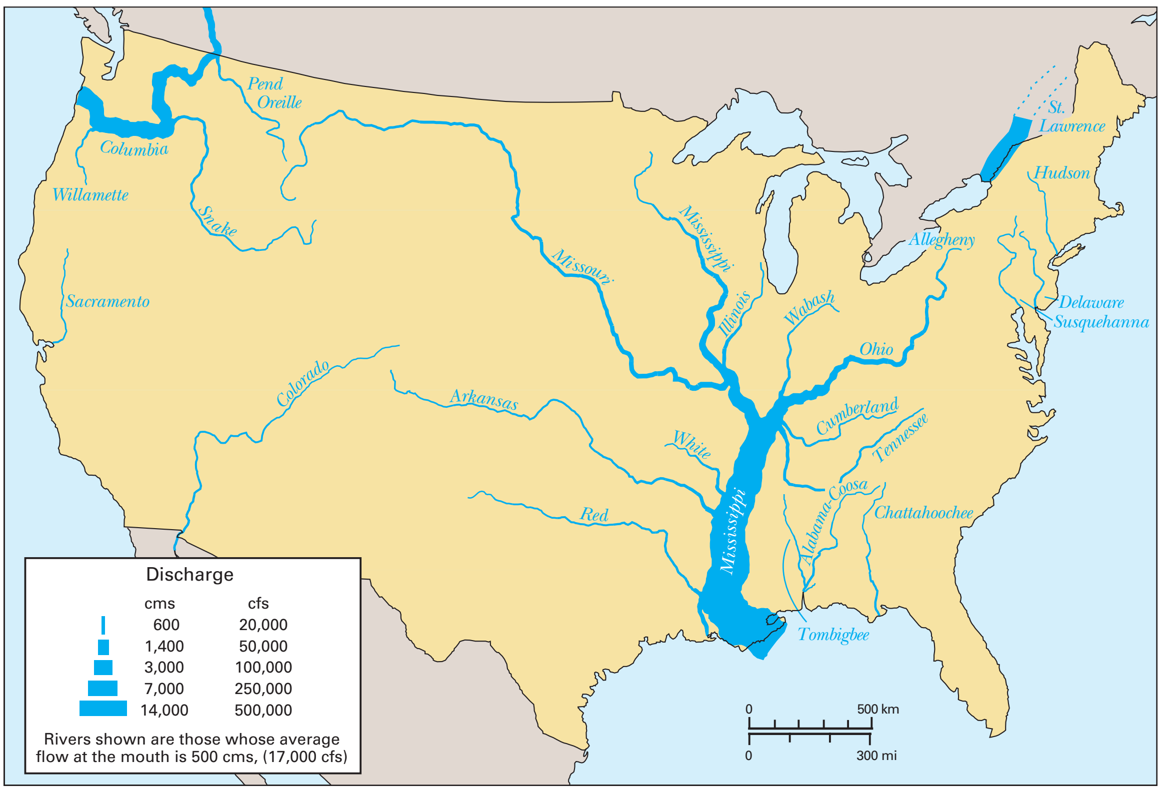
In stretches of rapids, where the stream flows swiftly, the stream channel will be shallow and narrow. In pools, where the stream flows more slowly, the stream channel will be wider and deeper to maintain the same discharge. Sequences of pools and rapids can be found along streams of all sizes.

Figure 11.16 is a map showing 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. You can see that 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

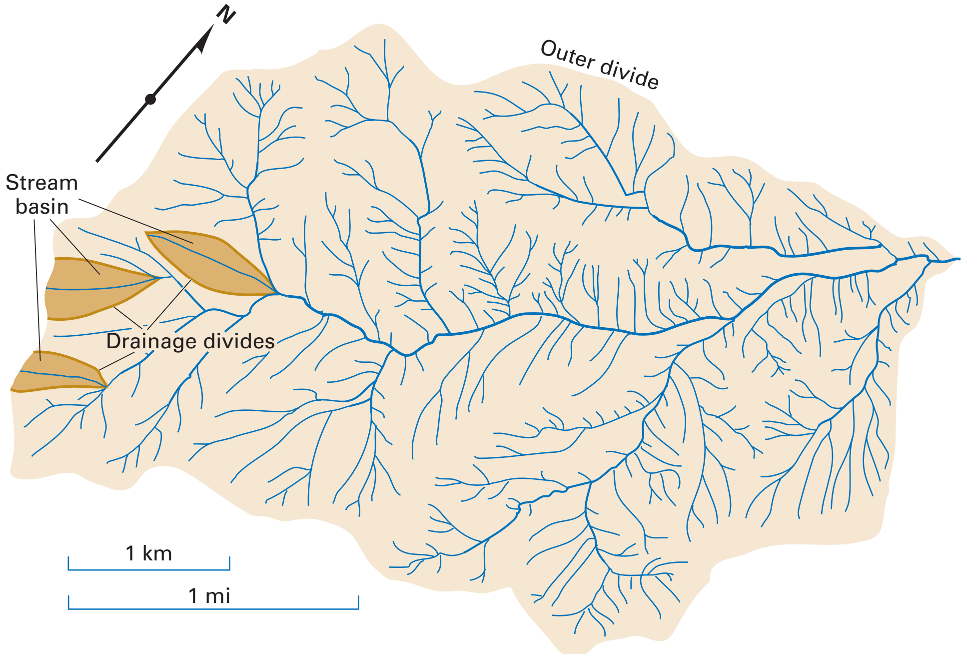
As runoff moves to lower and lower levels and eventually to the sea, it becomes organized into a branched network of stream channels. This network and the sloping ground surfaces next to the channels that contribute overland flow to the streams are together called a **drainage system**. *Drainage divides* mark the boundary between slopes

Drainage system
A branched network of stream channels and adjacent land slopes converging to a single channel at the outlet.



River discharge Figure 11.16

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.



Channel network of a stream FIGURE 11.17

Smaller and larger streams merge in a network 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. (Data of U.S. Geological Survey and Mark A. Melton.)

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 11.17). Drainage systems funnel overland flow into streams and smaller streams into larger ones.

CONCEPT CHECK STOP

What is overland flow?

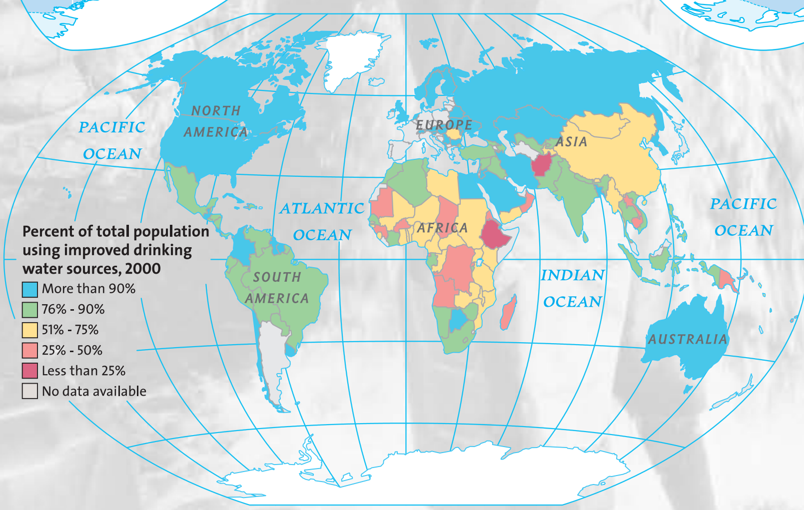
What is stream flow?

What is a drainage system?

WATER ACCESS AND USE

In arid and poorly developed regions, large proportions of inhabitants lack clean water supplies. Most water is consumed by agriculture for irrigation.

▲ **WATER GATHERERS**
Women wait to fill water jugs from an irrigation canal in southern Ethiopia. In this drought–plagued area, more than 80 percent of rural inhabitants lack access to clean drinking water.



▶ **ACCESS TO FRESH WATER**
In many regions, drinkable water is becoming scarce because of increasing demand and decreasing quality. Pollution of surface and ground water with contaminants and organisms is a major threat. Contamination of aquifers by pesticides and heavy metals is especially worrisome.

Visualizing
Freshwater Resources

WATER AVAILABILITY

Within a watershed, water availability depends on both precipitation and the number of people the water must support.

▼ PRIMARY WATERSHEDS AND CRITICAL AREAS

Watersheds receive and filter precipitation, collecting it in streams, rivers, lakes, and aquifers. Where water is abundant, large populations can be supported, but where it is scarce, watersheds can be stressed by human activities. Because watersheds are not limited to single countries or political regions, water conflicts arise, shown on the map by red triangles.

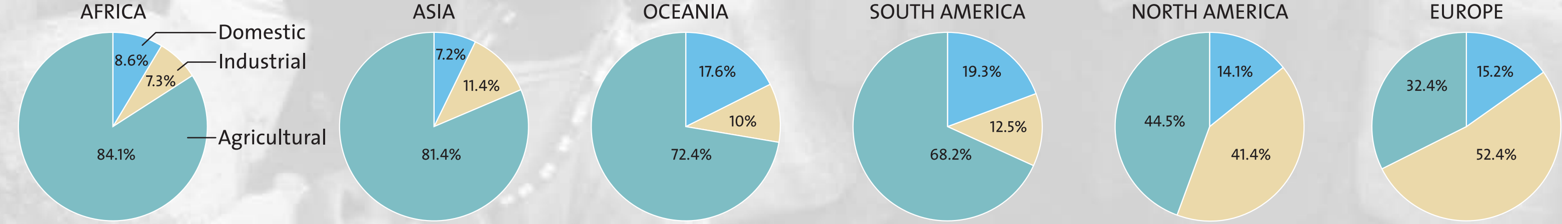
▶ WATER FOR POWER AND IRRIGATION

Massive water pipes funnel the Euphrates River to turbines in Turkey's Ataturk Dam, the centerpiece of a controversial plan to irrigate southeastern Turkey.

▼ GLOBAL IRRIGATION AND INDUSTRIAL WATER CONSUMPTION

In most of the world's watersheds, agriculture is the major consumer of fresh water. Irrigation is the primary use of most agricultural water, helping to provide food and fiber for human needs. Note that industrial use of water is much higher in North America and Europe, reflecting their more industrial economies.

Freshwater withdrawal as a percentage of total water utilization, 2000



Stream Flows and Floods

LEARNING OBJECTIVES

Identify the features of a hydrograph.

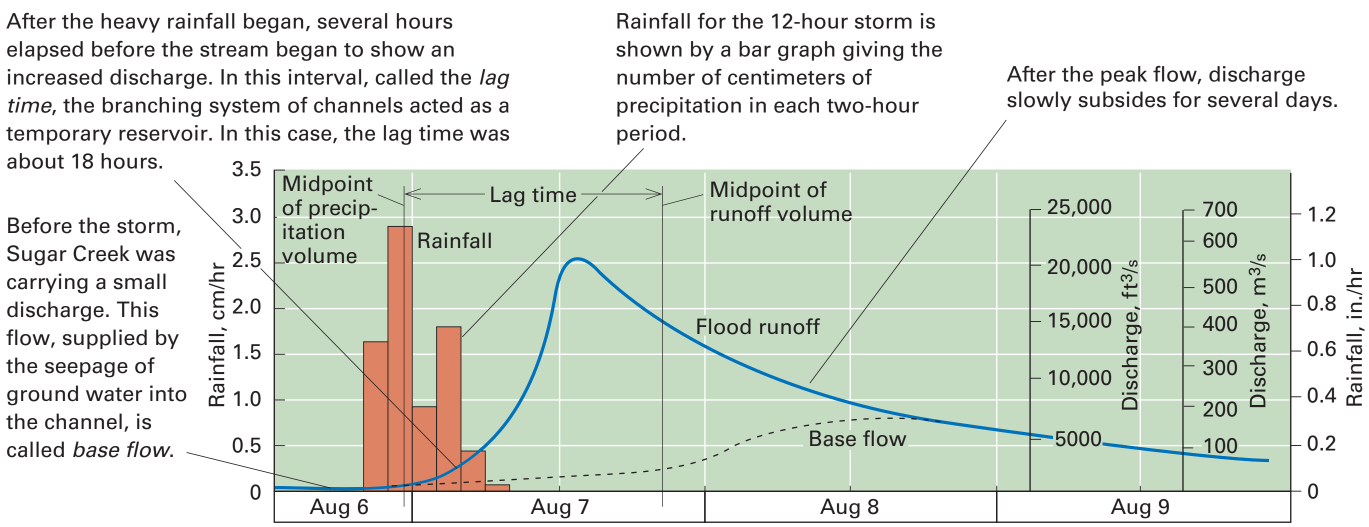
Explain why floods occur.

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 the discharge of a stream with time at a particular stream gauge. FIGURE 11.18 is a hydrograph for a drainage basin of about 800 km^2 (300 mi^2) in Ohio, with a moist continental climate.

The growth of cities and suburbs affects the flow of small streams in two ways (FIGURE 11.19). First, it is far more difficult for water to infiltrate the ground, which is increasingly covered in buildings, driveways, walks, pavements, and parking lots. 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 body 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



Sugar Creek hydrograph FIGURE 11.18

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 15 cm (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.

Urban waterflow FIGURE 11.19

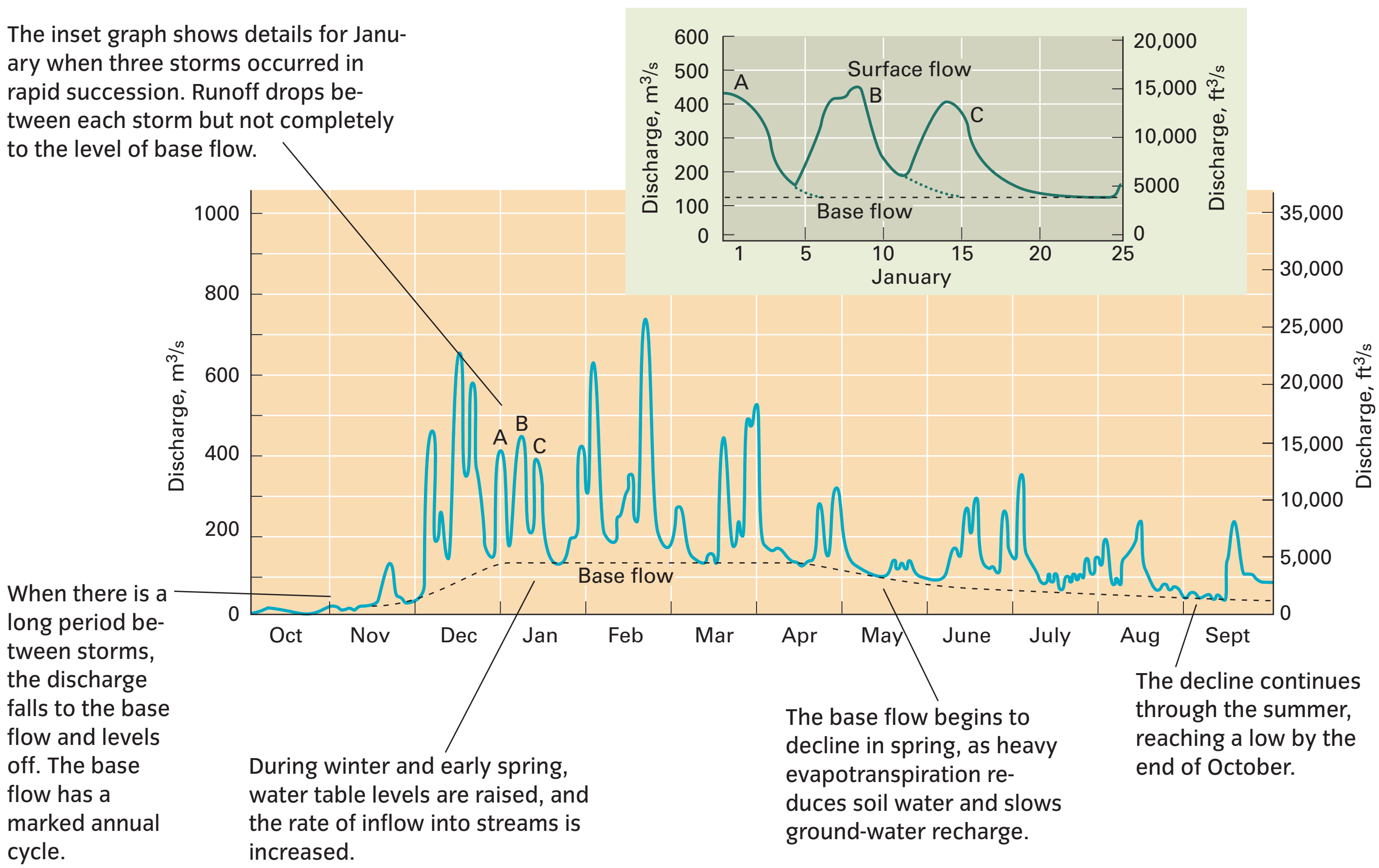
Impervious surfaces like this street in Bangkok increase runoff and hasten the flow of water into streams and rivers draining urban environments.

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.

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 11.20 is a hydrograph of the Chattahoochee River in Georgia, a fairly large river draining a watershed of 8700 km^2 (3350 mi^2), much of it in the southern Appalachian Mountains.

Chattahoochee River hydrograph FIGURE 11.20

This hydrograph shows the fluctuating discharge of the Chattahoochee River, Georgia, throughout a typical year. The sharp, abrupt fluctuations in discharge are produced by overland flow after rainfall periods lasting one to three days.



RIVER FLOODS

When the discharge of a river cannot be accommodated within its normal channel, the water spreads over the adjoining ground, causing flooding. Often the flooded area is cropland or forest, but sometimes it is occupied by houses, factories, or transportation corridors (FIGURE 11.21).

Floodplain
A broad belt of low, flat ground bordering a river channel that floods regularly.

Most rivers of humid climates have a **floodplain**—an area bordering the channel on one or both sides (FIGURE 11.22). 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 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, we see examples where even higher discharges cause rare and disastrous floods that inundate ground well above the floodplain.

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 85 offices located at strategic points along major river systems of the United

River flooding FIGURE 11.21

A 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.

B 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 flood of 1993.

Limpopo River floodplain FIGURE 11.22

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.

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 could potentially be affected.

CONCEPT CHECK STOP

What is a hydrograph?

Define the term floodplain.

What are the characteristics of streams that are prone to flash floods?

Which factors are used to forecast floods?

Lakes

LEARNING OBJECTIVES

Explain why lakes are important.

Define saline lakes and salt flats.

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 11.23). 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 (FIGURE 11.24). Lakes also lose water by evaporation. Lakes, like streams, are landscape features but are not usually considered to be landforms.

Lake Body of standing water that is enclosed on all sides by land.

Lakes are quite important for humans as sources of fresh water and food, such as fish. They can also be used to generate hydroelectric power, using dams. 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 many 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.

Where there aren't enough natural lakes, we create them by placing dams across the stream channels. So, many regions that once had almost no natural lakes now have many. Some are small ponds built to serve ranches and farms, while others cover hundreds of

Lakes and ponds FIGURE 11.23

▼ **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.

▼ **Pond** The shallow waters of this pond in Nicolet National Forest, Wisconsin, support an almost continuous cover of grasses and sedges.

Hydroelectric dam FIGURE 11.24

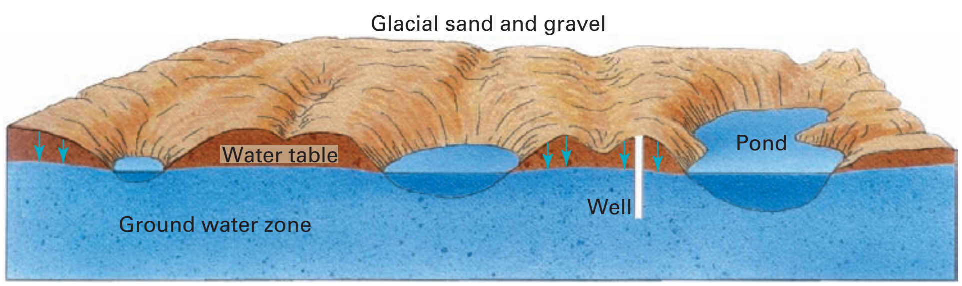
Mountain rivers are often dammed for hydropower because of their narrow canyons and steep slopes. Pictured is the Picote Dam on the Douro River, Portugal.

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 timescale, 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.

The water level of lakes and ponds in moist climates closely coincides with the surrounding water table (FIGURE 11.25). The water surface is maintained at this level as ground water seeps into the lake and as precipitation runs off.



Freshwater ponds FIGURE 11.25

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.

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 level will fall to a lower level.

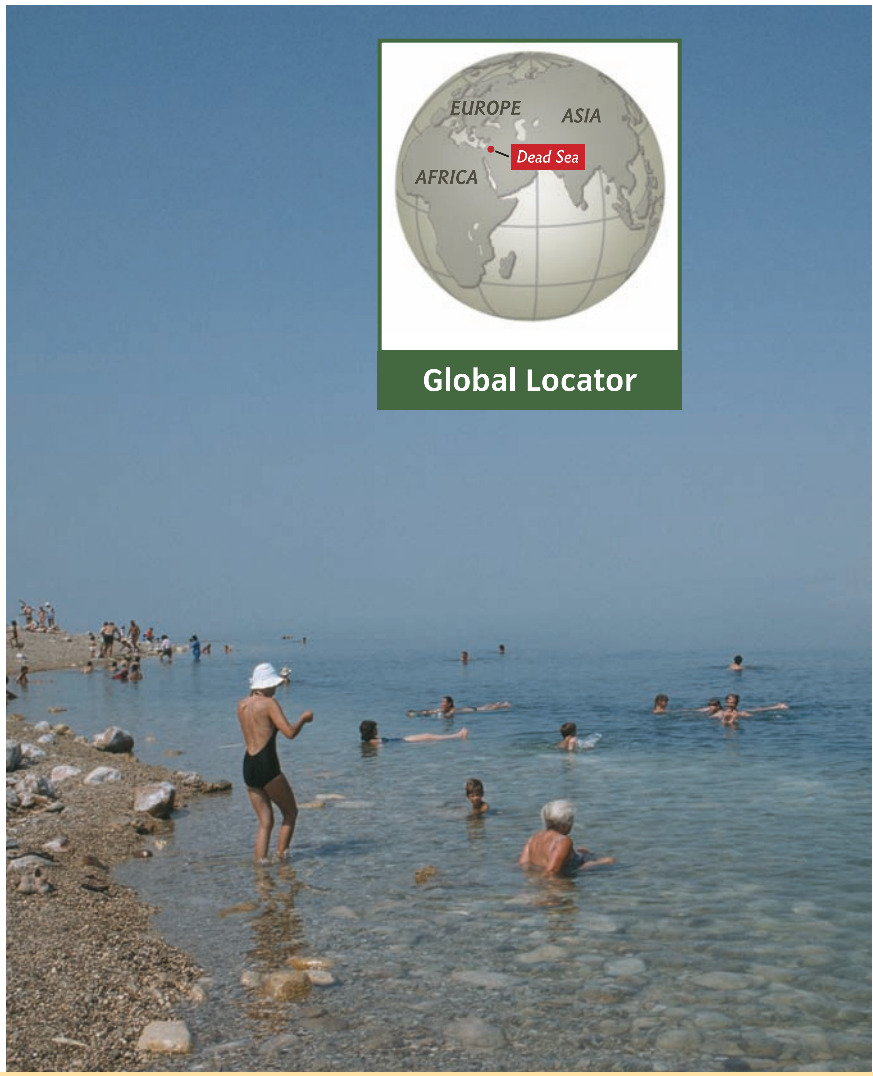
Salt often builds up in these lakes. Streams bring dissolved solids into the lake, and since evaporation removes only pure water, the salts remain behind. The *salinity*, or "saltiness," of the water slowly increases. Eventually, the salinity level reaches a point where salts are precipitated as solids (FIGURE 11.26).

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 11.27). The largest of all lakes, the Caspian Sea, has a surface elevation of –25 m (–82 ft). Both of these large lakes are saline.

In some cases the lake is missing. In regions where the climate encourages evaporation rather than input into the lake, we can find shallow empty basins covered

Salt encrustations FIGURE 11.26

These salt encrustations at the edge of Great Salt Lake, Utah, were formed when the lake level dropped during a dry period.



Dead Sea FIGURE 11.27

Swimmers in the Dead Sea float easily on the dense, salty water.

Bonneville Salt Flats FIGURE 11.28

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.

Aral Sea FIGURE 11.29

Now shrunken to a third of its former volume, the Aral Sea left many vessels stranded high and dry as it receded. Camel breeding has replaced fishing as a source of income in many former seaside villages.

with salt deposits instead of lakes. These are called *salt flats* or dry lakes (FIGURE 11.28). On rare occasions, these flats are covered by a shallow layer of water, brought by flooding streams.

The Aral Sea is an inland lake that is rapidly becoming saline because of human activity (FIGURE 11.29). The two major rivers that feed this vast Central Asian water body were largely diverted into irrigation of agricultural lands. With its water supply cut off, the lake dwindled to a shadow of its former self, decreasing in volume by 66 percent. As the lake's shoreline receded, the exposed lakebed became encrusted with salts. The lake's salinity increased from 1 percent to nearly 3 percent, making it almost as salty as sea water. Twenty of the 24 fish species native to the lake have disappeared.

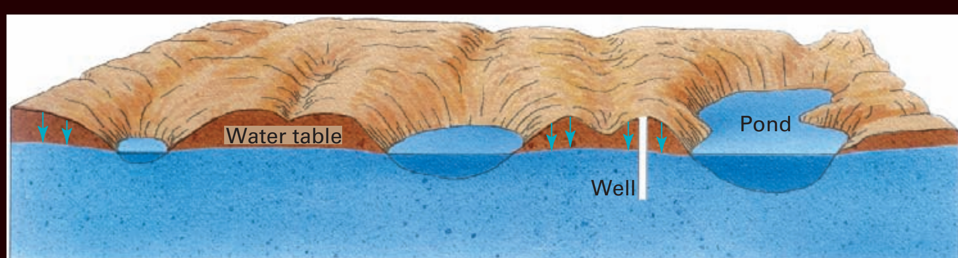
By contrast, some desert salts are quite valuable and have been profitably harvested from salt flats and sold as sea salt for human consumption. One well-known source of this salt is the Rann of Kutch, a coastal lowland in the tropical desert of westernmost India, close to Pakistan. Here the evaporation of shallow water of the Arabian Sea has long provided a major source of salt for people living nearby.

CONCEPT CHECK STOP

How are lakes defined?

Why are lakes important?

How do salt flats form?



Surface Water as a Natural Resource

Learning Objectives

Understand how surface water is used as a natural resource.

Describe how surface water can be polluted.

Fresh surface water is a basic natural resource essential to human agricultural and industrial activities (Figure 11.30). Runoff held in reservoirs behind dams provides water supplies for great urban centers, such as New York City and Los Angeles. When diverted from large rivers, surface water provides irrigation water for highly productive lowlands in arid lands, such as the Sacramento and San Joaquin valleys of California and the Nile Valley of Egypt. 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 liters (50 to 100 gallons) 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. (An exception is the Great Lakes system.) 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 once the reservoir is full, we must still restrict ourselves to using only as much water as is naturally supplied in precipitation.

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.

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 agricul-

Clean catch Figure 11.30

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.

tural 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 11.31). 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.

Water pollution FIGURE 11.31

Acid mine drainage is a major problem in areas of strip mining.

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.

CONCEPT CHECK STOP

How do we use surface water as a natural resource?

Name some common surface water pollutants. Where do they come from?

What is happening in this picture ?

This stunning photograph shows the Temple of the Sun in Carlsbad Caverns, New Mexico. Identify the stalactites, stalagmites, columns, and drip curtains in the picture. What rock is this cavern made from? How did these features form? What substance are these encrusted features made from?

VISUAL SUMMARY

1 The Hydrologic Cycle Revisited

1. The hydrologic cycle replenishes fresh water of the lands.
2. The soil layer diverts precipitation to the atmosphere as evapotranspiration, to ground water through percolation, and to streams and rivers as runoff.

2 Ground Water

1. Ground water occupies the pore spaces in rock and regolith. It moves in slow paths deep underground, recharging rivers, streams, ponds, and lakes.
2. Karst landscapes form when ground water dissolves limestone.
3. Landfills and dumps are common sources of ground-water contaminants.

3 Surface Water

1. Overland flow moves as a sheet across the land surface. Stream flow is confined to a channel.
2. Rivers and streams are organized into a drainage system that moves runoff from slopes into channels and from smaller channels into larger ones.

4 Stream Flows and Floods

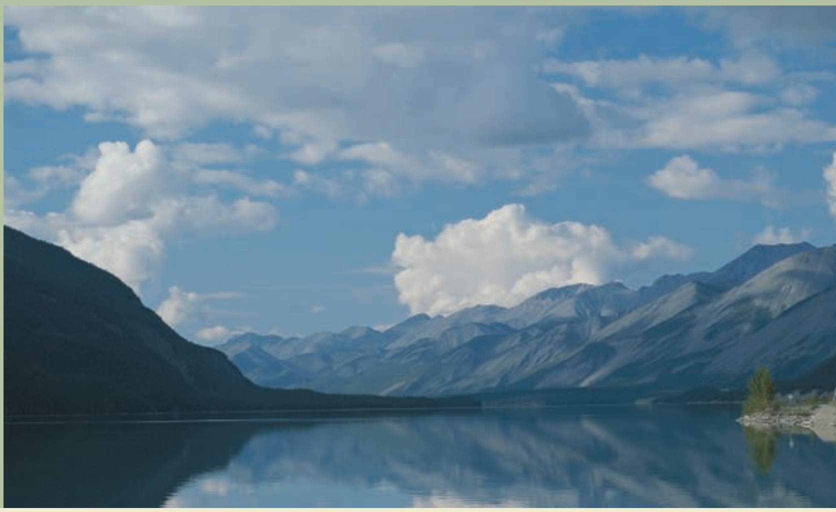
1. The hydrograph plots the discharge of a stream at a location through time.

2. Floods occur when river discharge increases and the flow can't be contained within the river's usual channel.

5 Lakes

1. Lakes are sources of fresh water and they can supply hydroelectric power.

2. Lakes in inland basins are often saline. When the climate changes, such lakes can dry up, creating salt flats.



6 Surface Water as a Natural Resource

1. Because fresh water is such a small part of the global water pool, it is important to carefully plan and manage water resources.

2. Water pollution arises from many sources, including industrial sites, sewage treatment plants, agricultural activities, mining, and processing of mineral deposits.

KEY TERMS

- **infiltration** p. 328
- **runoff** p. 328
- **ground water** p. 330
- **water table** p. 330
- **aquifer** p. 331
- **stream** p. 338
- **drainage system** p. 340
- **floodplain** p. 346
- **lake** p. 348

CRITICAL AND CREATIVE THINKING 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. What happens to precipitation falling on soil? How and under what conditions does precipitation reach ground water?

3. Sketch a cross section through the land surface showing the position of the water table. Draw arrows showing the flow directions of subsurface water and include the flow paths of ground water. Include a stream in your diagram. Label the saturated and unsaturated zones.

4. Why does water rise in an artesian well? Illustrate with a sketched cross-sectional diagram showing the aquifer, aquicludes, and the well.

5. Describe the key features of a karst landscape. How do they form?

6. How is ground water contaminated? Describe how a well might become contaminated by a nearby landfill dump.

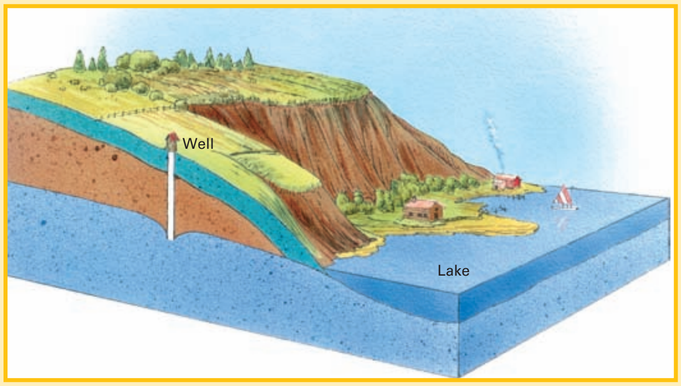
7. What is a drainage system? How are slopes and streams arranged in a drainage basin?

8. How are lakes defined? What are some of their characteristics? What factors influence the size of lakes?

9. 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.

SELF-TEST

1. Label the following regions on this diagram showing the zones of subsurface water: (a) the saturated zone, (b) the soil-water belt, (c) the unsaturated zone, and (d) the water table.



2. Where is the water table at its highest?
   a. under the lowest areas of land surface
   b. under the highest areas of land surface
   c. adjacent to perennial streams
   d. in lakes

3. A layer of rock or sediment that contains abundant, freely flowing ground water is known as a(n) _______________.
   a. aquiclude
   b. aquitard
   c. aquifer
   d. perched water table

4. Geographers apply the term _______________ to the topography of any limestone area where sinkholes, as shown in this photograph, are numerous and small surface streams are nonexistent.
   a. travertine
   b. karst
   c. carbonate
   d. dolomite

5. In cases where many water-pumping wells are in operation, the rate of ground-water depletion exceeds recharge to the point where ground water is often classified as a _______________ resource.

a. depleting
b. renewable
c. nonrenewable
d. sustainable

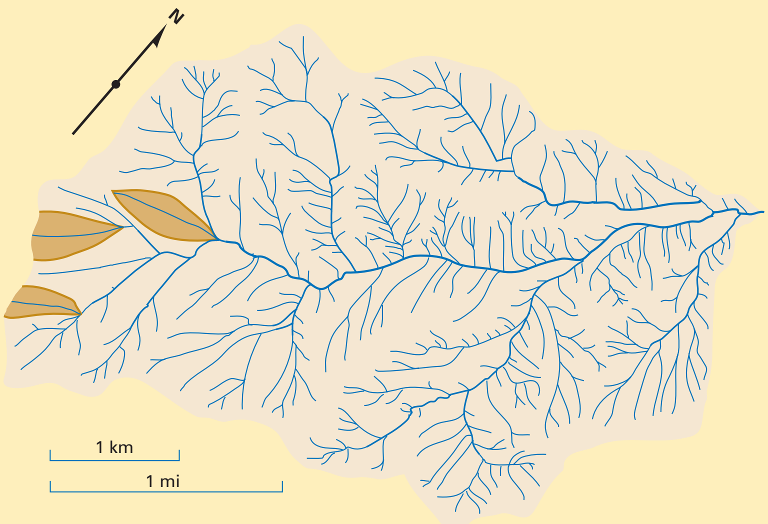
6. A source of ground-water contamination in coastal wells is _______________.

a. saltwater intrusion
b. solid-waste disposal
c. high-temperature incineration
d. air pollution

7. The _______________ of a stream is a narrow trough, shaped by the forces of flowing water.

a. course
b. fall
c. channel
d. mouth

8. On the diagram of the channel network of a stream, label the outer divide, stream basin, and drainage divides.



9. Stream flow at a given location is measured by its _______________.

a. gradient
b. volume
c. water velocity
d. discharge

10. A _______________ consists of a branched network of stream channels and adjacent slopes that feed the channels.

a. drainage system
b. drainage boundary
c. drainage divide
d. drainage basin

11. The most important factor determining the lag time between a period of heavy rainfall or snowmelt and a stream's increased discharge response is _______________.

a. the size of the drainage basin feeding the stream
b. the number of drainage systems involved
c. the amount of drainage basin rainfall or snowmelt
d. the steepness of the gradient of the drainage basin

12. A _______________ is a particular river surface height at a particular location above which floodplain inundation will occur.

a. lag-time stage
b. floodplain stage
c. center of mass of runoff
d. flood stage

13. Flash floods are characteristic of streams draining _______________ watersheds with _______________ slopes.

a. large; gentle
b. small; steep
c. small; gentle
d. large; steep

14. An important point about _______________ is that they are short-lived features on the geologic time scale.

a. rivers
b. floodplains
c. lakes
d. drainage basins

15. Lakes without outlets other than evaporation often show _______________.

a. salt buildup
b. a lesser surface area
c. silty bottoms
d. reduced volumes

Landforms Made by Running Water

12

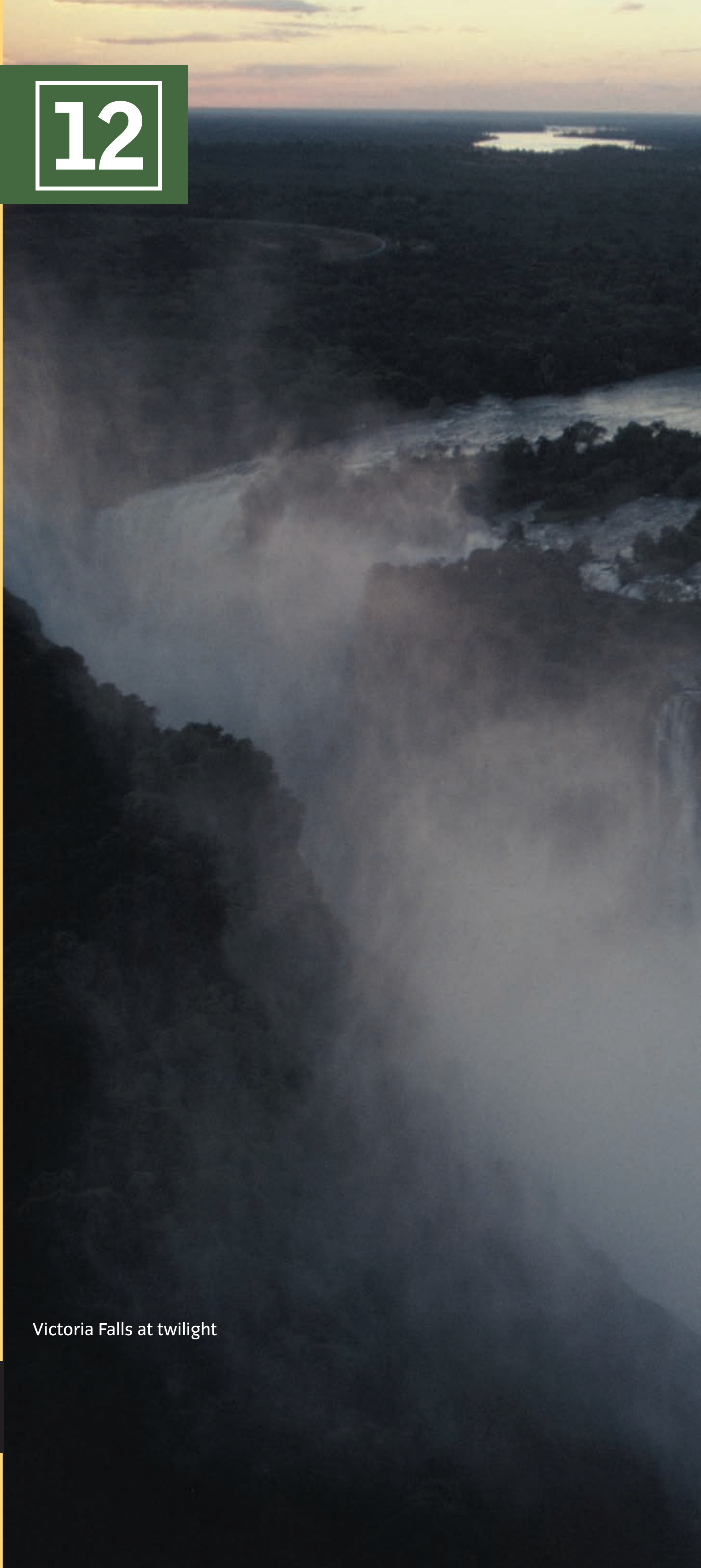
"Mosi-oa-Tunya" or "the smoke that thunders," as it was dubbed by the local Makololo tribe in the nineteenth century, is the largest single sheet of water in the world—over 100 meters tall and over one mile wide.

Today, we know this curtain of water as the Victoria Falls. The series of waterfalls are formed as the Zambezi River that borders Zambia and Zimbabwe plummets into a narrow chasm about 120 m (400 ft) wide, carved by its waters along a fracture zone in the Earth's crust.

The waterfall converts the calm river to a ferocious torrent. The loud roar produced as 9.1 million cubic meters (321 million cubic feet) of water per minute thunder over the edge of the basalt cliff can be heard from 40 km (25 miles) away.

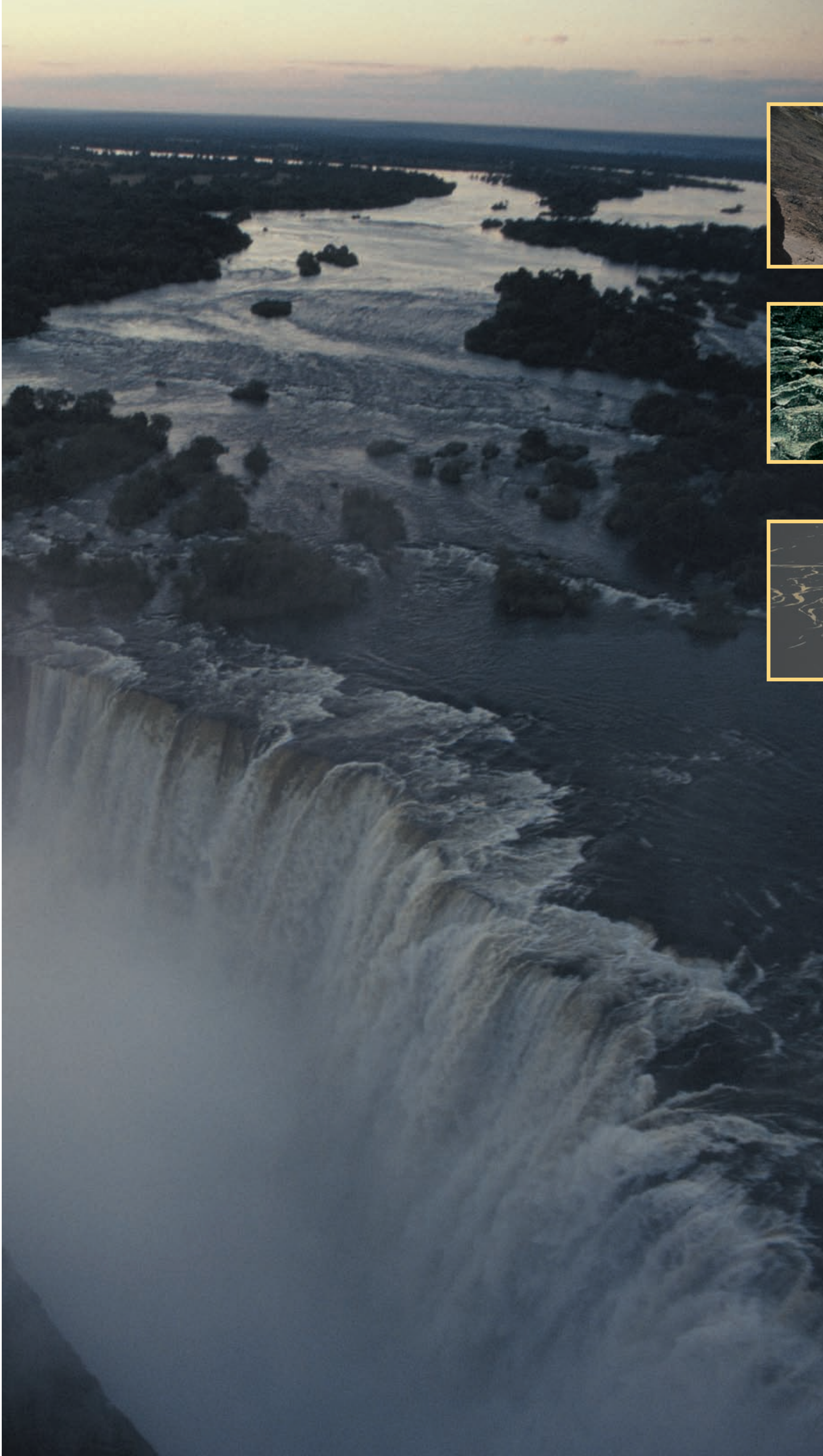
Humans have learned to harness the power of waterfalls, here and around the world. The first small power station was set up to generate hydroelectric power in the third gorge below Victoria Falls in 1938. In North America, the Niagara Power project exploits the 52-m (171-ft) drop over Niagara Falls by withdrawing water upstream of the waterfalls and carrying it through tunnels to generating plants located about 6 km (4 mi) downstream.

It's easy to imagine how the immense force of these spectacular waterfalls can mold the land below. Over the course of centuries, even gentle flows of running water have sculpted many of the distinctive landforms we see around us by eroding land and depositing sediment.



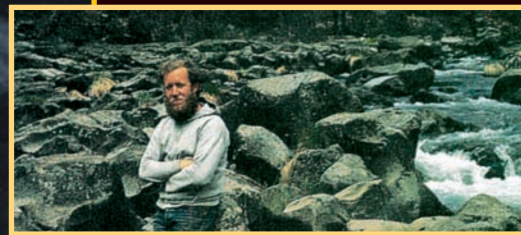
Victoria Falls at twilight

NATIONAL GEOGRAPHIC



CHAPTER OUTLINE

- Slope Erosion p. 360



- The Work of Streams and Stream Gradation p. 365

- Fluvial Landscapes p. 370

Slope Erosion

LEARNING OBJECTIVES

Define erosional and depositional landforms.

Identify three types of soil erosion.

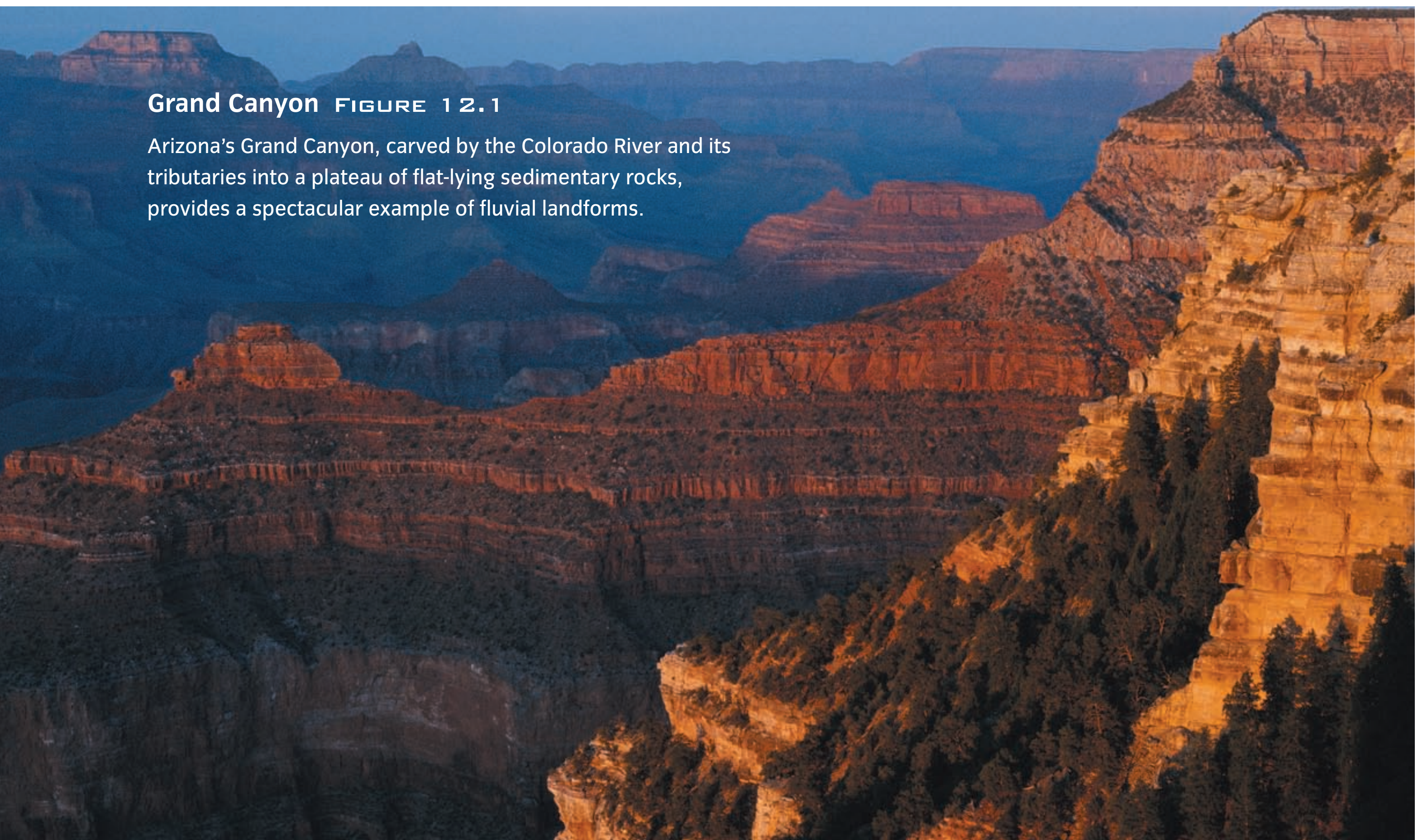
Most of the world's land surface has been sculpted by running water. Waves, glacial ice, and wind also carve out landforms, but for physical geographers, running water is the most important. That's because landforms made by glacial ice, wind, and waves are restricted to certain areas on the globe. We'll look at some of these other landform-creating agents in later chapters, but in this chapter we will concentrate on **fluvial landforms** (FIGURE 12.1).

Fluvial landforms Landforms shaped by running water.

Fluvial landforms are made by overland flow and stream flow. 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 mineral fragments that are carried into stream systems. In this way, running water erodes mountains and hills, carves valleys, and deposits sediment.

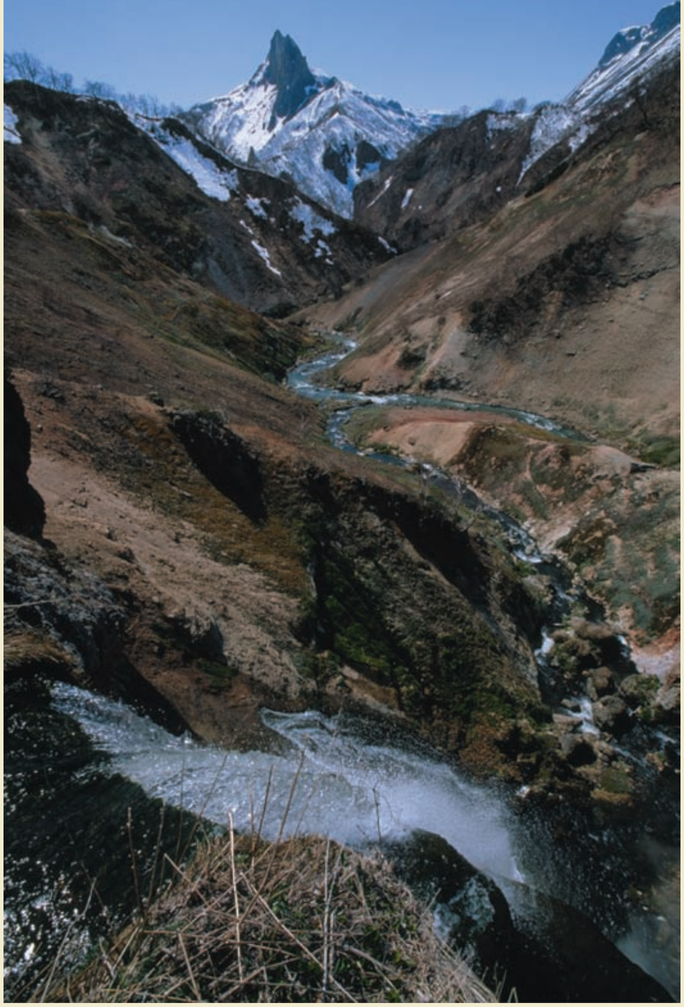
There are two major groups of landforms—erosional landforms and depositional landforms. As a crustal block is uplifted by plate tectonic activity, it is attacked by running water. Valleys form as rock is eroded away by fluvial agents (FIGURE 12.2A). The ridges, hills, or mountain summits that we see 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 that are removed from the parent rock mass are transported and deposited elsewhere, making an en-

Erosional landforms Landforms shaped by the removal of regolith or bedrock by erosion.



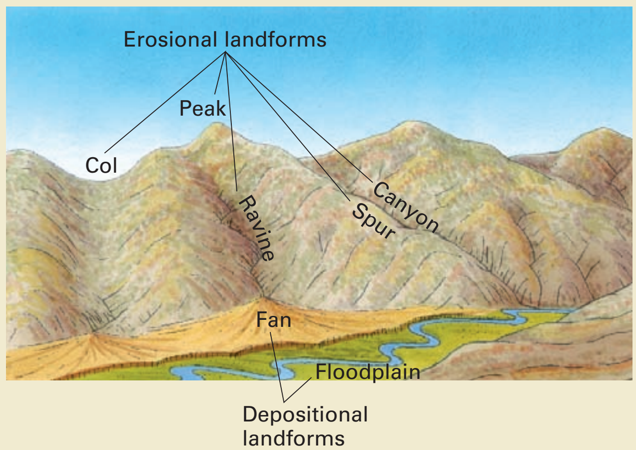
Grand Canyon FIGURE 12.1

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.



A **Ravine** This narrow valley, located in a biosphere reserve on the Kamchatka Peninsula, is an example of an erosional landform.

B **Alluvial fan** An alluvial fan in Wrangell Saint Elias National Park, Alaska, is a depositional landform.



C **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.

Erosional and depositional landforms FIGURE 12.2

Depositional landforms
Landforms made by the deposition of sediment.

tirely different set of surface features—the **depositional landforms** (FIGURE 12.2B).

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*, and it allows plant communities to maintain themselves.

ACCELERATED SOIL EROSION

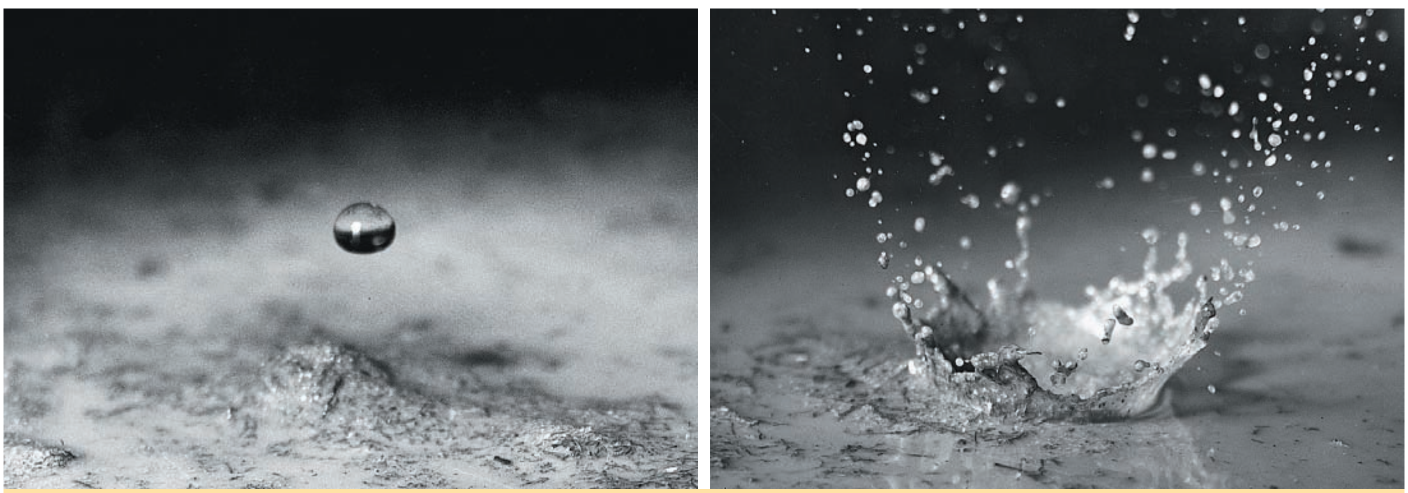
In contrast to this natural balance, human activities can enormously accelerate soil erosion rates. Destroying vegetation and clearing land for cultivation sets the stage for a series of drastic changes. If there's no foliage to intercept rain and no ground cover from fallen leaves and stems, raindrops 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 rare natural events, such as forest fires, 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 12.3). 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 ground surface's resistance to erosion under overland flow. Even deep layers of overland flow can only cause a little soil erosion on slopes that have a protective covering of grass sod. This is because the grass stems are tough and elastic, creating friction with the moving water and taking up the water's energy. Without such a cover, the water can easily dislodge soil grains, sweeping them downslope.

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 rapidly, turning into gullies—steep-walled, canyon-like trenches whose upper ends grow progressively upslope (FIGURE 12.4). Ultimately, accelerated soil erosion creates a rugged, barren topography.

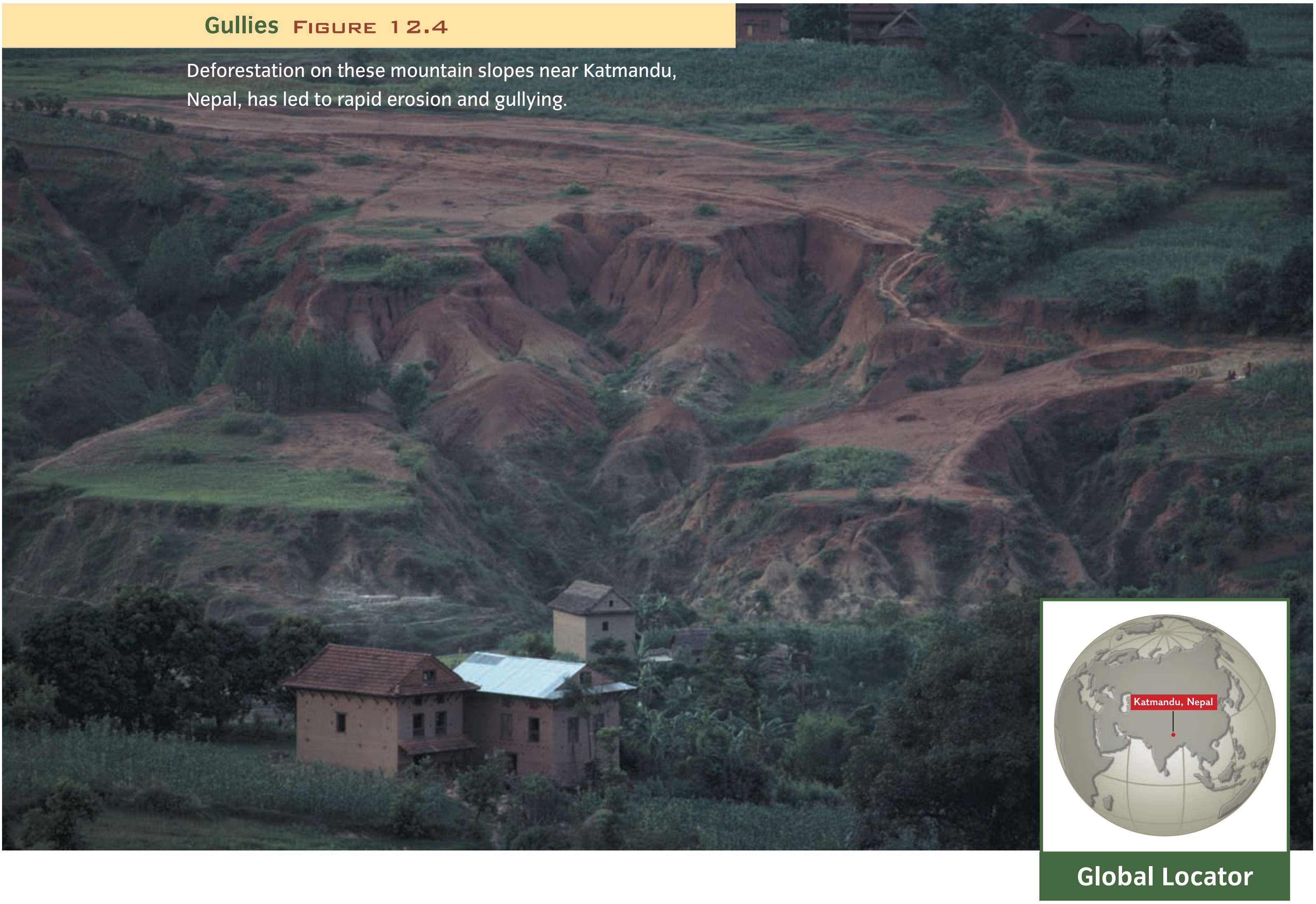


Soil erosion by rain splash FIGURE 12.3

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.

Gullies FIGURE 12.4

Deforestation on these mountain slopes near Katmandu, Nepal, has led to rapid erosion and gullying.



Soil particles picked up by overland flow will be carried downslope. Eventually, they reach the base of the slope, stopping where the surface slope becomes more gentle and meets the valley bottom. The 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.

Alluvium Any sediment laid by a stream that is found in a stream channel or in low parts of a stream valley subject to flooding.

SLOPE EROSION IN SEMIARID AND ARID ENVIRONMENTS

So far, we've been talking about slope erosion in moist climates where there are natural forests and 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.

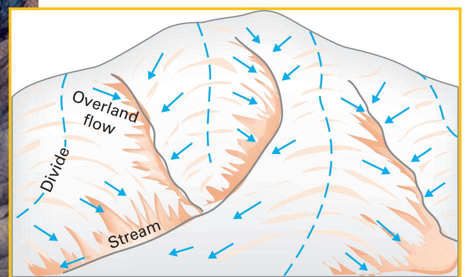
What a Geographer Sees

Badlands

Landscapes such as the one shown in this striking photo at Zabriskie Point, Death Valley National Monument, California, were named "mako sica"—literally "bad lands"—by the Native American Lakota tribe. French trappers called them "les mauvaises terres à traverser" or "the bad lands to cross."

These regions are indeed difficult to travel over, thanks to their steep slopes and loose soil. A geographer passing through would observe that this maze of small stream channels and slopes has a clay-rich soil, making it especially vulnerable to erosion by overland flow. Erosion rates here are too fast for plants to take hold, and no soil can develop.

Badlands have existed naturally throughout much of geologic time. But they can also be created by poor agricultural practices that disturb the vegetation cover of the clay.



Overland flow from slopes sweeps clay particles into the stream channels.

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. We have to be careful with these sensitive, marginal environments because they won'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 and arid lands, as you can see in "What a Geographer Sees: Badlands."

CONCEPT CHECK **STOP**

What do we call landforms created by running water?

Describe two groups of such landforms.

What is splash erosion?

What factors accelerate soil erosion?

The Work of Streams and Stream Gradation

Learning Objectives

Describe stream erosion, stream transportation, and stream deposition.

Define stream load.

Explain 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 body of the stream by turbulent water motion or are dissolved and held in solution. The transported particles are finally deposited on the stream bed 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 stream bed, 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 12.5).

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.

Potholes FIGURE 12.5

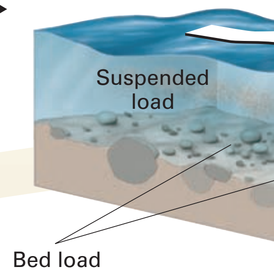
These potholes in lava bedrock were created by abrasion on the bed of a swift mountain stream. The holes are produced when a shallow depression in the bedrock of a stream bed acquires one or several grinding stones, which are spun around and around by the flowing water, carving a hole in the rock.

Process Diagram

Graded streams

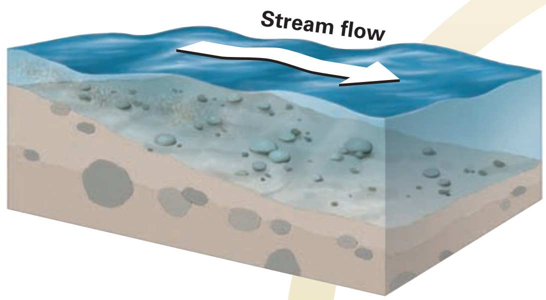
Graded Streams Every stream channel adjusts to the amount of sediment supplied to it at each segment. This graphic shows how a stream segment responds to either an increase (left) or a decrease (right) in the amount of sediment it receives. In both cases, the stream channel reaches *equilibrium*. Over 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*.

A Stream channel A stream channel carries sediment that has been supplied by runoff from a stream basin and from flow.

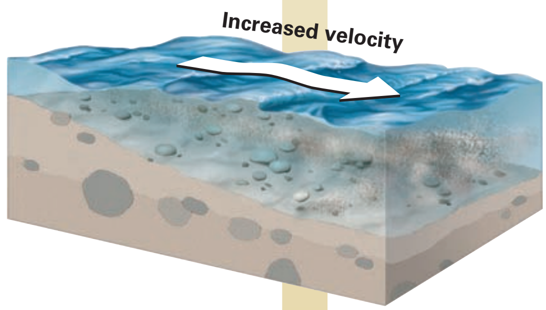


INCREASED SEDIMENT

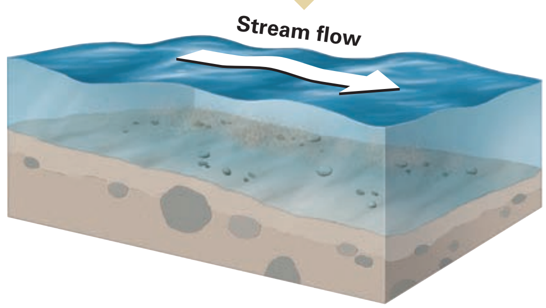
B Increased sediment If more sediment accumulates each year in the stream channel than can be carried away, the channel surface builds up, which increases the stream's slope.



C Increased velocity With increased slope comes increased stream velocity and a greater capacity to carry sediment.



D Equilibrium Eventually, the slope will stabilize so that the stream just carries away the sediment that it receives.



H 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.

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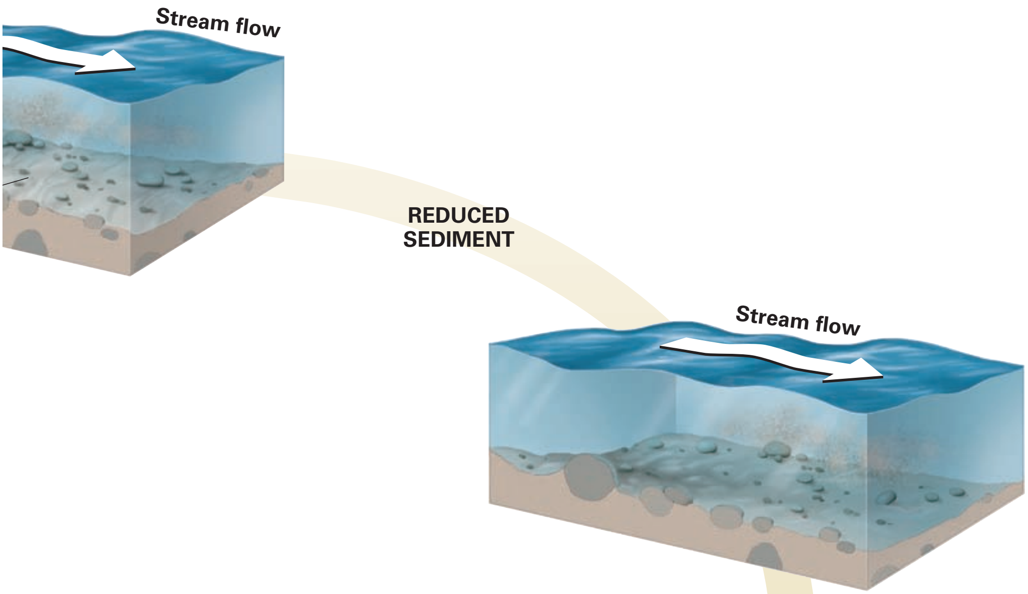
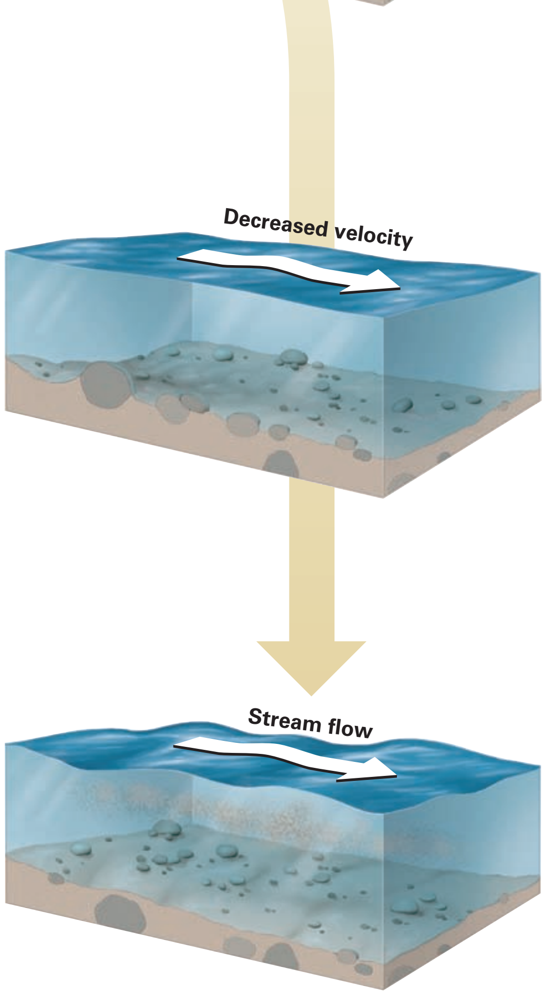
college/strahler



◀ **E Reduced sediment** If the sediment flow to the stream is reduced, the stream will gradually erode its channel downward, reducing its slope.

▲

I 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 river banks.



◀ **F Decreased velocity** Reducing its slope also reduces the stream's velocity, and therefore its capacity to carry sediment.

◀ **G Equilibrium** Eventually, the slope will stabilize so that the stream just carries away the sediment that it receives.

STREAM TRANSPORTATION

The solid matter carried by a stream is the **stream load**. FIGURE 12.6 illustrates that stream load is carried in three ways—dissolved, suspended, or as 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.

Stream load
Solid matter carried by a stream in dissolved form (as ions), in suspension, and as bed load.

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 metric tons per day passing downstream at a given location.

A stream's capacity increases sharply as its 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 eight to sixteen times. So, most of the conspicuous changes in a stream channel occur in a flood.

When water flow increases, a stream that's 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.

STREAM GRADATION

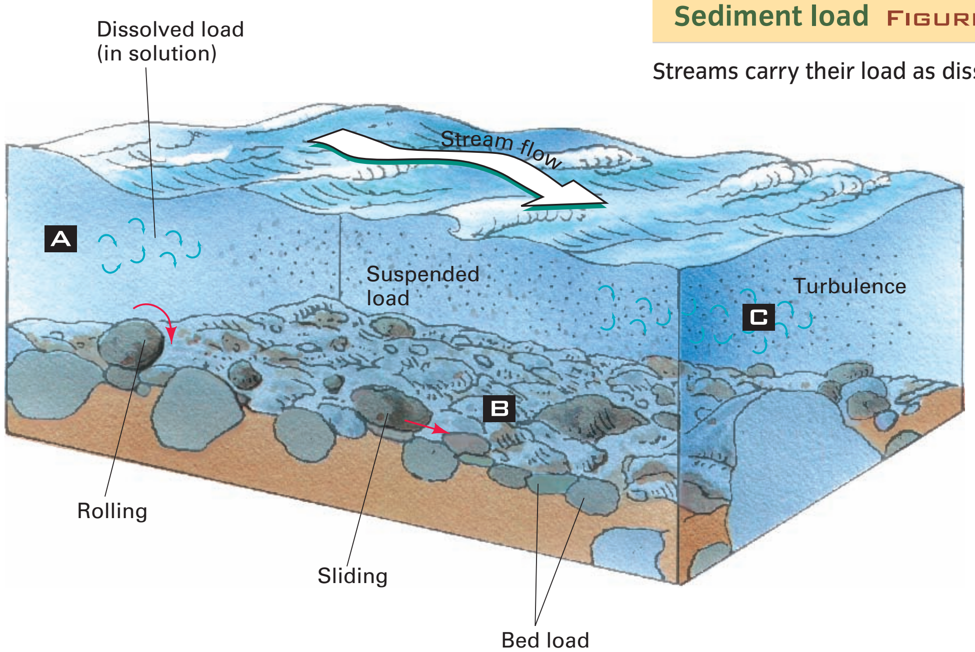
Most major stream systems have gone through thousands of years of runoff, erosion, and deposition. Over time, the gradients of different parts of the stream adjust so that they just carry the average load of sediment that they receive from slopes and inflowing channels. A stream in this condition is called a **graded stream**. How does this come about? The process diagram "Graded streams" answers this question by looking at one segment of a stream.

Graded stream
Stream with a gradient adjusted so that average bed load transport balances average bed load input.

FIGURE 12.7 shows how the stream gradation process over a landscape creates *floodplains* and **alluvial**

Sediment load FIGURE 12.6

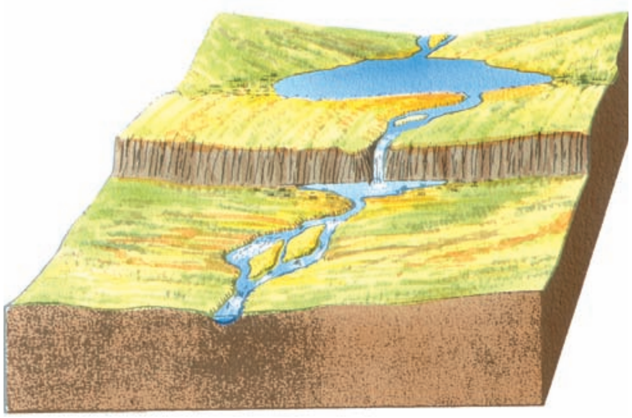
Streams carry their load as dissolved, suspended, and bed load.



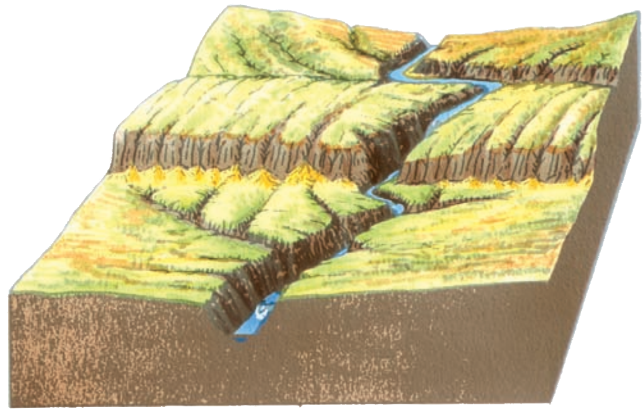
A Dissolved matter is transported invisibly in the form of chemical ions. All streams carry some dissolved ions created by mineral alteration.

B Sand, gravel, and larger particles move as bed load, rolling or sliding close to the channel floor.

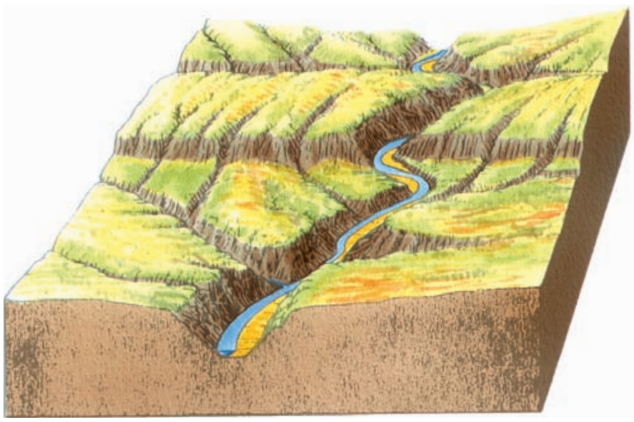
C Clay and silt are carried in suspension—that is, they are held within the water by the upward elements of flow in turbulent eddies in the stream.



A 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.



B 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.



C Once the stream is graded, floodplains develop. The river begins to wander sidewards, cutting into the side slopes, creating a curving path. Alluvium accumulates on the inside of each bend.

D 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 steep valley walls.

Evolution of a graded stream and its valley FIGURE 12.7

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Alluvial meanders
Sinuous bends of a graded stream flowing in the alluvial deposit of a floodplain.

meanders over time. Once the floodplain has developed, 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. As a result, in a humid climate, gorge-like valleys gradually disappear, becoming open valleys with soil-covered slopes 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.

CONCEPT CHECK STOP

What are the three activities associated with stream movement?

Name three ways that streams can erode. Describe each process.

Identify three types of stream load.

What is a graded stream? How long does it take for a stream to reach a graded condition and erode a broad valley?

Fluvial Landscapes

LEARNING OBJECTIVES

Describe landscapes associated with stream gradation.

Explain the geographic cycle.

GREAT WATERFALLS

As we saw at the opening of the chapter, faulting and dislocation of large crustal blocks have resulted in spectacular waterfalls on several east African rivers. But such large waterfalls are comparatively rare the world over. That's because, as we learned in the previous section, the stream gradation process drains lakes and removes falls and rapids.

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 12.8). 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.

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 load at downstream points, and these changes in turn require channel readjustments. One such change is the buildup of alluvium in the valley floors.

Picture a stream transporting sediment. Think about 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 stream bed, 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.

Aggradation
Raising of stream channel altitude by continued deposition of bed load.

Aggradation changes the channel cross section from a narrow and deep form to a wide and shallow

Niagara Falls FIGURE 12.8

This panoramic image shows the Niagara River as it plunges over the Canadian (Horseshoe) Falls (foreground, right) and the American Falls (center). The river, which connects Lakes Erie and Ontario, provides water for domestic and industrial uses as well as hydroelectric power.

Braided stream FIGURE 12.9

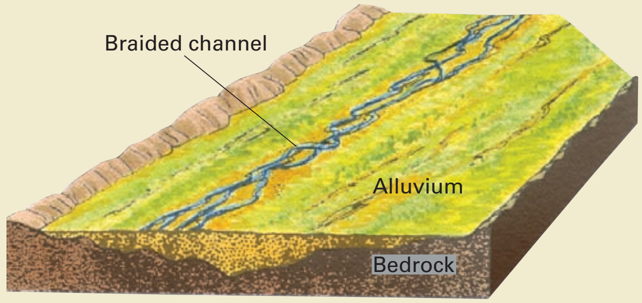
The braided channel of the Chitina River, Wrangell Mountains, Alaska, shows many channels separating and converging on a floodplain filled with coarse rock debris left by a modern valley glacier at the head of the valley. Glacial activity played a major role in shaping stream systems of North America and Eurasia during the recent Ice Age. Valley aggradation similar to that seen here was widespread near the edges of the great ice sheets of the Ice Age. The accumulated alluvium filled most valleys to depths of several tens of meters.

one. The new sediment deposits encourage the flow to divide into multiple threads, which rejoin and subdivide repeatedly to create a braided stream (FIGURE 12.9). The coarse channel deposits spread across the former floodplain, burying fine-textured alluvium under the coarse material.

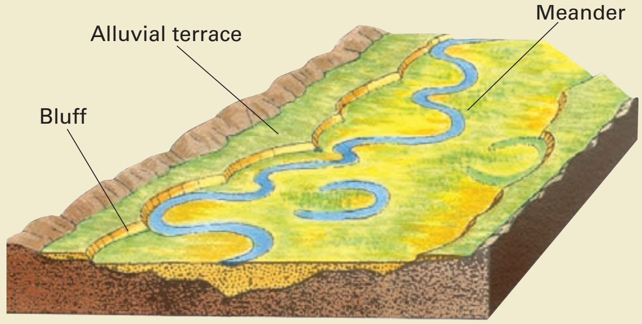
Why does alluvium build up on valley floors, inducing stream aggradation? Alluvium can accumulate after accelerated soil erosion. Other causes of aggradation are related to major changes in global climate, such as the onset of an ice age. FIGURE 12.10 examines how an aggrading stream in a valley creates features called *alluvial terraces*. 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 hill slopes, 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.

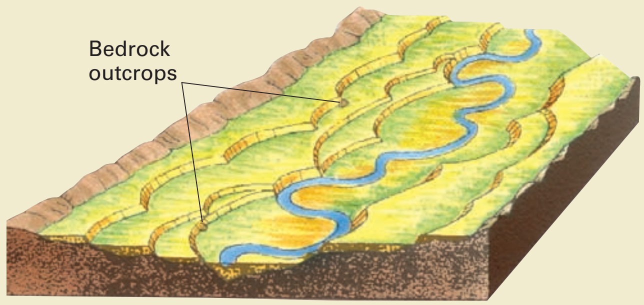
Alluvial terrace formation FIGURE 12.10



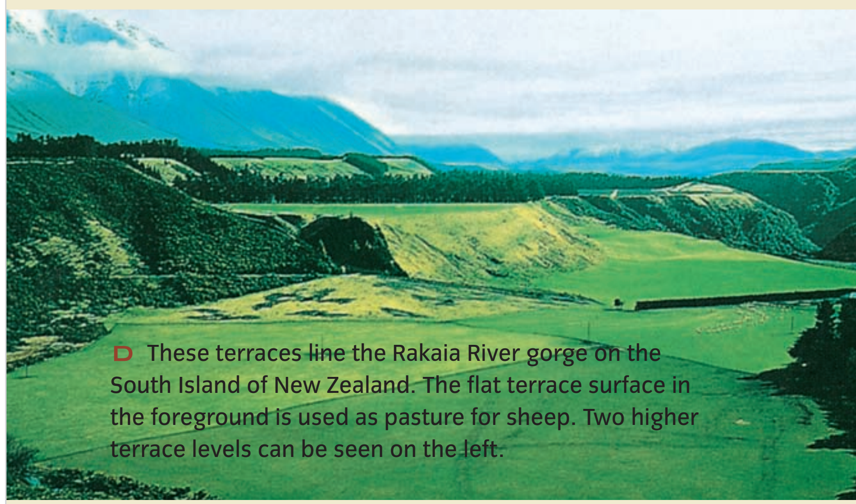
A Suppose that the stream's bed load is cut off, for example, because the ice sheets providing rock debris have disappeared. In addition, reforestation covers the neighboring slopes, stopping coarse mineral particles from entering the stream through overland flow. The stream is now below its transporting capacity.



B The channel becomes both deeper and narrower, in response, 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.



C This leaves step-like alluvial surfaces on both sides of the valley. The treads of these steps are called alluvial terraces.



D 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.

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* 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 normally experiences overbank floods each year or two, when there is a large water surplus over the watershed (FIGURE 12.11).

FIGURE 12.12 illustrates the typical landforms of an alluvial river and its floodplain, including *bluffs*, *ox-bow lakes*, *natural levees*, and *backswamps*. When the floodplain is inundated, water spreads from the main channel over adjacent floodplain deposits. As the current slackens, sand and silt are deposited in a zone next to the channel, creating *natural levees*—belts of higher land on either side of the channel. Between the levees and the bluffs that bound the floodplain is lower ground, called the backswamp. Overbank flooding also infuses the soil with dissolved minerals. The resupply of nutrients helps floodplain soils retain their remarkable fertility, even though they are located in regions of rainfall surplus from which these nutrients are normally leached away.

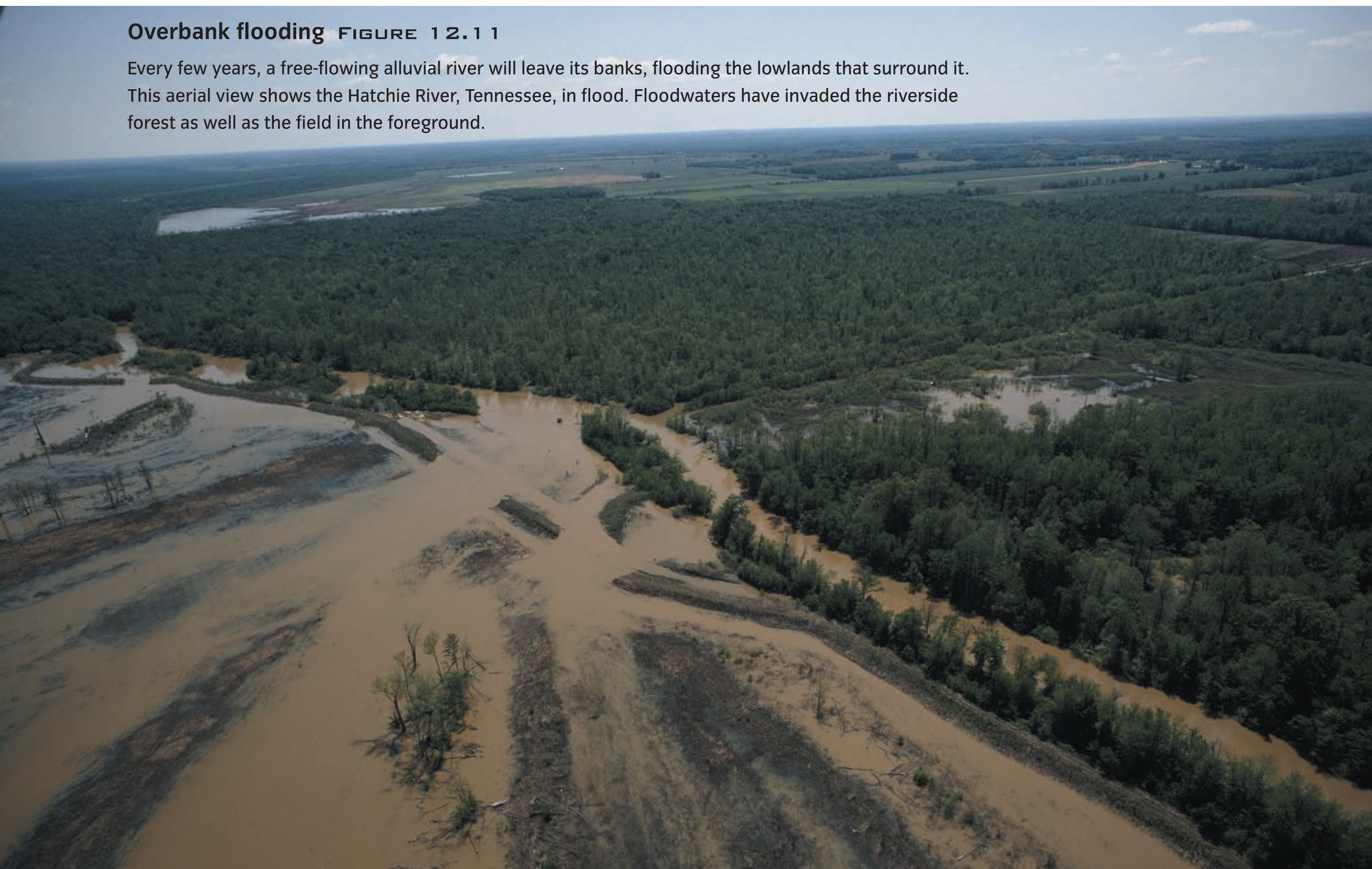
ENTRENCHED MEANDERS

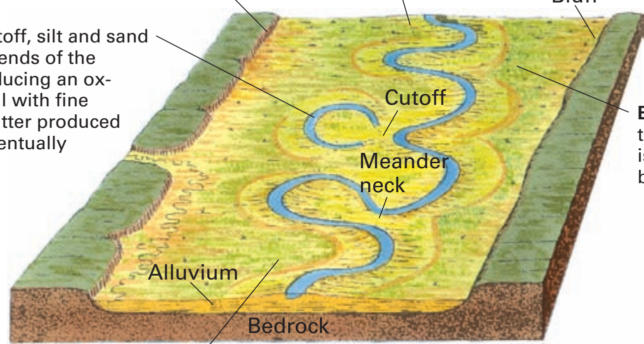
What happens when a broadly meandering river is uplifted by rapid tectonic activity? The uplift increases the river's gradient, and in turn, its velocity, so that it cuts downward into the bedrock below. This forms a steep-walled inner gorge. On either side of the gorge there will be the former floodplain, 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

Overbank flooding FIGURE 12.11

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.





Floodplain landforms of an alluvial river FIGURE 12.12

gorge. We call these sinuous bends *entrenched meanders* (FIGURE 12.13) 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

Entrenched meanders FIGURE 12.13

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 (1400 ft) deep.

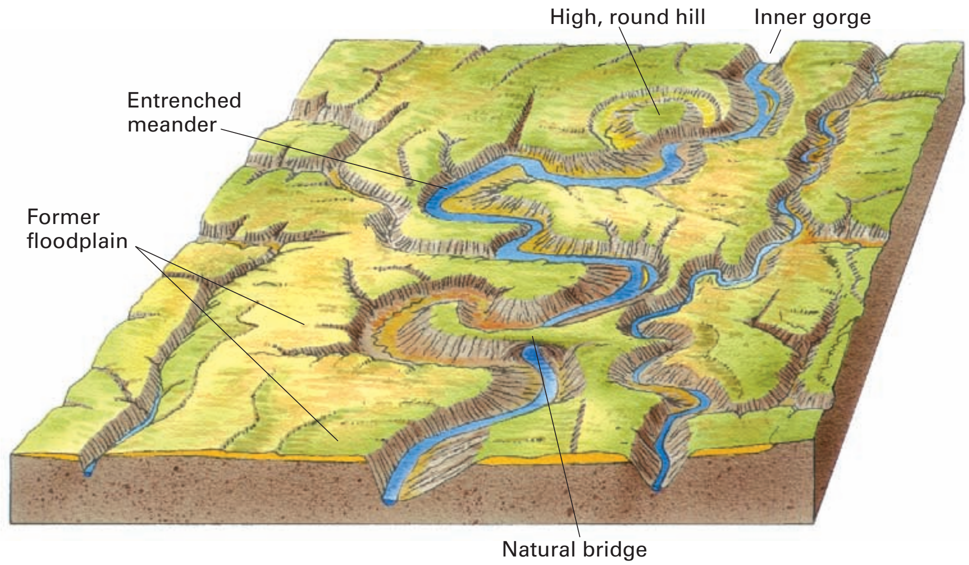
Cutoff entrenched meander FIGURE 12.14

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.

the valley wall by the deep abandoned river channel and the shortened river course (FIGURE 12.14). 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 (FIGURE 12.15).

Diagram of entrenched meanders FIGURE 12.15

Uplift of a meandering stream has produced entrenched meanders. One meander neck has been cut through, forming a natural bridge.



ALLUVIAL FANS

One very common landform built by braided, aggrading streams is the **alluvial fan** (FIGURE 12.16). 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. In fact, some desert fans are many kilometers across.

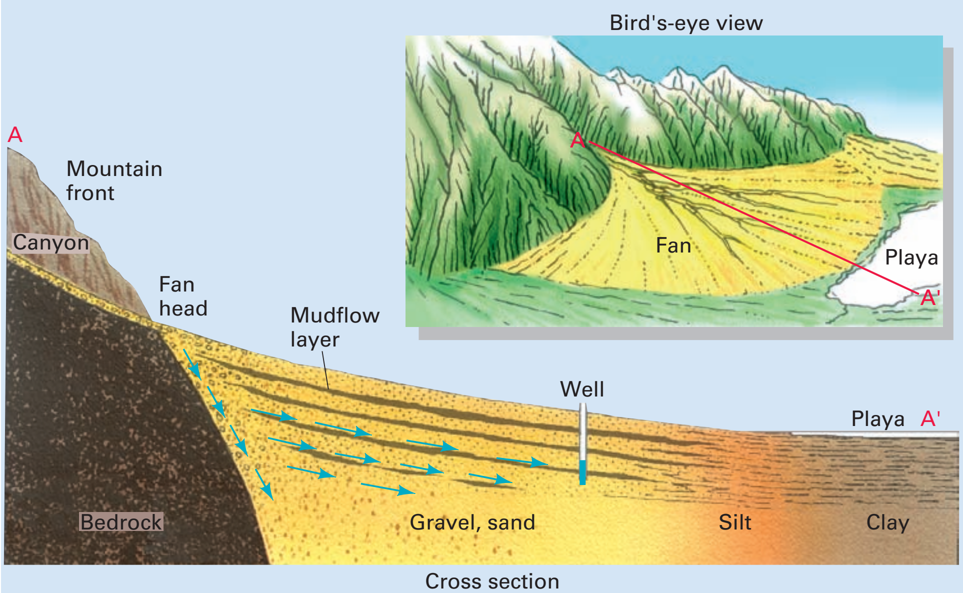
Alluvial fan
Gently sloping, conical accumulation of coarse alluvium deposited by a braided stream.

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 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. In fact, in many fan areas, we have lowered the water table in a short time by heavily pumping these reservoirs for irrigation. In comparison, it takes an extremely long time for these ground-water reserves to be recharged from precipitation. One serious side effect of removing too much ground water is subsidence.

Alluvial fans FIGURE 12.16

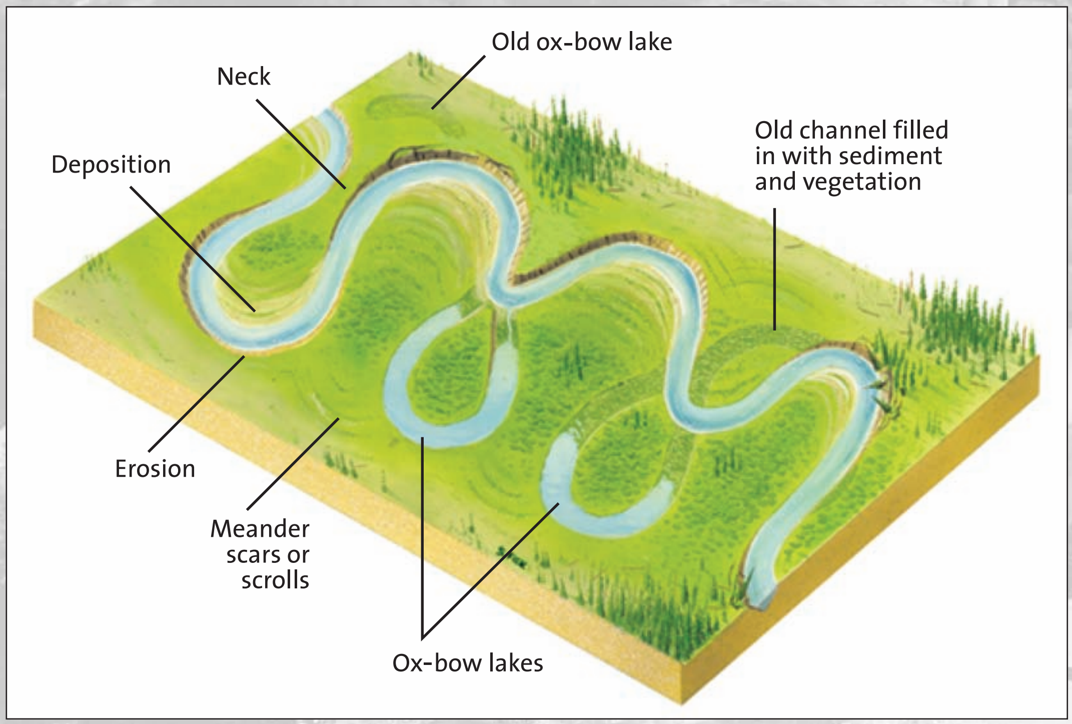
A This vast alluvial fan extends out onto the floor of Death Valley. The fans are built by streams carrying rock waste from a great uplifted fault block, the Panamint Range, located to the west of the valley.



B A cross section shows mudflow layers interbedded with sand layers, providing water (arrows) for a well in the fan.

WORK OF RIVERS AND STREAMS

The downhill flow of water in channels creates erosional landforms as the water picks up sediment and carries it away. Depositional landforms result when sediment is deposited in river floodplains and deltas.



▲ **MEANDERS**
Meanders are the smooth, rounded bends of rivers that increase in size as the river grows and its floodplain widens. They grow outward and migrate downstream. When meanders touch, the river quickly takes the shortcut, leaving a meander scar or ox-bow lake. Large floods can produce major changes in the shape of a river's course.

Visualizing

Landforms of Running Water

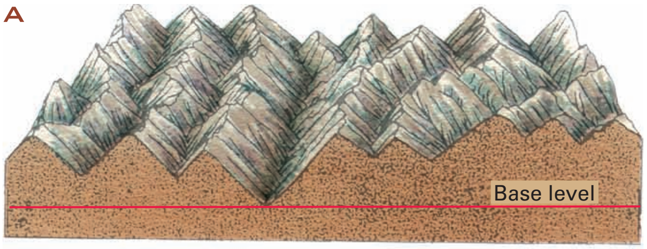
◀ **ALTO GOLFO BIOSPHERE RESERVE, MEXICO**
Like veins on a leaf or limbs on a tree, branching patterns are one of nature's repeating forms. This striking photo, taken from the Colorado River Delta, shows a system of channels carved into layers of mud by the ebb and flow of tidal currents.

▲ **BLYDE RIVER CANYON, SOUTH AFRICA**
Plunging down the slope of South Africa's great Eastern Escarpment, the Blyde River carved this steep, colorful canyon in flat-lying sedimentary rocks. In the far distance is the Lowveld, an interior plain leading to the Kruger National Park, the world's largest game reserve.

▲ **RIVER RECREATION**
Rivers provide natural transportation routes, allowing coastal boats and barges to reach inland cities. But rivers also transport smaller craft and their passengers on journeys taken just for the thrill of it.

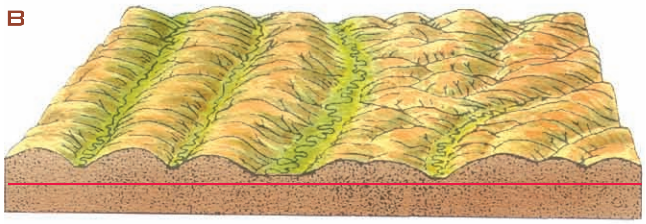
The geographic cycle of William Morris Davis

A



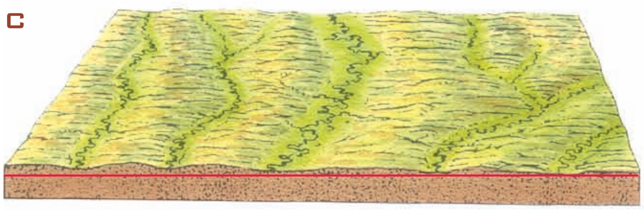
Youthful stage A landscape, made up of many drainage basins and their branching stream networks, has been rapidly uplifted by tectonic forces. The region is rugged and the rate of erosion is rapid. Almost all of the surface is well above the base level, an elevation that is just sufficient to allow streams to drain to the ocean.

B



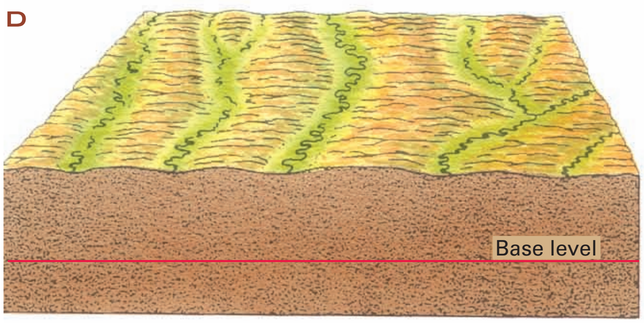
Mature stage After a time, the main streams become graded, transporting rock debris out and eventually lowering the land surface. The sharp peaks and gorges of the youthful stage become rounded.

C



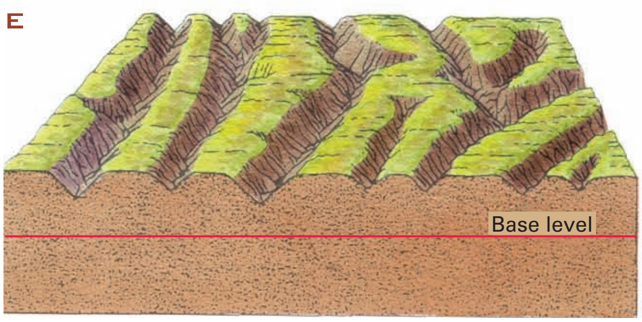
Old age The gradients of streams and valley-side slopes gradually lower. The land surface approaches sea level at a slower pace. After millions of years, the land surface is reduced to a low, gently rolling surface called a peneplain, which is very close to the base level.

D



Peneplain uplift The peneplain is now uplifted by plate tectonic activity.

E



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.

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THE GEOGRAPHIC CYCLE

As we've seen, 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. The process diagram, "The geographic cycle" looks at this in more detail.

Geographic cycle
Theory suggesting that landscapes go through stages of development and that the rejuvenation of landscapes arises from tectonic uplift of the land.

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 upon it, including both forces of uplift and denudation activities that wear down rocks.

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 hill slopes and stream gradients remain steep in order to maintain a graded condition while eroding a strong rock like massive granite.

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. The proper 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.

CONCEPT CHECK **STOP**

Why aren't there many huge waterfalls around the world?

Identify four landforms found in the floodplain of an alluvial river.

What is the difference between a floodplain meander and an entrenched meander?

Name two approaches that geographers use to understand how landscapes evolve over vast stretches of time.

What is happening in this picture?

The Mississippi River floodplain

- This aerial photo shows the floodplain of the meandering Mississippi River.
- The image shows two examples of a curved characteristic landform of an alluvial floodplain. Can you pick them out? What are these features called? How do they develop?

VISUAL SUMMARY

1 Slope Erosion

1. Running water erodes, transports, and deposits rock material, forming both erosional and depositional landforms.
2. In most natural landscapes, soil erosion and soil formation rates are more or less equal.

2 The Work of Streams and Stream Gradation

1. Stream channels carve into soft materials by hydraulic action. Where stream channels flow on bedrock, channels are deepened by abrasion.
2. Stream load increases greatly as velocity increases. And velocity increases as stream gradient increases.
3. Over time, streams tend to a graded condition, in which their gradients are adjusted to move the average amount of water and sediment supplied to them by slopes. Lakes and waterfalls are short-lived events that give way to a smooth, graded stream profile.

3 Fluvial Landscapes

1. Streams build up their beds by aggradation, when provided with a sudden inflow of material. When inflow ceases, streams resume downcutting, leaving behind alluvial terraces.
2. Alluvial rivers are large rivers with low gradients that move large quantities of sediment. They form cutoff meanders, ox-bow lakes, and other typical landforms. Entrenched meanders are created when a meandering alluvial river is uplifted.
3. The geographic cycle organizes fluvial landscapes in a cycle of uplift and subsequent erosion. The equilibrium approach views uplift and erosion as continuous processes.

KEY TERMS

- **fluvial landforms** p. 360
- **erosional landforms** p. 360
- **depositional landforms** p. 361
- **alluvium** p. 363
- **stream load** p. 368
- **graded stream** p. 368
- **alluvial meanders** p. 369
- **aggradation** p. 370
- **alluvial fan** p. 375
- **geographic cycle** p. 379

CRITICAL AND CREATIVE THINKING QUESTIONS

1. Compare erosional and depositional landforms. Sketch an example of each type.
2. Describe slope erosion. When and how does sheet erosion occur? How does it lead to rill erosion and gullying?
3. Contrast the two terms *colluvium* and *alluvium*. Where on a landscape would you look for each one?
4. Explain how badlands form.
5. How do streams erode their bed and banks? Describe three processes.
6. What is stream load? Identify its three components. In what form do large rivers carry most of their load? How does the ability of a stream to move sediment downstream depend on its velocity?
7. What is a graded stream? Describe how a graded stream forms. What effects does the gradation process have on waterfalls, rapids, and lakes?
8. Define the term *alluvial river*. Sketch the floodplain of a graded, meandering river. Identify key landforms on the sketch and describe how they form.
9. Describe the evolution of a fluvial landscape according to the geographic cycle. How does the equilibrium approach to landforms differ from interpretation using the geographic cycle?
10. 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.

SELF-TEST

1. Landforms shaped by _______________ are described as fluvial landforms.
   a. glacial ice
   b. wave action
   c. denudation
   d. running water

2. Landforms that are shaped by progressive removal of the bedrock mass are _______________ landforms.
   a. initial
   b. erosional
   c. fluvial
   d. ablation

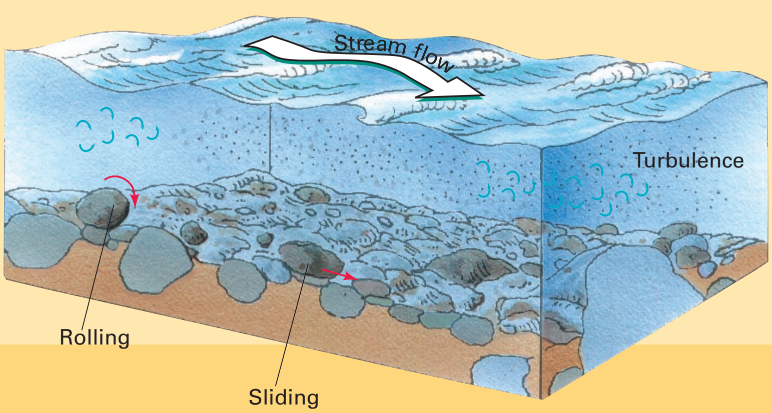
3. In steep sloped landscapes, a destructive form of soil erosion called _______________ results in many closely spaced channels in response to torrential rain episodes.
   a. rill erosion
   b. sheet erosion
   c. furrow erosion
   d. gully erosion

4. The term _______________ is used to describe any stream-laid sediment deposit.
   a. colluvium
   b. alluvium
   c. fluvium
   d. sediment

5. The process of mechanical wear by the rolling of cobbles and boulders along the beds of streams is called _______________.
   a. deflation
   b. ablation
   c. abrasion
   d. grinding

6. Chemical rock weathering processes such as acid reactions and solution collectively refer to a mechanism known as _______________.
   a. erosion
   b. demineralization
   c. salinization
   d. corrosion

7. Streams carry sediment as they flow. On the diagram, label (a) suspended load and (b) bed load. What is the third type of load carried by streams?



8. The maximum solid load of debris that can be carried by a stream at a given discharge is a measure of the _______________.
   a. stream suspension pattern
   b. deposition rate
   c. stream capacity
   d. stream velocity

9. Stream velocity increases stream capacity because _______________ becomes more intense.
   a. carrying capacity
   b. turbulence
   c. suspension
   d. flow

10. In the early stages of gradation and tributary extension, the capacity of a stream _______________ the load supplied to it.
   a. exceeds
   b. increases
   c. erodes
   d. weathers

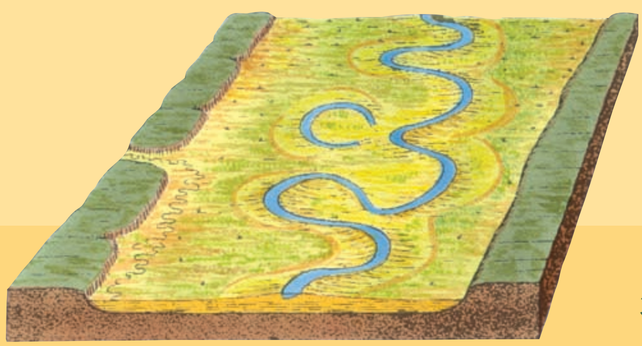
11. A gradual reduction in the channel gradient of a stream leads to _______________.
   a. a greater capacity to carry suspended load
   b. an increase in stream velocity
   c. a reduced ability of the stream to carry bed load
   d. greater erosion at the mouth of the stream

12. An equilibrium condition in which the slopes of all stream channels form a coordinated network that is just able to carry the sediment load contributed by the drainage basin is referred to as a(n) _______________.
   a. braided stream
   b. meandering stream
   c. graded stream
   d. entrenched stream

13. Waterfalls in East Africa have been formed due to _______________.
   a. block faulting of large crustal blocks
   b. glacial activity in new river channels
   c. undermining of softer basement rocks
   d. overhanging lava flows

14. When a stream's bed load capacity is exceeded, the excess coarse sediment will start to accumulate on the stream bed during a process referred to as _______________.
   a. degradation
   b. aggradation
   c. sedimentation
   d. accumulation

15. The diagram shows a variety of landforms created by an alluvial river. Label the following features: (a) a bluff, (b) the floodplain, (c) a meander neck, and (d) an ox-bow lake.



Landforms Made by Waves and Wind

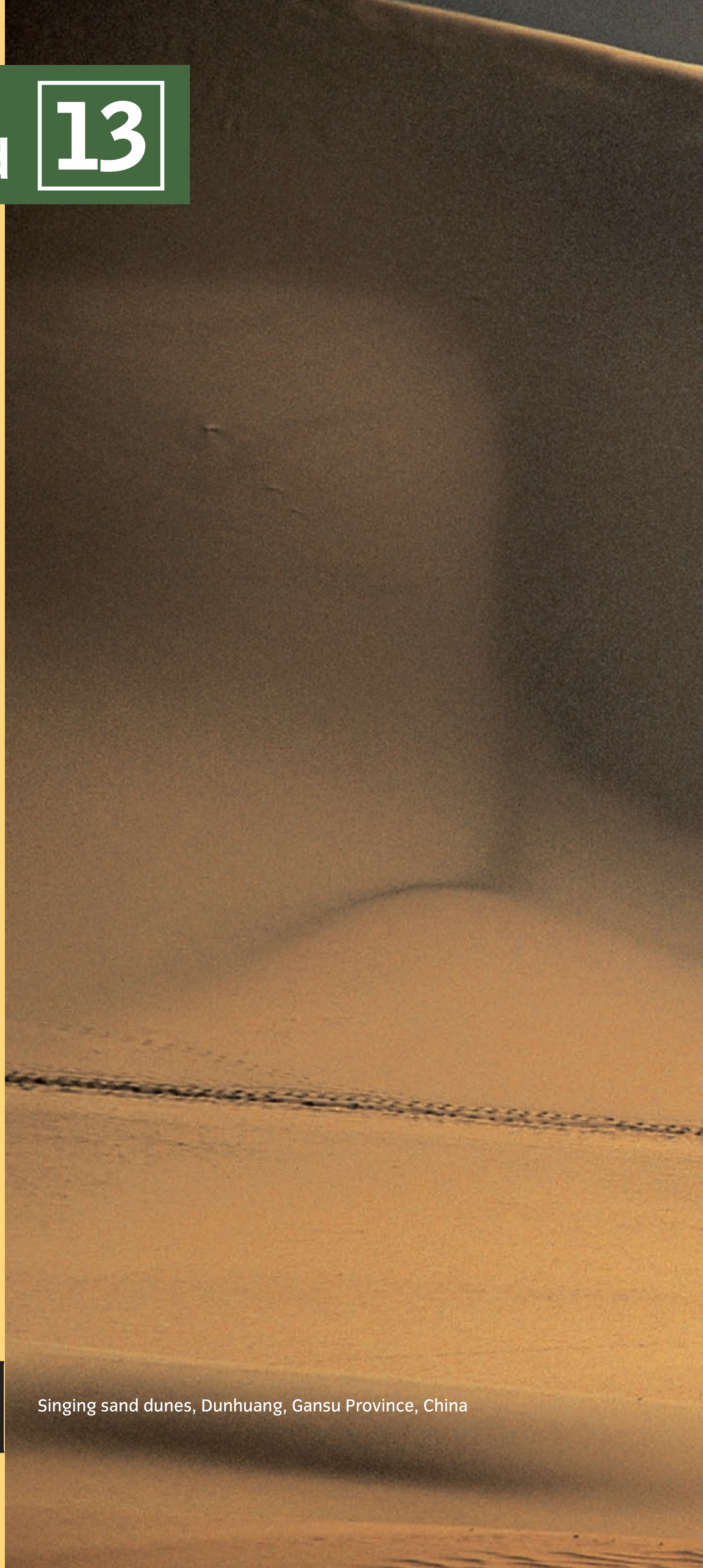
13

Marco Polo believed it was the work of "evil desert spirits." Traveling through the Gobi Desert, he described bizarre noises that filled the air with the "sounds of all kinds of musical instruments and also of drums and the clash of arms."

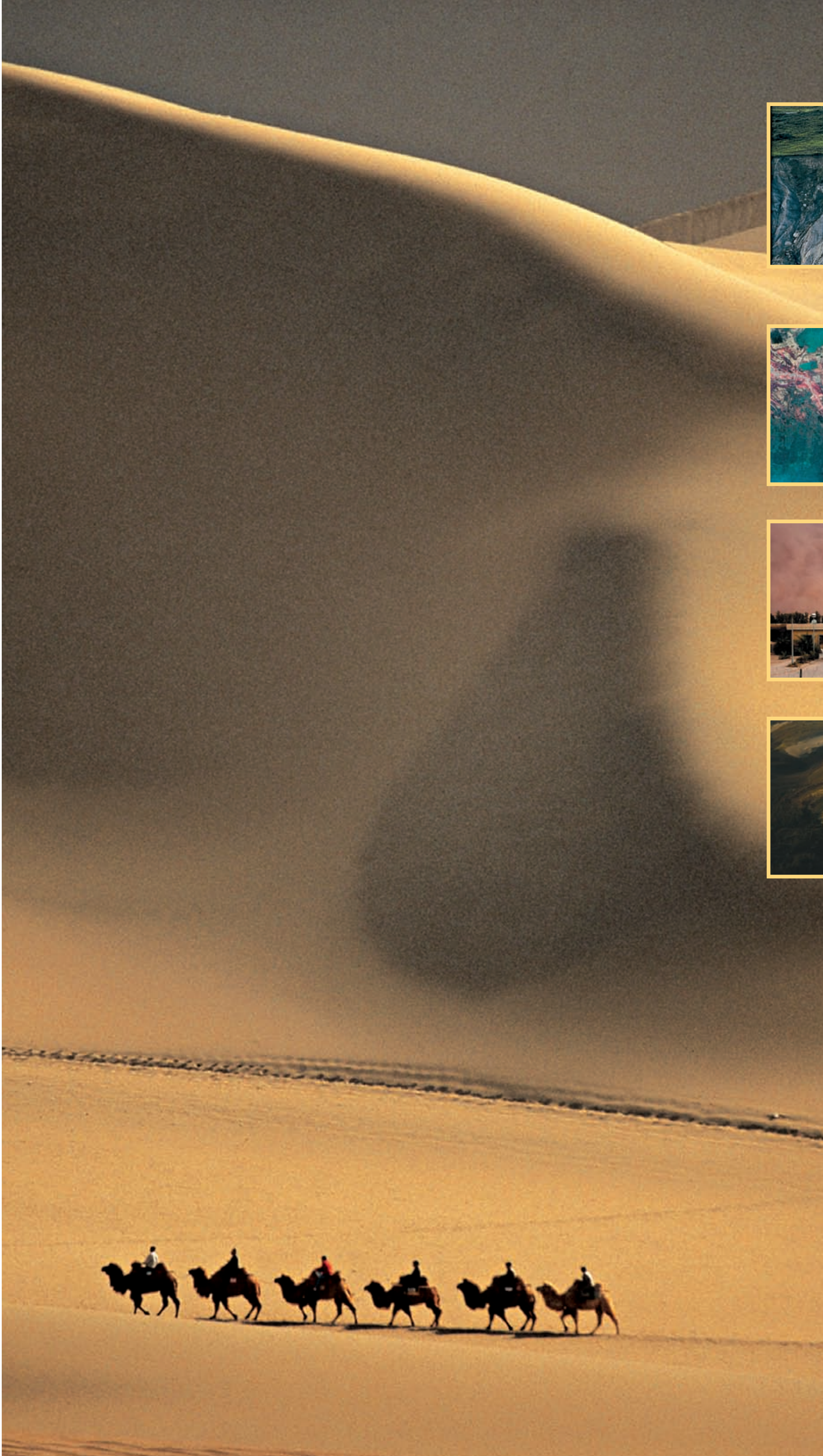
Singing sand dunes, as they are known, have been a part of desert folklore for centuries—they are even mentioned in the *Arabian Nights*. But they aren't just fantasy. Scientists, including Charles Darwin, have also noted the haunting sounds. Some dunes are said to squeak, while others boom. The dunes are reported to sound like drum rolls or galloping horses, and even to be melodic at times. Dune songs have been reported to last for up to 15 minutes and can sound as loud as a low-flying airplane.

What causes these strange noises? A sand dune is a hill of loose sand shaped by the wind. Active dunes constantly change form under wind currents. Scientists believe that the songs are created by avalanches of sand on the dune. As the sand grains bounce down, they begin to move with the same frequency, setting up a hum. But the precise mechanism for generating such distinct sounds remains controversial. Not all sand dunes sing, and it's not clear why some dunes can sing while others can't—adding another layer of mystery.

Wind action is responsible for creating the immense and beautiful sand dunes—singing or not—that we find in deserts. Together with waves, the wind has also shaped coastlines around the world.



Singing sand dunes, Dunhuang, Gansu Province, China



CHAPTER OUTLINE

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- Types of Coastlines p. 392

- Wind Action p. 401

- Eolian Landforms p. 406

The Work of Waves and Tides

Learning Objectives

Understand wave breakers, swash, and backwash.

Describe the formation of marine scarps, marine cliffs, notches, arches, and stacks.

Explain how littoral drift shapes beaches.

Discuss tidal currents.

Wind power can move material directly, picking up fine particles and carrying them along. Or it can act indirectly by generating a wave on the sea that in turn transports and erodes surface materials. Acting directly or indirectly, wind power is an agent that shapes distinctive landforms, along with running water, glacial action, and mass wasting. What makes wind and breaking waves different from these other agents is that they can move material against the force of gravity.

THE WORK OF WAVES

Waves are the most important agents that shape coastal landforms (FIGURE 13.1). 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.

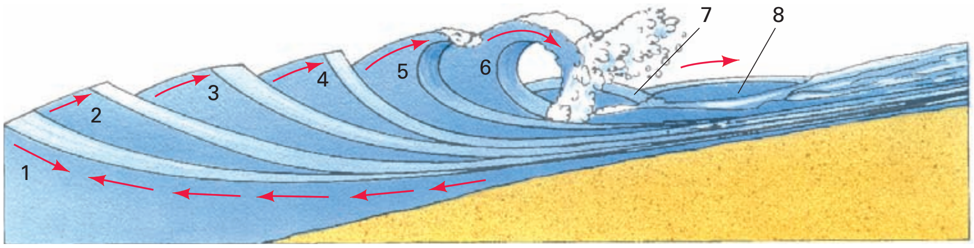
Note that throughout this chapter we will use the term **shoreline** to mean the shifting line of contact between water and land. When we use the word **coastline**, or simply *coast*, we're referring to the zone in which coastal processes operate or have a strong influence. The coastline

Shoreline Shifting line of contact between water and land.

Coastline (coast) Zone in which coastal processes operate or have a strong influence.

Storm waves FIGURE 13.1

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.



Breaking wave FIGURE 13.2

As the wave approaches the beach (1–3), it steepens (4–5), and finally falls forward (6–7), rushing up the beach slope (8).

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.

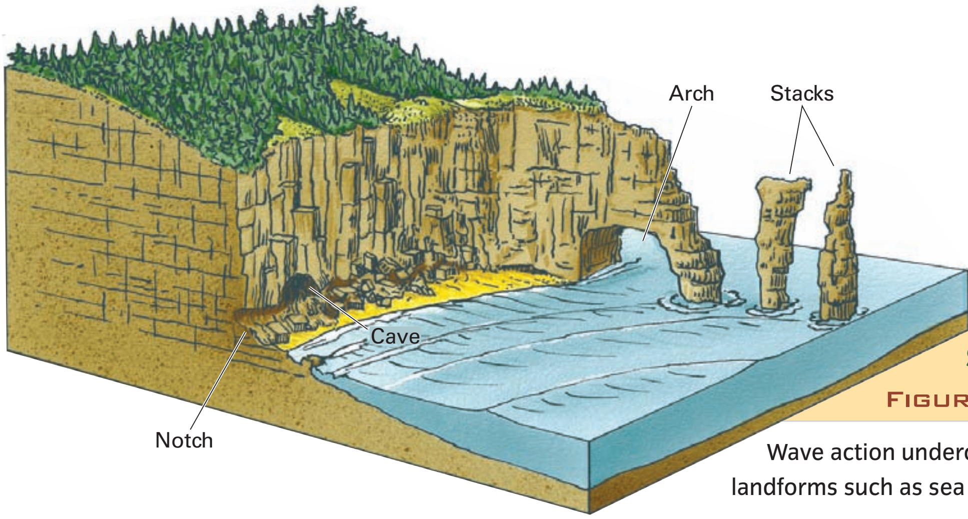
As mentioned, waves don't lose much energy as they travel across the deep ocean. But what happens when a wave reaches the shore? As it reaches shallow water, the drag of the bottom slows and steepens the wave. However, the wave top maintains its forward velocity and eventually falls down onto the face of the wave, creating a breaker (FIGURE 13.2). Many 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," as it is popularly called, can be strong enough to 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 can appreciate 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 (FIGURE 13.3.) The marine scarp retreats steadily as it's attacked by storm waves.

Retreating shoreline FIGURE 13.3

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.



Sea caves, sea stacks and arches FIGURE 13.4

Wave action undercuts the marine cliff or headlands, creating landforms such as sea stacks and arches.

Marine cliff Rock cliff shaped and maintained by the undermining action of breaking waves.

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, and these are thrust against the bedrock of the cliff. The impact breaks away new rock fragments, and the cliff is undercut 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, this retreat is exceedingly slow (FIGURE 13.4).

BEACHES AND LITTORAL DRIFT

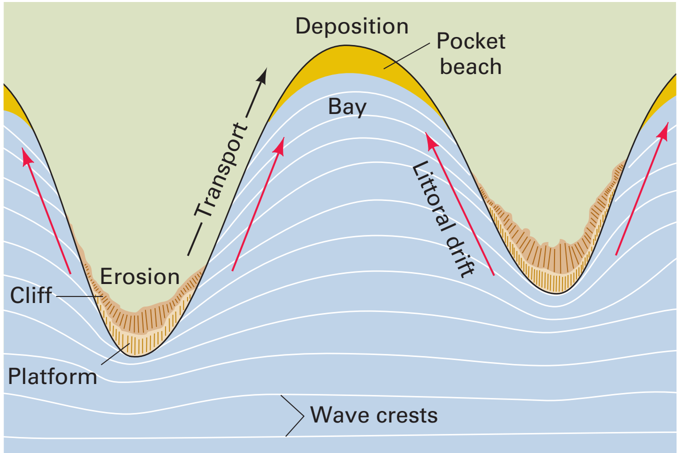
Beach Thick, wedge-shaped deposit of sand, gravel, or cobbles in the zone of breaking waves.

Where there's a lot of sand, it accumulates as a thick, wedge-shaped deposit, or **beach**. Beaches absorb the energy of breaking waves. During short periods of storm activity, the beach is cut back, and sand is carried offshore a short distance by the heavy wave action. But the sand is slowly returned to the beach during long periods when waves are weak. In this way, a beach will stay quite stable—but alternating through narrow and wide configurations over many years.

Although most beaches are made from particles of fine to coarse quartz sand, some beaches are built from rounded pebbles or cobbles (FIGURE 13.5). Still others are formed from fragments of volcanic rock or even shells.

Rock beach FIGURE 13.5

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.



Pocket beach FIGURE 13.6

When the coastline has prominent headlands that project seaward and deep bays, approaching wave fronts slow when the water becomes shallow. This slowing effect causes the wave front to wrap around the headland. Sediment is eroded from cliffs on the headland and 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*.

Littoral drift
Transport of sediment parallel with the shoreline by the combined action of beach drift and longshore current transport.

Breaking waves also produce currents that move sediment along the shoreline in a process called **littoral drift,** which is described in the process diagram on the following page. Where the beach is straight, littoral drift forms bars and sandspits. Where the shoreline includes resistant headlands, littoral drift builds pocket beaches in bay heads from sediments eroded from the headlands (FIGURE 13.6).

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 13.7).

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 FIGURE 13.7

Severe storms during the winter of 1993 carved out an inlet in this barrier beach on the south shore of Long Island, New York. A system of groins has trapped sand, protecting the far stretch of beach. The beach in the foreground, without groins, has receded well inland of the houses that were once located on its edge.

TIDAL CURRENTS

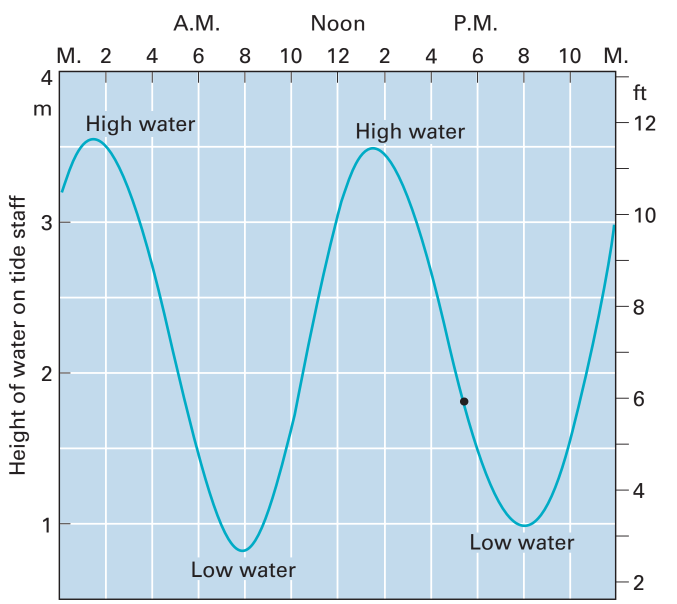
Most marine coastlines are influenced by the *ocean tide*—the rhythmic rise and fall of sea level under the influence of changing attractive forces of the Moon and Sun on the rotating Earth. If the tides are large, the changing water level and the tidal currents set up play an important role in shaping coastal landforms. **FIGURE 13.8** 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 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. 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 the shore-drifting processes that try 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 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 13.9**). A thick layer of peat eventually forms at the salt marsh surface.



Tide curve FIGURE 13.8

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 2.8 m (9.2 ft).

Salt marsh FIGURE 13.9

Saltwater 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.

CONCEPT CHECK STOP

When do waves expend most of their energy?

What is a marine cliff? What other landforms do we associate with marine cliffs?

Define littoral drift.

How are tidal currents related to tide levels?

Littoral drift

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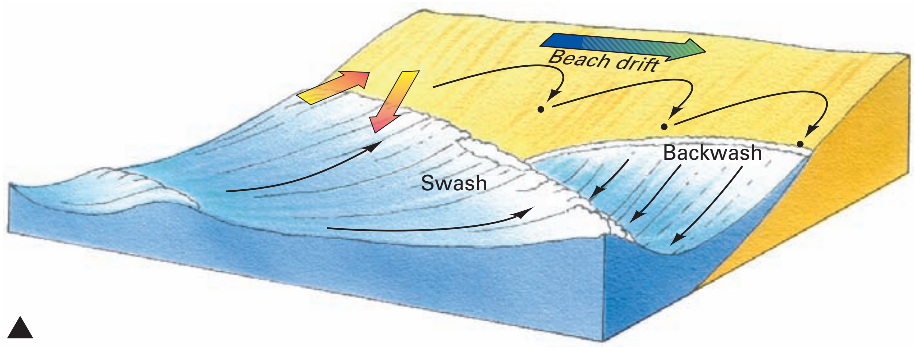
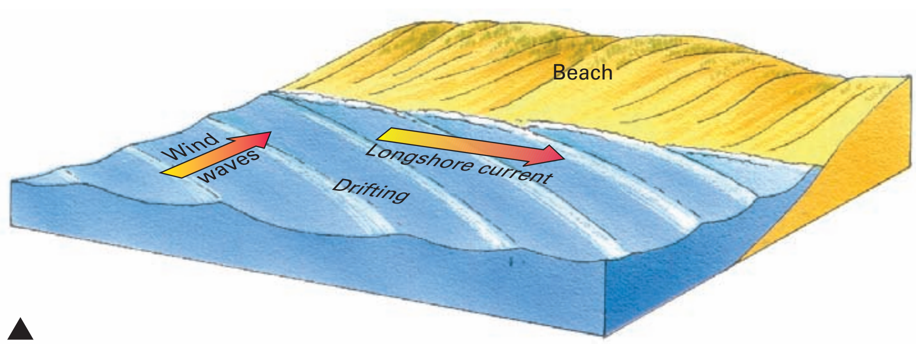
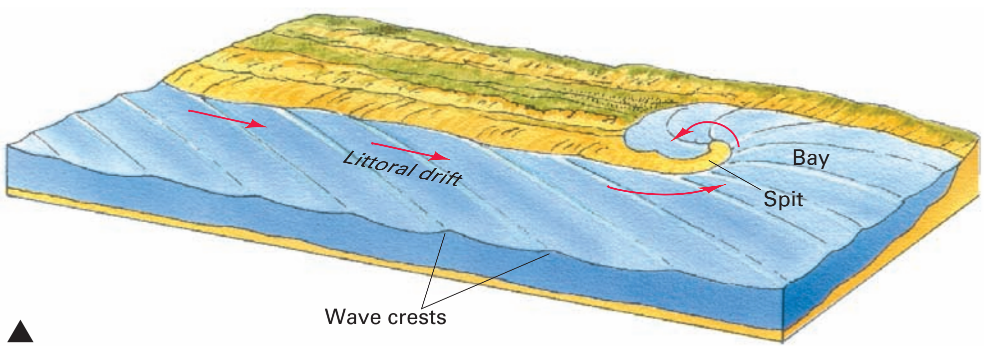
The cycle of swash and backwash produced by breaking waves transports sand and shapes beaches, in a process known as littoral drift.



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, so individual rock particles are transported long distances along the shore.



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.

Process Diagram

Types of Coastlines

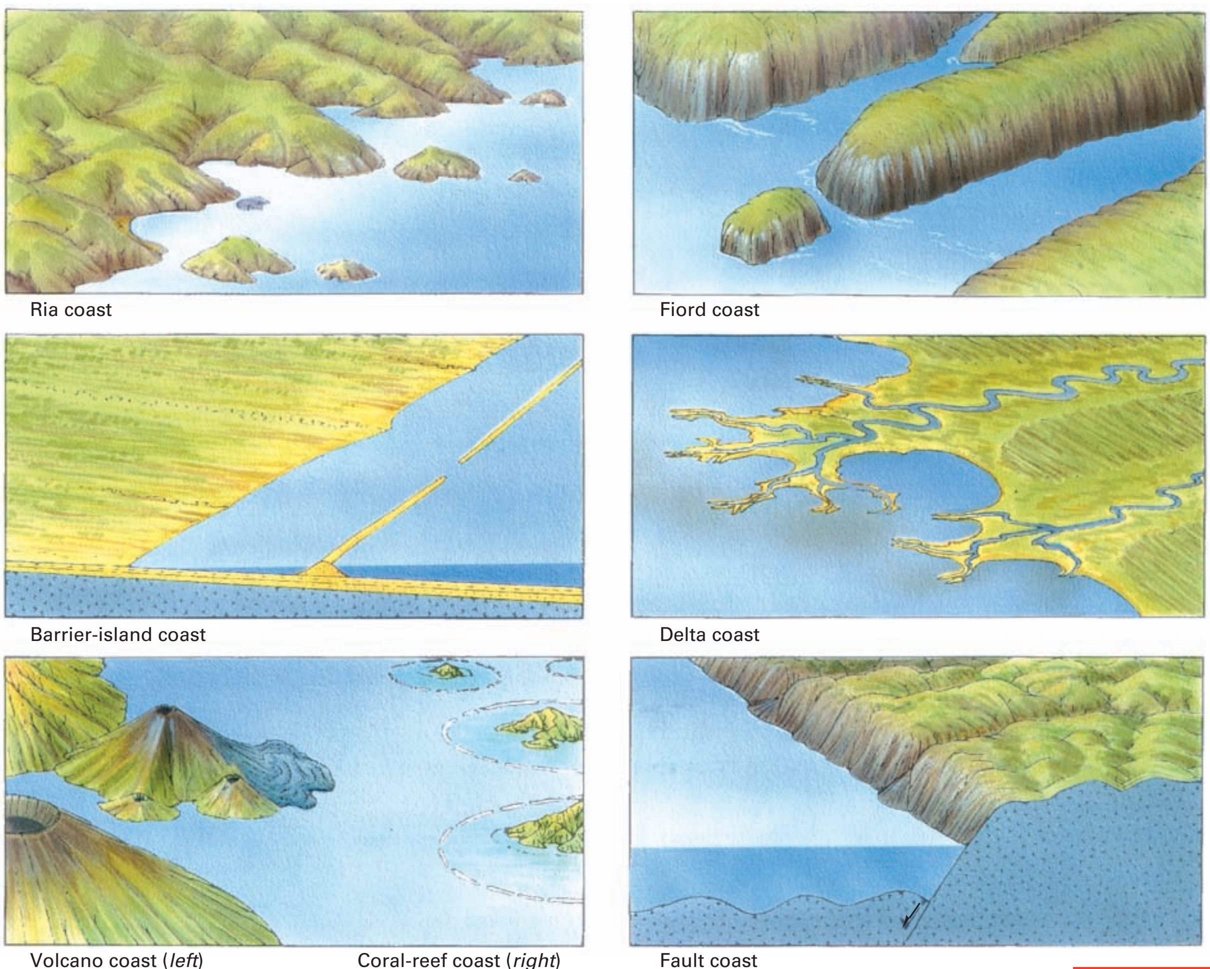
LEARNING OBJECTIVES

Describe the seven types of coastline and explain how they form.

Explain the formation of raised shorelines and marine terraces.

Describe the impact of sea-level rise on 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 13.10. Shorelines of *submergence* are formed when the rising sea level partially drowns a coast or when part of the crust 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. Barrier-island coasts are emergence shorelines. Volcano coasts result when new land is built out into the ocean by volcanoes and lava flows. Delta coasts are produced by the growth of river deltas, and finally there are coasts built by the growth of coral reefs.



Seven types of coastlines FIGURE 13.10

These sketches illustrate the important features of seven types of coastlines.

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SHORELINES OF SUBMERGENCE

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. The process diagram, “Evolution of a ria coastline,” describes the formation in more detail.

The *fiord coast* is similar to the ria coast (FIGURE 13.11). Steep-walled fiords are created from submerged glacial troughs rather than from submerged stream valleys, as in the case of ria coasts.

Fiord coast FIGURE 13.11

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 to form broad, steep-sided valleys that are now flooded. Fiordland National Park, South Island, New Zealand.

BARRIER-ISLAND COASTS

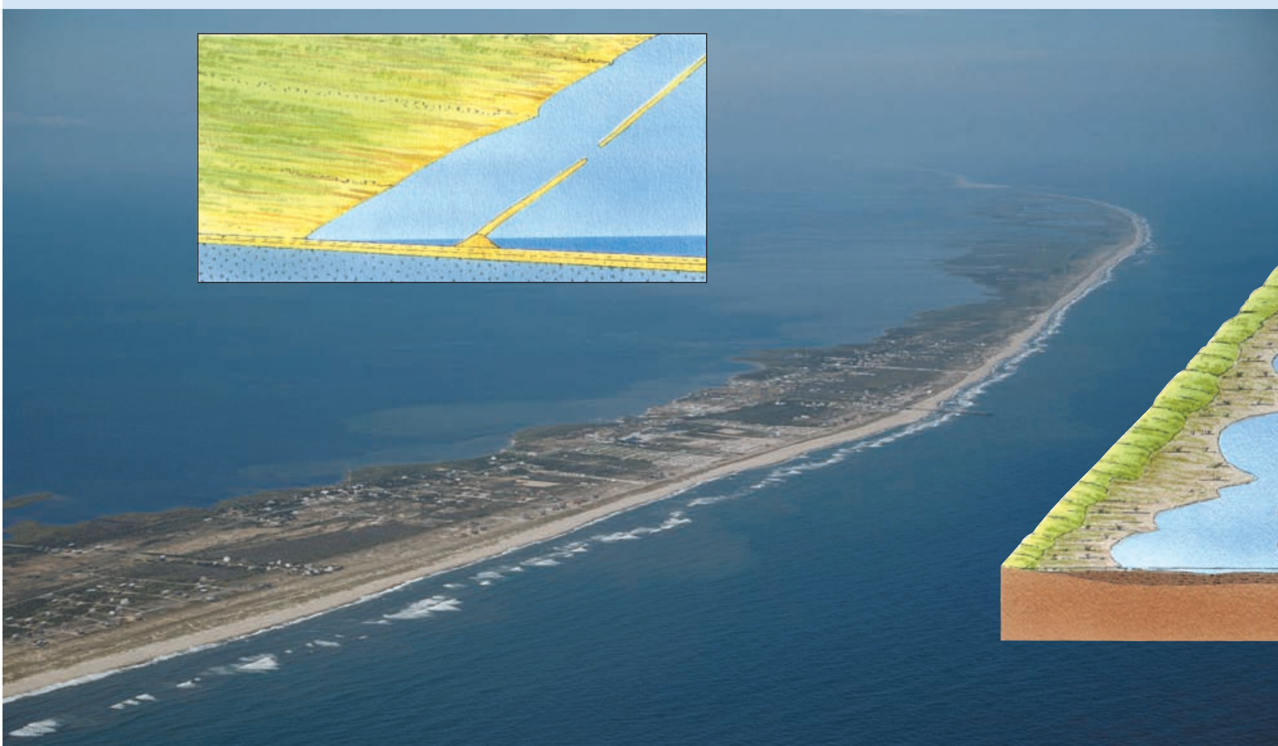
The *barrier-island coast* is associated with a recently emerged coastal plain (FIGURE 13.12). A barrier island of sand, lying a short distance from the coast, is created by wave action. The offshore slope is very gentle on a barrier island.

You can see *barrier islands* along much of the Atlantic and Gulf coasts. These low ridges of sand are built by waves and increase in height as sand dunes grow on them. Behind the barrier island there is a *lagoon*—a broad expanse of shallow water in places largely filled with tidal deposits.

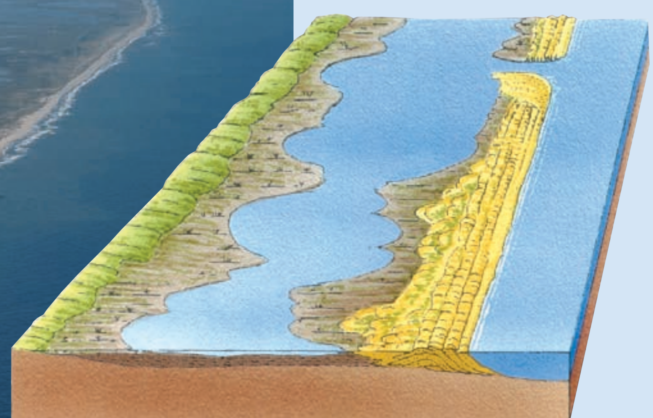
We find characteristic gaps, known as *tidal inlets*, along the barrier island. Strong currents flow back and forth through these gaps as the tide rises and falls. New inlets are formed in severe storms, and then kept open by the tidal current. In some cases, the inlet will be closed later by shore drifting of beach sand.

Barrier island coast FIGURE 13.12

A Where a gently sloping coastal plain meets the ocean, wave action builds a coastline of barrier islands and beaches. Shown here is the Outer Banks of North Carolina.



B 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.



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 13.13). 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 saltwater, they clot together into larger particles that settle to the seafloor.

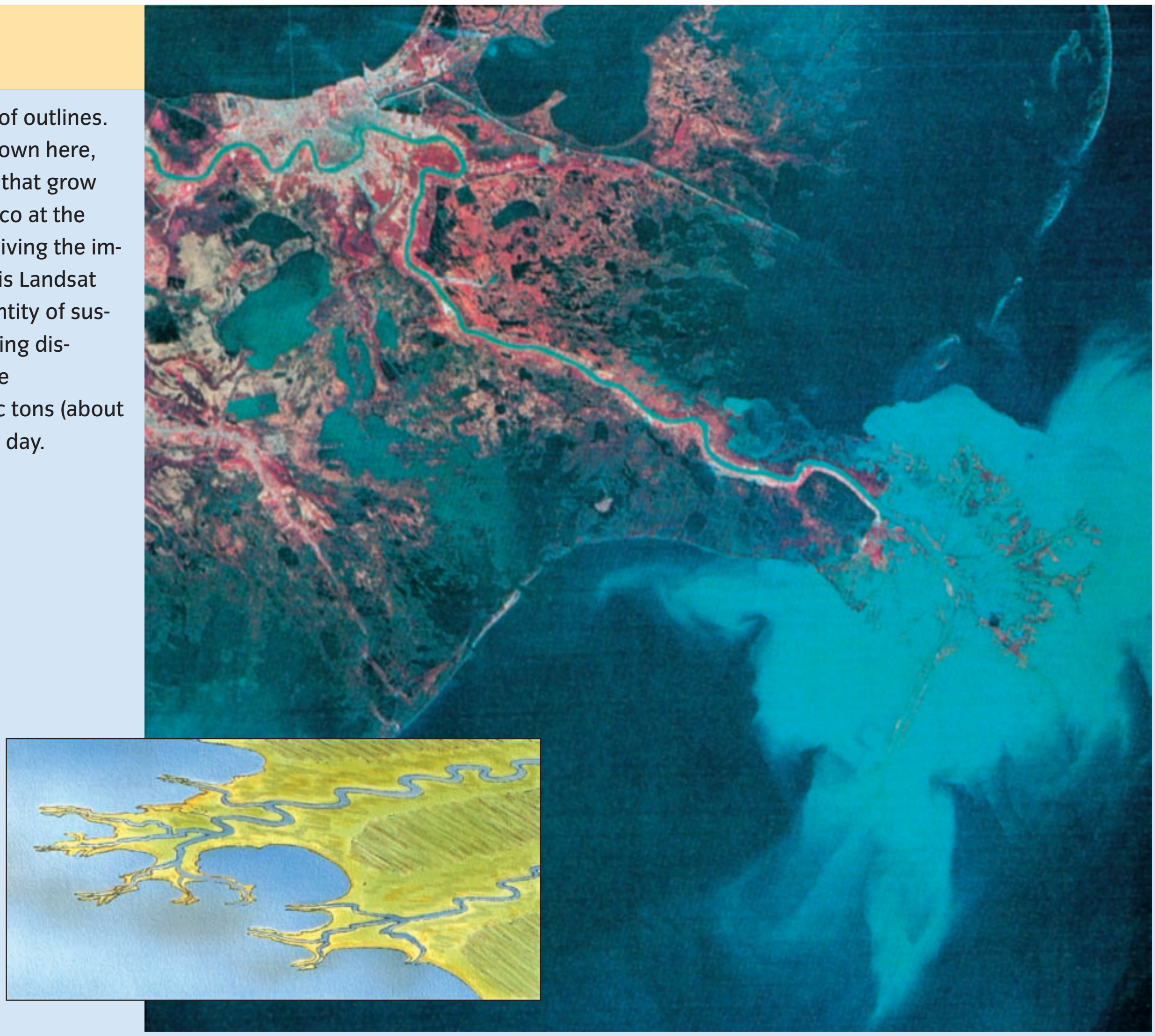
Delta Sediment deposit built by a stream entering a body of standing water.

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.

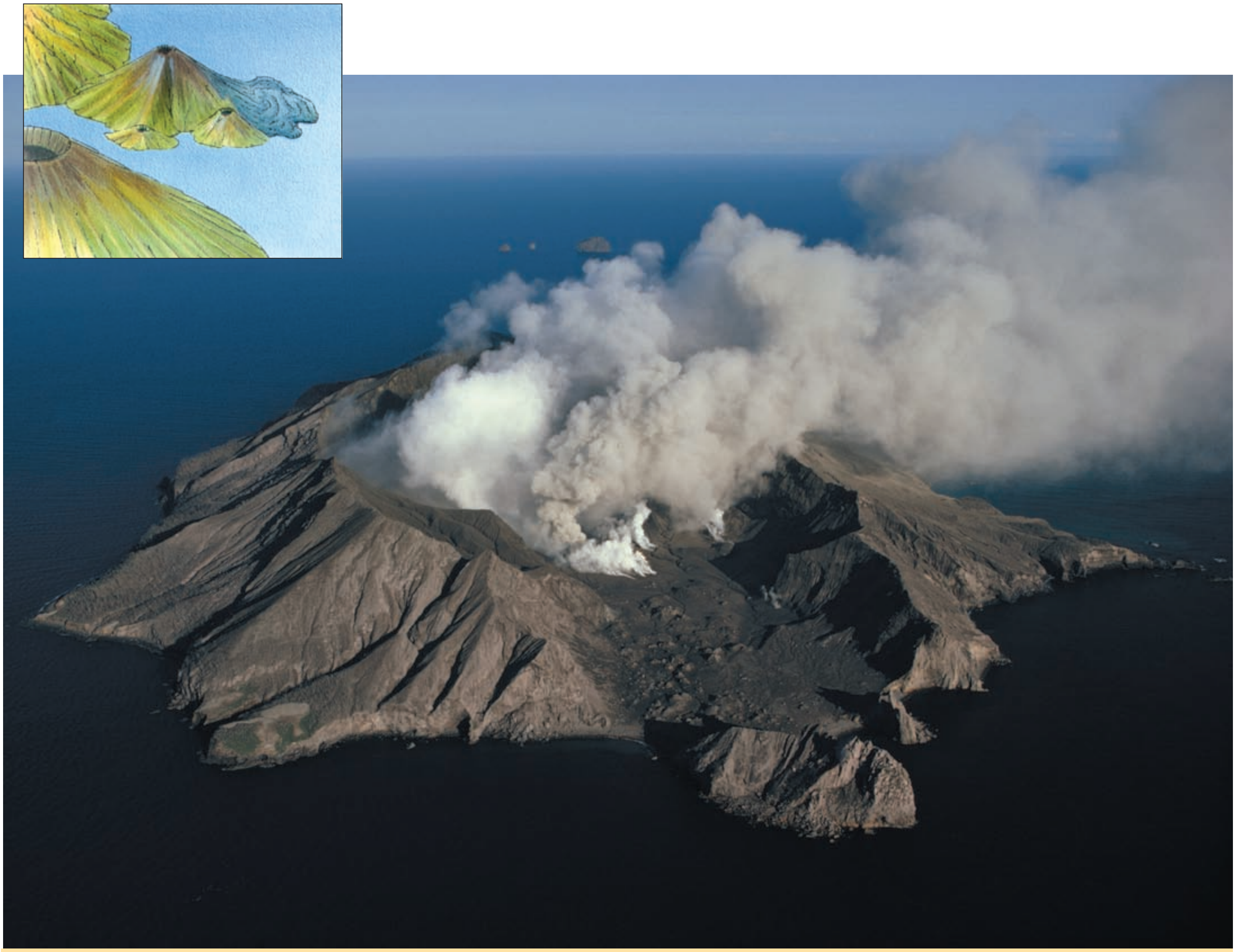
VOLCANO AND CORAL-REEF COASTS

Volcano coasts arise where volcanic deposits—lava and ash—flow from active volcanoes into the ocean (FIGURE 13.14). Wave action erodes the fresh deposits,

The delta coast
FIGURE 13.13



Deltas show a wide variety of outlines. The Mississippi Delta, as shown here, 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 Landsat image shows the great quantity of suspended clay and fine silt being discharged by the river into the Gulf—about 1 million metric tons (about 1.1 million English tons) per day.



Volcano coast FIGURE 13.14

White Island, New Zealand, is an active stratovolcano. Waves have notched its flanks into steep cliffs as abundant rainfall has carved valleys into its flanks. The large central crater, opening out toward the viewer, was formed by the collapse of three overlapping circular craters.

Coral reef Rock-like accumulation of carbonates secreted by corals and algae in shallow water along a marine shoreline.

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. 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, we don't find reefs opposite the mouths of muddy streams. Coral reefs are remarkably flat on top. They are exposed at low tide and covered at high tide.

Evolution of a ria coastline

Evolutionary stages of a ria coatline A ria coast is deeply embayed, resulting from submergence of a land mass.

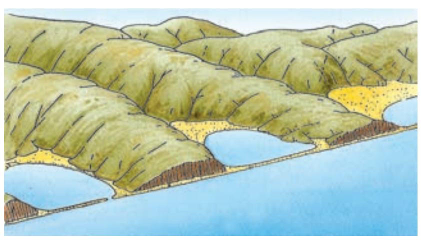
Before submergence This is the terrain before sea level rises (or the crust subsides, or both). Active streams have carved the valleys and continue to do so.

Submergence Rising sea levels and/or crustal sinking submerge existing coastline. The shoreline rises up the sides of the stream-carved valleys, creating narrow embayments. Streams that occupied the valleys add freshwater to the embayments, making them estuaries of mixed fresh and saline waters. Streams also provide sediment to the shoreline.

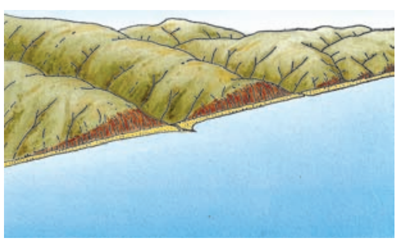
Cliff formation Wave attack forms cliffs on the exposed seaward sides of islands and headlands.

Sandspit formation 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 with respect to the land for a long time, the coast may evolve into a cliffed shoreline of narrow beaches.



This view of Ria Ortigueira, Coruña, Spain, shows many of the features of the ria coastline, including submerged valleys, islands, and sand bars.

Coral reef coast FIGURE 13.15

Coral reefs fringe the Island of Moorea, Society Islands, South Pacific Ocean. The island is a deeply dissected volcano with a history of submergence.

There are three distinctive types of coral reefs—fringing reefs, barrier reefs, and atolls. *Fringing reefs* are built as platforms attached to shore (FIGURE 13.15). 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 in the ocean. 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. "What a Geographer Sees: Bleached anemones" looks at the impact on corals of global warming and rising levels of carbon dioxide in the atmosphere.

FAULT COAST

The final type of coastline is a *fault coast* (FIGURE 13.16). Faulting of the coastal margin of a continent can bring the shoreline down, so that it rests against a fault scarp.

Fault coast FIGURE 13.16

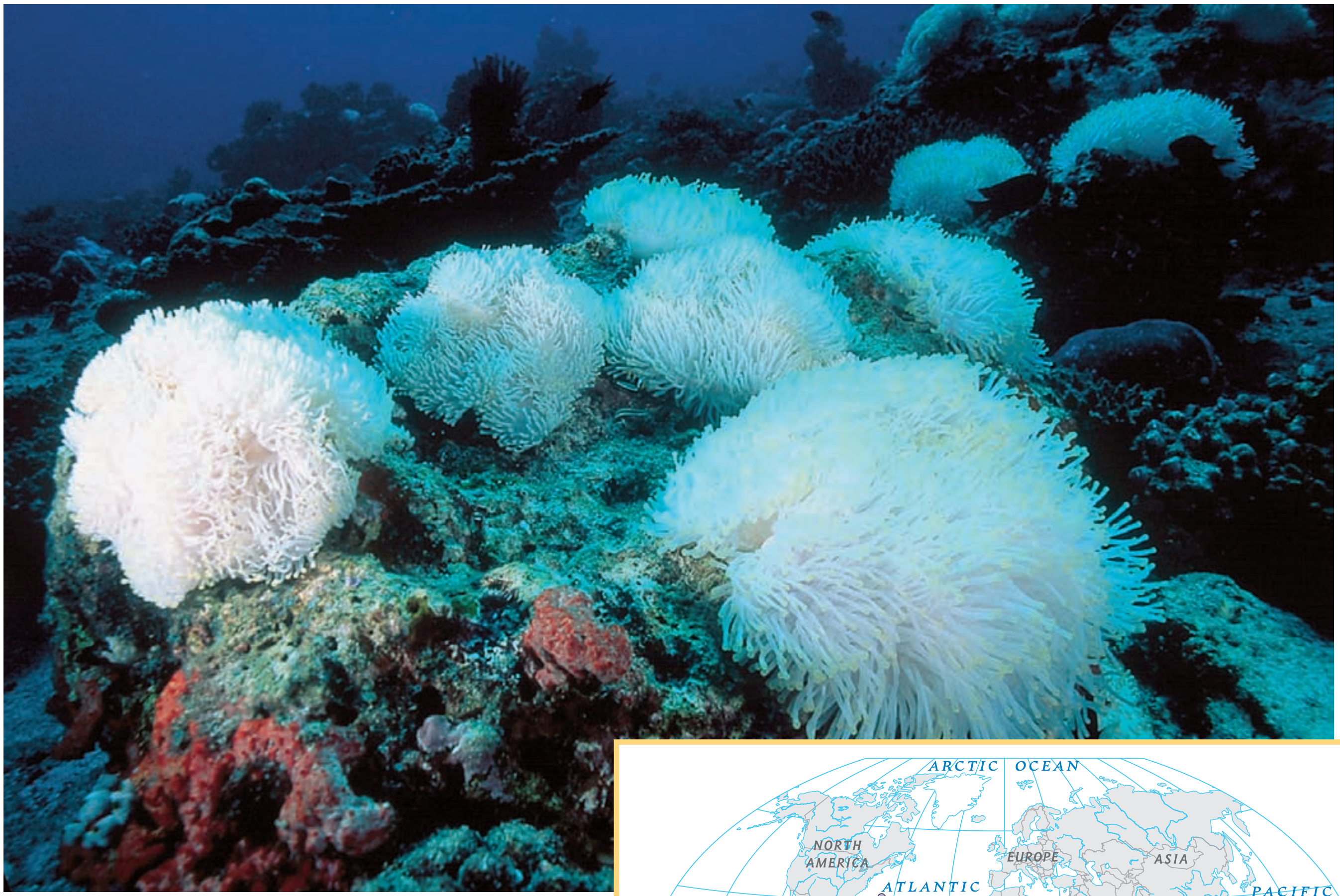
The marine cliff in this photo of Daly City, California, marks the trace of the San Andreas fault. Although the primary motion along the San Andreas fault is horizontal, here vertical motion has been significant.

Bleached anemones

We're used to photos showing beautiful, colorful corals. But these sea anemones, observed in the shallow waters of the Maldive Islands, have turned white. What has happened to them?

Geographers are familiar with the sight of bleached anemones. Major coral bleaching occurs during strong El Niños, where water temperatures increase by 1°C (1.8°F) or more. The heat forces the corals to expel the algae that usually live symbiotically inside their structures. The algae are responsible for the coral animals' color. More important, the coral need the algae to survive. If the heat stress is temporary, the corals can recover. But if permanent, the corals die.

Thus, long-term global warming could devastate coral life. Geographers are also worried about the impact of rising carbon dioxide levels in the atmosphere on corals. As more CO_2 dissolves in sea water, it becomes harder for corals to build their skeleton structure.



Fifty percent of coral reefs worldwide are threatened by human activities. The violet dots on the map indicate coral reefs which are diseased.

RAISED SHORELINES AND MARINE TERRACES

The active life of a shoreline is sometimes cut short by a sudden rise of the coast through tectonic activity. When this happens, we get a *raised shoreline*. If marine cliffs and abrasion platforms lie on the coast, they'll be abruptly lifted above the level of wave attack. The former abrasion platform becomes a **marine terrace**. Of course, that doesn't stop attacks from running water, which begin to erode the terrace as soon as it is formed. The terrace may also be partially buried under alluvial fan deposits.

Marine terrace
Former abrasion platform elevated to become a step-like coastal landform.

Raised shorelines are common along the continental and island coasts of the Pacific Ocean because here tectonic processes are active along the mountain and island arcs. Repeated uplifts create a series of raised shorelines with a step-like arrangement (FIGURE 13.17).

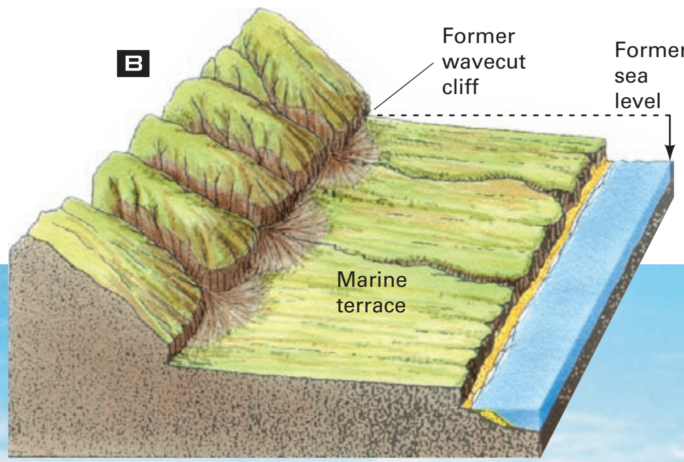
Marine terrace FIGURE 13.17

A This series of 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).

B A raised shoreline becomes a cliff parallel with the newer, lower shoreline. The former abrasion platform is now a marine terrace.

A

B



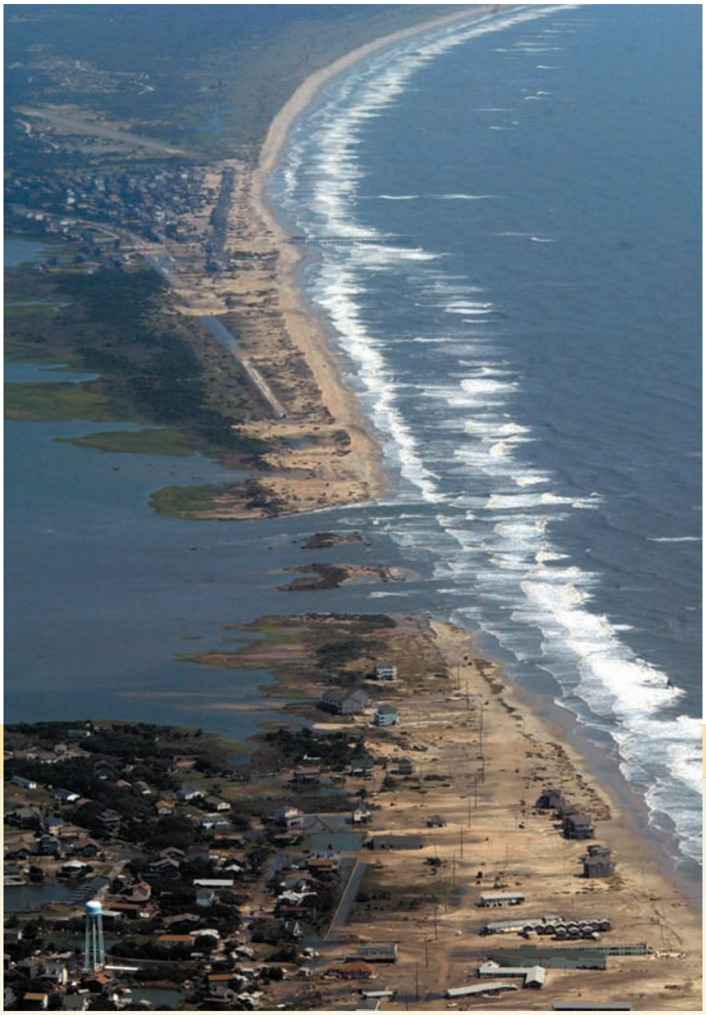
RISING SEA LEVEL

As global temperatures increase, the sea level will rise. This is because glaciers and snow packs will start to melt and the upper layers of the ocean will expand as they get warmer. According to current estimates, global warming will cause the sea level to rise by about 20 to 60 cm (8 to 24 in.) between now and 2100.

Sea-level rise will have a number of effects. Most coastal erosion occurs in severe storms. Global warming will increase extreme weather conditions, and sea-level rise will push beaches, salt-marshes, and estuaries landward (FIGURE 13.18). Land subsidence will also increase, with recent estimates suggesting that as much as 22 percent of the world's coastal wetlands could be lost by the 2080s. This would have a major effect on commercially important fish and shellfish populations.

Sea-level rise FIGURE 13.18

▲ **Coastal erosion** Wave action has undermined the bluff beneath these two buildings, depositing them on the beach below.



▲ **New inlet** 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.

CONCEPT CHECK STOP

Name the seven types of coastlines.

How are marine terraces formed?

What effects might a significant rise in sea level have?

Wind Action

Learning Objectives

Explain wind abrasion and deflation.

Describe how deflation forms blowouts and desert pavements.

Discuss dust storms.

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*. "Visualizing Eolian Landforms" presents a global map showing where these 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). But in coastal environments, beaches also provide a supply of loose sand to be shaped. Here the wind shapes coastal dunes, even 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 sand and dust particles against an exposed rock or soil surface, wearing down the surface by the impact of the particles.

Wind abrasion usually only blasts sand against 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. If they didn't, they would quickly be cut through at the base.

Deflation is the removal of loose particles from the ground. The cutting tools used in abrasion are mineral particles carried by the wind. By contrast, deflation only uses air currents. It acts on loose soil or sediment and so dry river courses, beaches, and areas of recently formed glacial deposits are susceptible to deflation. In dry climates, much of the ground surface can be deflated because the soil or rock is largely bare of vegetation.

Deflation Lifting and transport in turbulent suspension by wind of loose particles of soil or regolith from dry ground surfaces.

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 grains. So, 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.

A *blowout* is a shallow depression produced by deflation (FIGURE 13.19). The size of the depression

Blowout FIGURE 13.19

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.

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.

Mud cracks in a playa surface FIGURE 13.20

Playas cover the floors of closed depressions in dry climates with a flat surface formed when sediment-laden waters flood the valley, then evaporate. This small playa has been flooded recently and is now covered with mud cracks.

Deflation is also active in semidesert and desert regions. In Chapter 11, we saw that the centers of desert basins often hold saline lakes or former lake deposits. When fine sediment and salt accumulate in these dry basins, they create an extremely flat basin floor called a *playa*. In the southwestern United States, playas often occupy large areas (FIGURE 13.20). Deflation has reduced many 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 13.21). 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.

Desert pavement FIGURE 13.21

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.

Dust storm FIGURE 13.22

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.

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 meters (FIGURE 13.22). 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.

CONCEPT CHECK STOP

What are the two ways that wind erodes?

Which process produces blowouts and desert pavements?

Where do we find dust storms?

Which weather front do we associate with dust storms?

LANDFORMS MADE BY WIND

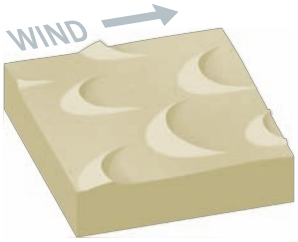
Wind moves loose sand across the landscape, gathering it into dunes of different shapes and patterns. Wind also carries silt, which can remain airborne for long distances and accumulate in deep layers.

▲ **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 that formed deep layers in continental interiors. These wind-borne deposits are known as *loess*.

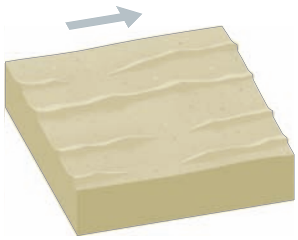
NATIONAL GEOGRAPHIC

Visualizing
Eolian Landforms

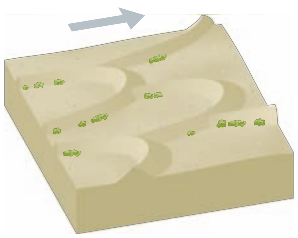
SAND DUNES



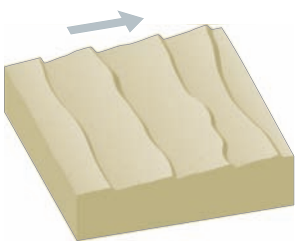
BARCHAN
The most common type of sand dune, the points of these crescent-shaped dunes lie downwind.



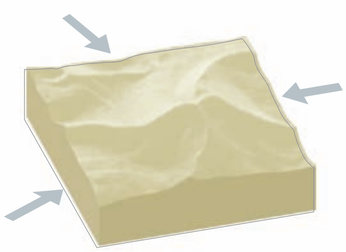
LONGITUDINAL
These are narrow, lengthy sand ridges that lie parallel to the prevailing wind direction.



PARABOLIC
Similar in shape to barchans, the points of these crescent-shaped dunes lie upwind.



TRANSVERSE
Looking like sandy sea waves, these dunes form perpendicular to the prevailing wind.



STAR
Formed by winds blowing from many directions, these pyramidal sand mounds grow upward.

▶ The steep slopes of sand dunes provide a unique recreational activity—sliding downhill on a boogie board at White Sands National Monument, New Mexico.

◀ This "sand sea" of transverse dunes in the Namib Desert, Namibia, resembles a wave-covered ocean surface frozen in place. The intense red color is produced by iron oxide, which stains the quartz dune grains.

▶ Dust storms can transport fine particles of silt and clay for long distances and build thick deposits of loess. In this photo, American Marines in Kuwait endure a dust storm while awaiting the order to invade Iraq in 2003.

Eolian Landforms

LEARNING OBJECTIVES

Explain how sand dunes form and move.

Describe the different types of sand dune.

Define loess.

Explain how induced deflation occurs.

SAND DUNES

A **sand dune** is any hill of loose sand shaped by the wind. Dunes are one of the most common types of eolian, or wind-generated, landforms. They 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 form 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.

Sand dune Hill or ridge of loose, well-sorted sand shaped by wind and usually capable of downwind motion.

Dune sand is usually composed of quartz, which is extremely hard and doesn't easily decay. 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*.

One common type of sand dune is an isolated heap 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 13.23). Barchan dunes usually rest on a flat, pebble-covered ground surface. They begin as a sand drift in

Barchan dune
FIGURE 13.23

A This row of barchan dunes is 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°.

B Where the sand supply is somewhat smaller, barchan dunes move over the surface as individual crescents with points extended downwind.

A sand sea of transverse dunes
FIGURE 13.24

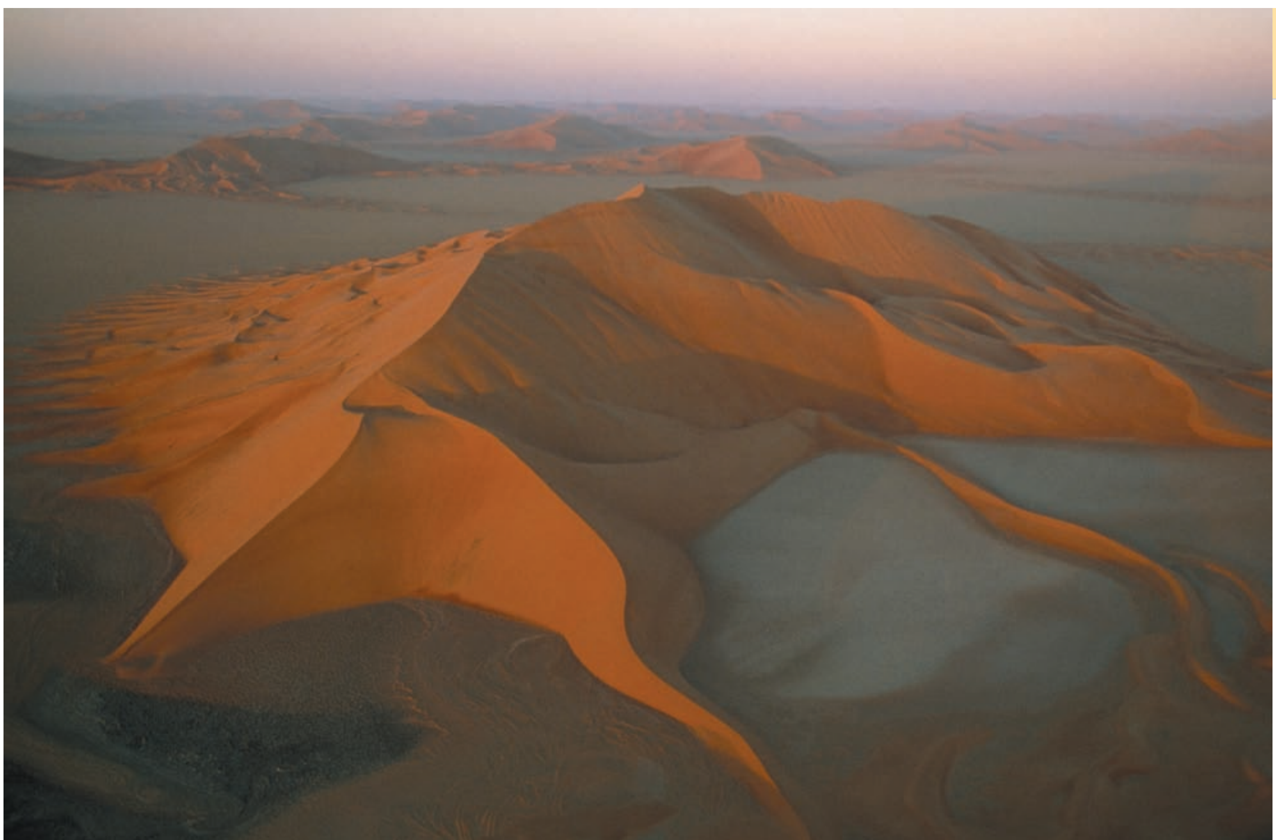
The sand ridges have sharp crests and are asymmetrical, the gentle slope being on the windward side and the steep slip face on the lee side. There are deep depressions between the dune ridges. Sand seas require enormous quantities of sand, supplied by material weathered from sandstone formations or from sands in nearby alluvial plains. Transverse dune belts also form next to beaches that supply abundant sand and have strong onshore winds. This photo provides an example from Baja California, Mexico.

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.

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 13.24). The entire area is known as a *sand sea* because it resembles a storm-tossed sea that's suddenly been frozen.

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 13.25). You can also see star dunes in the deserts of the border region between the United States and Mexico.



Star dune
FIGURE 13.25

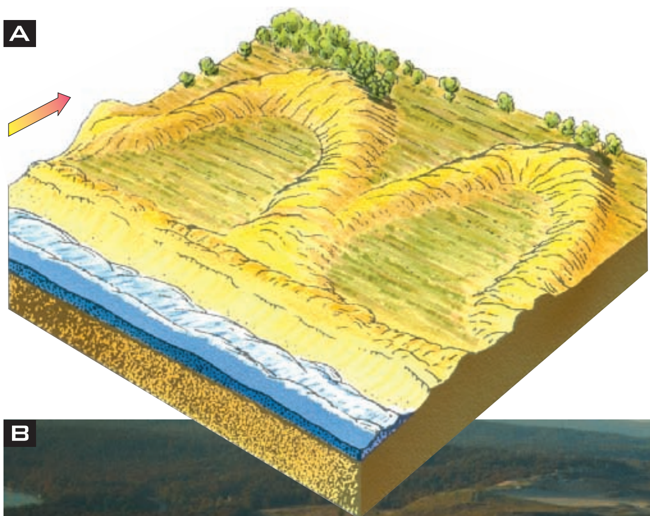
These large sand hills with dune crests radiating away from the center are known as star dunes. They are common in the Sahara and Arabian deserts and are stable, almost-permanent features of the desert landscape.

Parabolic dunes have the opposite curvature, with respect to wind direction, as the barchan dune. A common type of parabolic dune is the *coastal blowout dune* (FIGURE 13.26). On semiarid plains, where vegetation is sparse and winds are strong, groups of parabolic blowout dunes develop to the lee of shallow deflation hollows.

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 13.27).

Coastal blowout dunes FIGURE 13.26

A



A Parabolic dunes form next to beaches, where there is 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 advances over the lower ground and buries forests, killing the trees.

B This dunescape of coastal blowout dunes is 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, that push sand inland.

B

Longitudinal dunes FIGURE 13.27

Longitudinal dunes are parallel to the prevailing wind direction. Shown here are longitudinal dunes adjacent to Lake Eyre in South Australia.

COASTAL FOREDUNES

We usually find a narrow belt of dunes in the region landward of beaches. These *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 13.28). 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 FIGURE 13.28

Beachgrass thriving on coastal foredunes has trapped drifting sand to produce a dune ridge. Queen's County, Prince Edward Island, Canada.

LOESS

In several large midlatitude areas of the world, the surface is covered by deposits of wind-transported silt that has settled out from dust storms over many 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 13.29A). 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 dwellings both in China and in Central Europe because it's easily excavated.

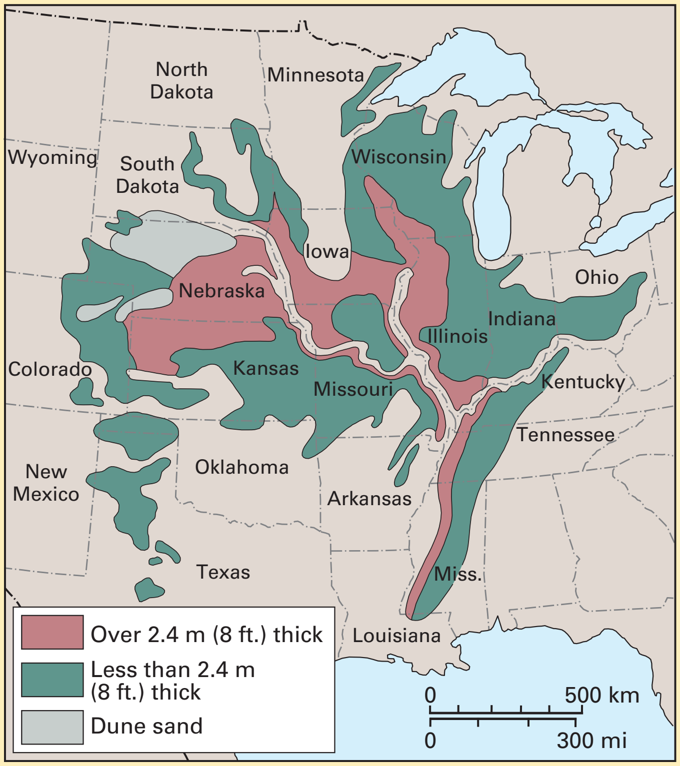
Loess Surface deposit of wind-transported silt.

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. Loess deposits are also common in the United States, Central Europe, Central Asia, and Argentina.

In the United States, there are thick loess deposits in the Missouri-Mississippi Valley (FIGURE 13.29B). 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 FIGURE 13.29

A This thick layer of wind-transported silt in New Zealand was deposited during the Ice Age. Loess has excellent cohesion and often forms vertical faces as it wastes away.



B 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.

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

The "Dust Bowl" of the 1930s resulted from *induced deflation*. When short-grass prairie in a semiarid region is cultivated without irrigation, it makes the ground much more susceptible to deflation. 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 dust storms generated by turbulent winds. Strong cold fronts frequently sweep over this area and lift dust high into the troposphere at times when soil moisture is low.

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).

CONCEPT CHECK **STOP**

Name the different types of sand dunes.

How are coastal foredunes stabilized?

What is loess?

What is induced deflation?

What is happening in this picture?

- A battered house, suspended on stilts, sits in the surf on a sandy Atlantic beach. Its windows and doors are sealed with plywood, and waves break underneath it. A pile of wooden debris is heaped up nearby. What's happening here?
- 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.
- As global warming continues, global climate models predict that severe storms will become more common, as will scenes like this.

VISUAL SUMMARY

1 The Work of Waves and Tides

1. Waves act at the shoreline. They expend their energy as breakers, which erode hard rock into marine cliffs and create marine scarps.
2. Beaches, usually formed of sand, are shaped by the swash and backwash of waves. Wave action produces littoral drift, which moves sediment parallel to the beach.
3. Tidal forces cause sea level to rise and fall rhythmically, creating tidal currents in bays and estuaries that redistribute fine sediments.

2 Types of Coastlines

1. Coastlines of submergence result when coastal lands sink below sea level or sea level rises rapidly. Scenic ria and fiord coasts are examples. Other coastlines include barrier-island, delta, volcano, coral-reef, and fault coasts.
2. Along some coasts, rapid uplift has occurred, creating raised shorelines and marine terraces.

3 Wind Action

1. Wind action creates landforms through abrasion and deflation.
2. Deflation creates blowouts in semidesert regions and lowers playa surfaces in deserts. In arid regions, deflation produces dust storms.

4 Eolian Landforms

1. Sand dunes form when a source provides abundant sand that can be moved by wind action. Types of dunes include barchan, transverse, parabolic, star, and longitudinal dunes.

2. Coastal foredunes are stabilized by dune grass and help protect the coast against storm wave action.

3. Loess is a surface deposit of fine, wind-transported silt.

4. Human activities can hasten the action of deflation by breaking protective surface covers of vegetation and desert pavement.

KEY TERMS

- **shoreline** p. 386
- **coastline** p. 386
- **marine cliff** p. 388
- **beach** p. 388
- **littoral drift** p. 389
- **delta** p. 394
- **coral reef** p. 395
- **marine terrace** p. 399
- **deflation** p. 401
- **sand dune** p. 406
- **loess** p. 410

CRITICAL AND CREATIVE THINKING QUESTIONS

1. What is littoral drift, and how is it produced by wave action?

2. Identify progradation and retrogradation. How can human activity influence retrogradation?

3. Consult an atlas 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 you used to identify the coastline type.

4. How are marine terraces formed?

5. What is deflation, and what landforms does it produce? What role does the dust storm play in deflation?

6. How do sand dunes form? Describe and compare barchan dunes, transverse dunes, star dunes, coastal blowout dunes, parabolic dunes, and longitudinal dunes. Sketch the dunes, showing the wind direction for the barchan, transverse, parabolic, and longitudinal dunes.

7. What is the role of coastal dunes in beach preservation? How are coastal dunes influenced by human activity? What problems can result?

8. Define the term *loess*. What is the source of loess, and how are loess deposits formed?

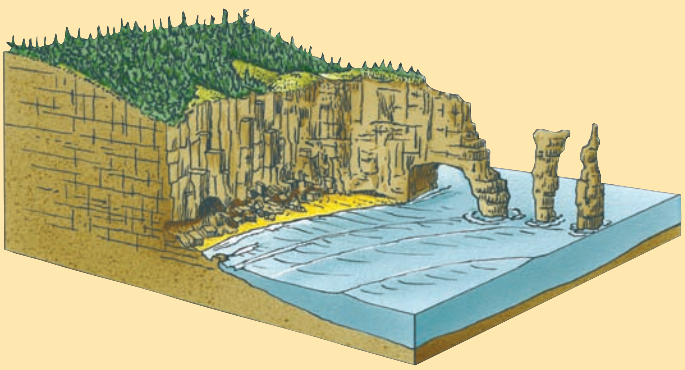
SELF-TEST

1. The shifting line of contact between water and land is referred to as a __________ while a broader term __________ refers to a zone in which coastal processes operate or have strong influence.
   a. coastline; shoreline
   b. beach, coastline
   c. shoreline, coastline
   d. seashore, coastline

2. Where a river empties into an ocean bay, the bay is termed a(n) __________.
   a. estuary
   b. shoreline
   c. coast
   d. coastline

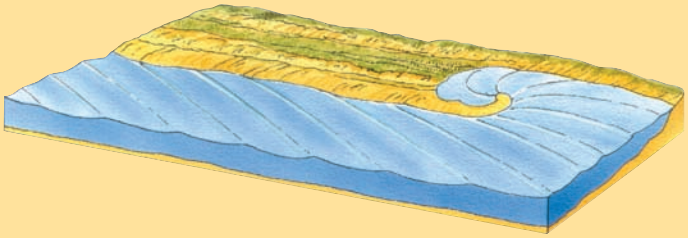
3. The most important agent shaping coastal landforms is __________ action.
   a. storm
   b. stream
   c. salinization
   d. wave

4. The diagram shows some of the landforms created by wave action against a marine cliff. Label the deep basal indentation that marks the line of most intense wave erosion. What is this feature called?



5. 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 is called __________.
   a. retrogradation
   b. progradation
   c. propagation
   d. retreading

6. Littoral drift, as shown in the diagram, includes __________.
   a. beach drift and ebb tide
   b. ebb tide and longshore drift
   c. beach drift and longshore drift
   d. flood tide and ebb tide



7. Tidal currents are made up of two opposing currents called __________ currents.
   a. longshore and littoral
   b. ebb and flood
   c. longshore and flood
   d. ebb and littoral

8. The diagram shows a deeply embayed coast, which results from submergence of a landmass dissected by streams. What is this coastline called?

9. Broad expanses of isolated shallow water called __________ are common features immediately adjacent to barrier-island coastlines.
   a. salt marshes
   b. marine terraces
   c. lagoons
   d. tidal inlets

10. The deposition of sediments by a stream or river entering a large body of standing water often produces a __________.

a. delta
b. ria
c. marine terrace
d. fault

11. __________ coasts are unique in that the addition of new land is made by organisms in warm oceans.

a. Delta
b. Coral-reef
c. Ria
d. Volcano

12. __________is formed when fine particles of silt and clay are removed from the surface by wind deflation. Subsequent deposition of the wind-transported silt and clay particles produce __________ deposits that help enrich soils with nutrients.

a. Desert bedrock, loess
b. Caleche, loess
c. Loess, silt
d. Desert pavement, loess

13. A __________ sand dune is one that has the outline of a crescent, and the points of the crescent are directed downwind.

a. barchan
b. transverse
c. star
d. parabolic

14. A great sand sea, like the one found in the Sahara desert, is called a(n) __________.

a. beach
b. desert pavement
c. reg
d. erg

15. One distinctive type of sand dune, shown in the photograph, is a __________ dune.

a. barchan
b. transverse
c. star
d. parabolic

Glacial Landforms and the Ice Age

14

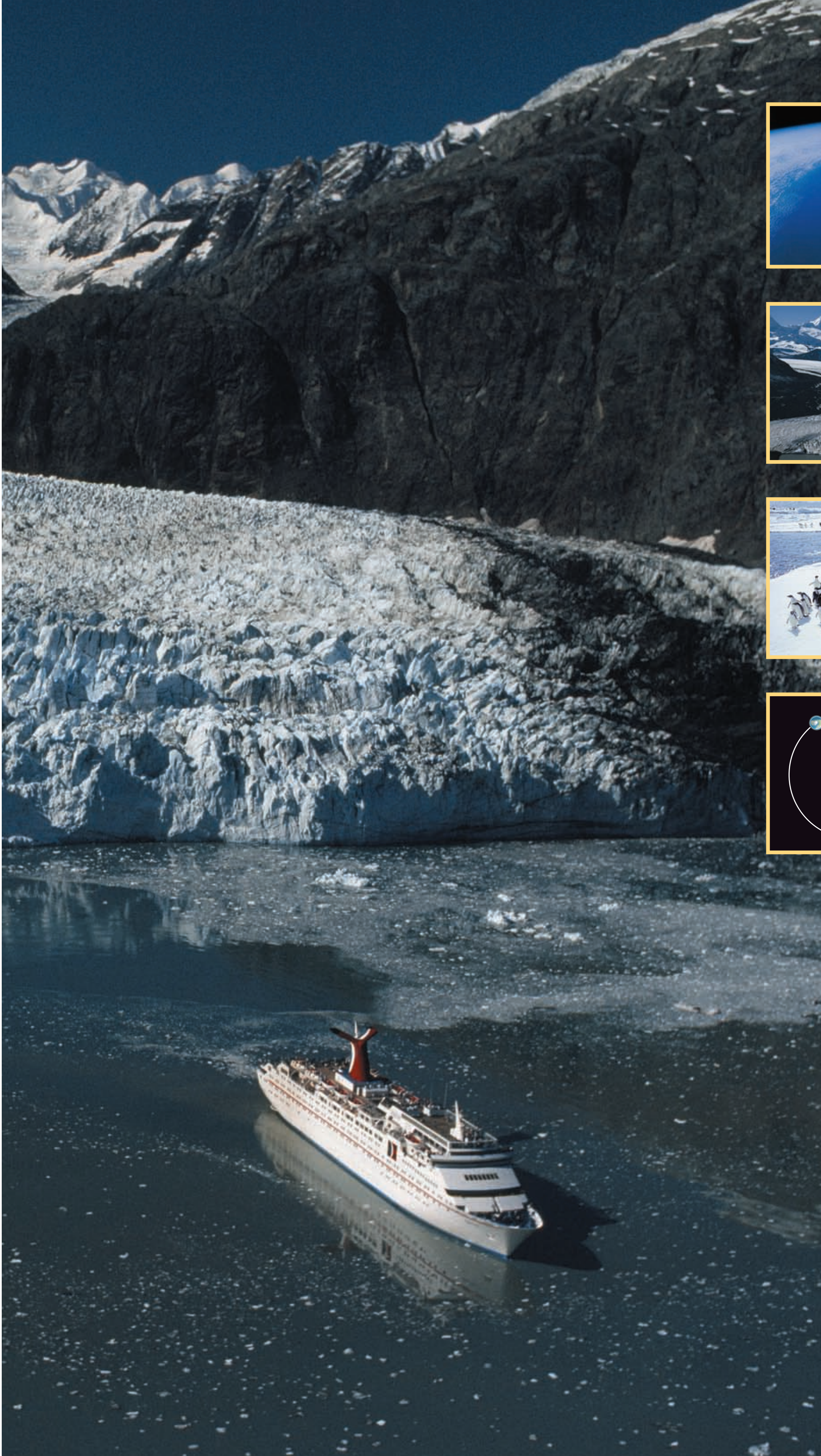
Glacier Bay is a drowned valley. Once filled with a huge tongue of glacial ice, this steep-walled fiord now houses only sea water and small drifting ice fragments. Low, rocky peaks stand on either side of the bay's mouth, sculpted by the ice into stark angular shapes composed of points and edges. Ahead are the high peaks of the Saint Elias Mountains, entirely capped with white.

Entering the mouth of the bay, you will soon see the Marjerie Glacier. Its snout is fractured into tall, vertical columns with features that seem almost like horizontal steps at the top. Beneath a top white layer of decaying ice and snow, the ice is a bright greenish-blue. The color is so intense that the ice seems to glow from within. The ice is also noisy. It groans, screeches, clicks, and pops.

Flowing slowly and majestically, glacial ice makes and moves sediment, creating many types of distinctive landforms. If you live in or visit a glaciated region, you'll see lots of evidence of glaciation. From ponds formed by the melting of buried ice blocks to the great hills of sediments dumped by glacial ice sheets at their margins, glaciers have drastically modified much of the landscape.

Glacial ice still exists today in two great accumulations of continental dimensions—the Greenland and Antarctic Ice Sheets—and in many smaller masses in high mountains.

Marjerie Glacier, Glacier Bay, Alaska



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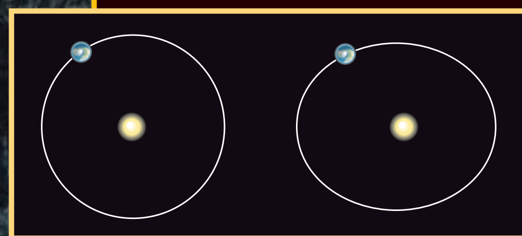

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Glaciers

Learning Objectives

Explain how glaciers form.

Define ice sheets and alpine 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 (Figure 14.1).

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 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.

When we think of ice, most of us picture a brittle, crystalline solid. But large bodies of ice, with a great thickness, are much more plastic. That's because the huge pressure on the ice at the bottom of an ice mass forces it to lose its rigidity. This means that a huge body 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 (Figure 14.2).

Greenland ice sheet Figure 14.1

The Greenland ice sheet, seen here in a photo from space, occupies more than 1.7 million sq km (about 670,000 sq mi) and covers about seven-eighths of this vast island. The view here is of the southern tip, showing snow-covered terrain of hills and fiords around the central mass of ice.

Alpine glaciers Figure 14.2

Rising on the flanks of Mount Blackburn, the Nabesna Glacier, in Wrangell Saint Elias National Park, Alaska, is the longest valley glacier in North America. The dark stripe down the middle of the glacier is a medial moraine of rocky debris formed by the joining of lateral moraines as two ice streams flow together.

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.

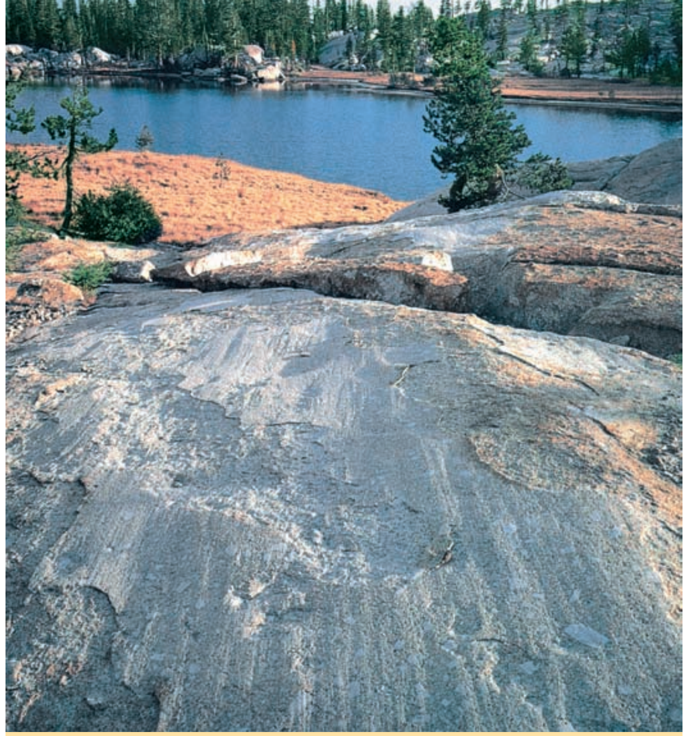
We can see that glacial ice will form in regions where there are low temperatures and high amounts of snowfall. This can occur at both high elevations and high latitudes. In mountains, glacial ice can form even in tropical and equatorial zones if the elevation is high enough to keep average annual temperatures 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.

Alpine glacier Long, narrow mountain glacier occupying the floor of a trough-like valley.

Ice sheet Large thick plate of glacial ice moving outward in all directions.

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 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.



Glacial abrasion FIGURE 14.3

This grooved and polished surface, now partly eroded, marks the former path of glacial ice. Cathedral Lakes, Yosemite National Park, California.

Glaciers and ice sheets erode and deposit great quantities of sediment. The rock fragments held within the ice scrape and grind against bedrock (FIGURE 14.3). 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.

CONCEPT CHECK STOP

How does a glacier form? Why does it move?

What is an alpine glacier?

Where do we find ice sheets today?

Name two ways that glaciers erode the surfaces around them.

Describe these processes.

Alpine Glaciers

Learning Objectives

Describe how alpine glaciers form.

Explain how alpine glaciers produce landforms.

Define fiord.

FIGURE 14.4 shows a cross section of an alpine glacier, illustrating a number of features. Although the uppermost layer of a glacier is brittle, the ice beneath behaves as a plastic substance that flows slowly (FIGURE 14.5). An alpine glacier can also slide downhill, lubricated by meltwater and mud at its base.

A glacier sets up 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 move forward or melt.

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 movement, known as *surges*. A surging glacier may travel

Cross section of an alpine glacier

FIGURE 14.4

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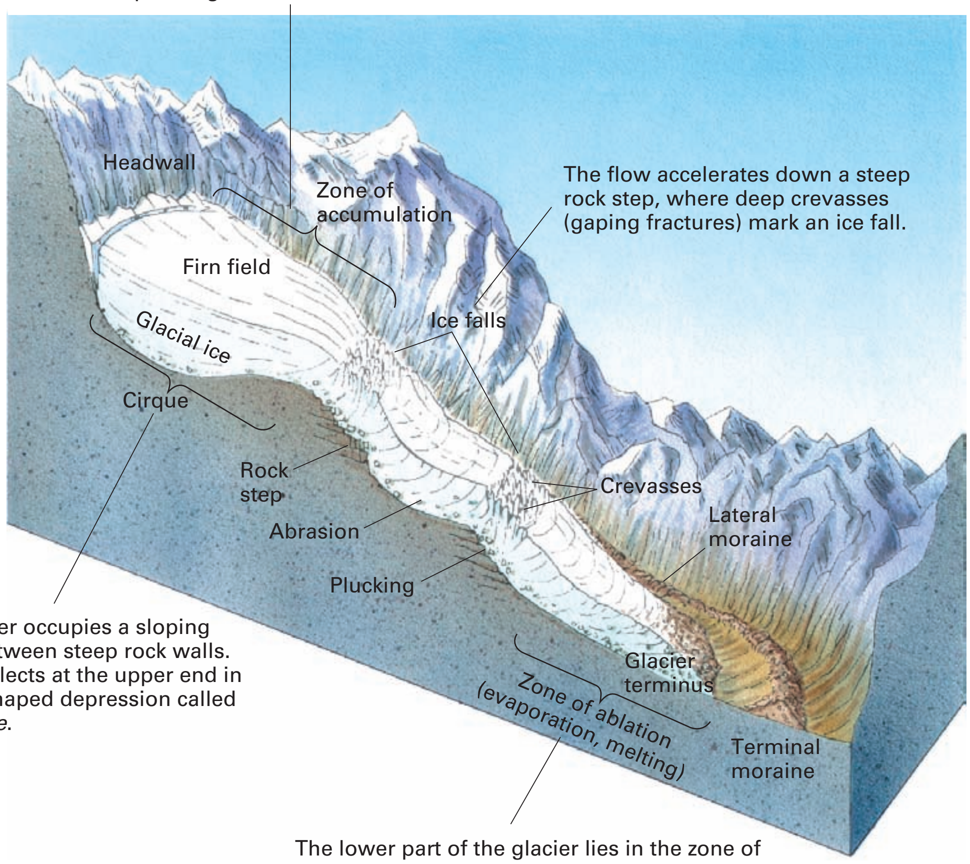
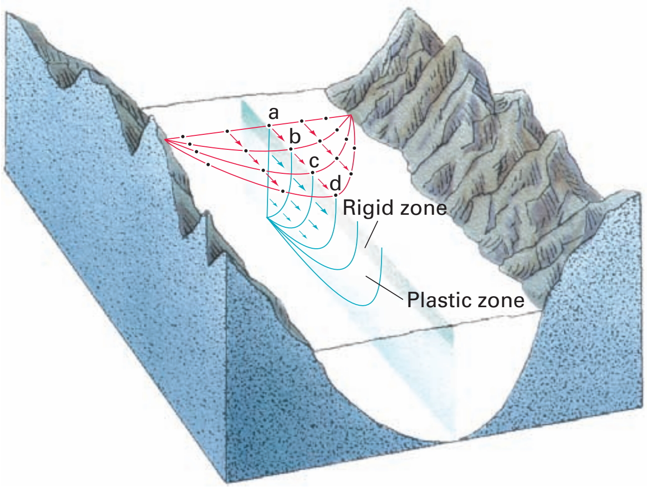




Motion of glacial ice FIGURE 14.5

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.

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.

LANDFORMS MADE BY ALPINE GLACIERS

The process diagram, "Landforms produced by alpine glaciers," shows how alpine glaciers create *arêtes*, *horns*, *cols*, *moraines*, *tarns*, *hanging valleys*, and glacial troughs. As large, distinctive features in areas of rugged terrain, glaciers are readily viewed from space. FIGURE 14.6 shows a satellite image of some of the features described in the process diagram.

Glacier flow strips away loose regolith, then deepens and widens the glacial valley so that after the ice has finally melted, a deep, steep-walled **glacial trough** remains behind from the trunk glacier. Tributary glaciers also produce troughs, but they are smaller in cross section and less deeply eroded by their smaller glaciers. Because the floors of these troughs lie above the level of the main trough, they are called *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.

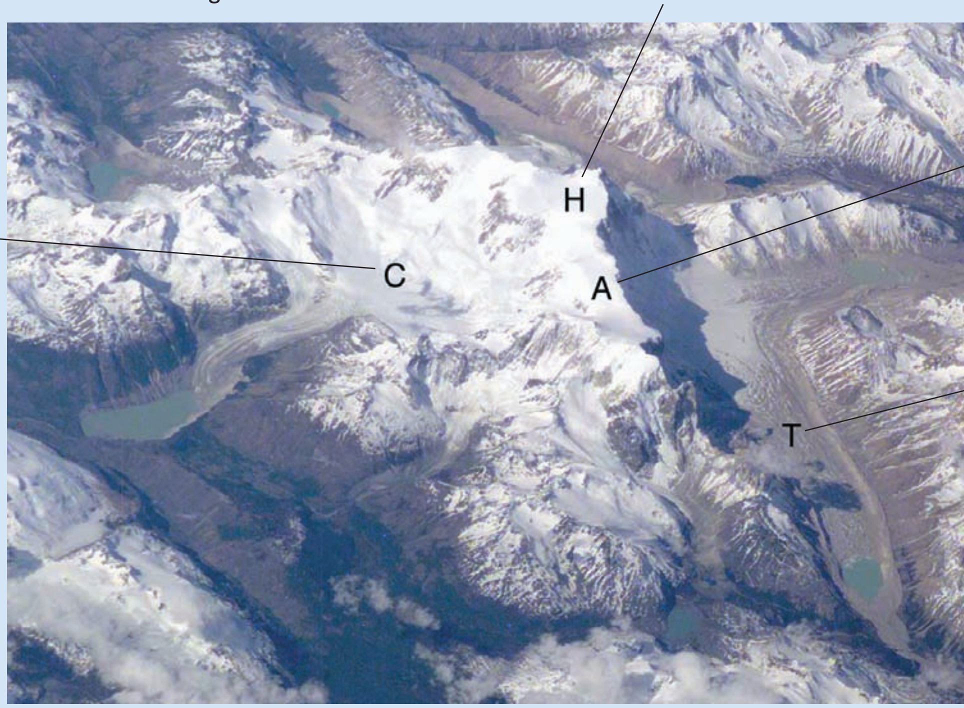
Glacial trough
Deep, steep-sided rock trench formed by alpine glacier erosion.

Andean alpine glacial features FIGURE 14.6

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.

The cirque, now only partly filled with glacial ice.

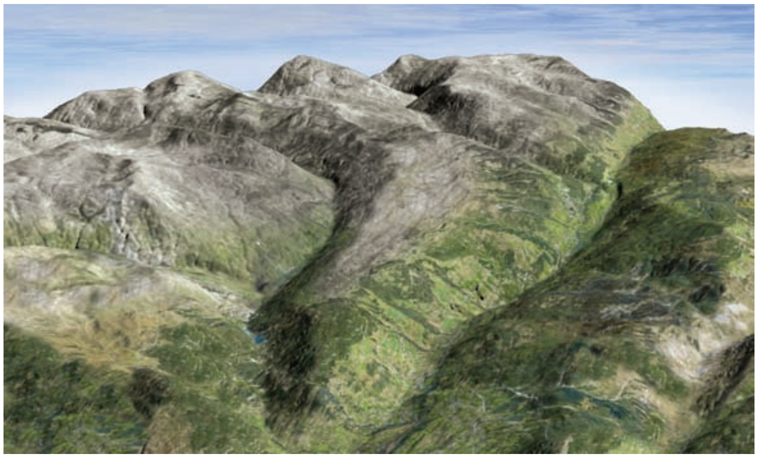


Leading away from the horn to the south is a long, sharp ridge, or arête.

Behind the peak is a glacial trough.

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 valleys down to hard bedrock.



A

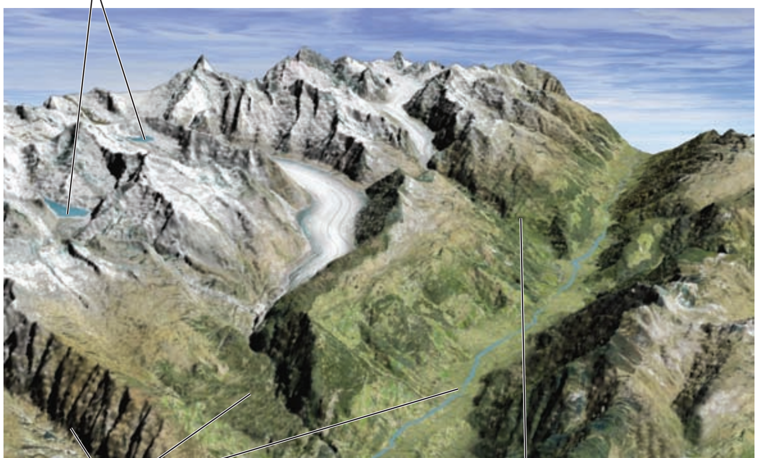
Before glaciation This region has been sculptured entirely by weathering, mass wasting, and streams. The mountains look rugged, with steep slopes and ridges. Small valleys are steep and V-shaped, while larger valleys have narrow floodplains filled with alluvium and debris.

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.

D

Melting glaciers As glaciers diminish they reveal their handiwork in distinctive landforms.

Tarn Rock basin high in smaller valleys that becomes a small glacial lake.



Glacial troughs When the ice disappears, a system of steep walled troughs is revealed.

Hanging valley Smaller tributary valleys that join the main glacier valley may be left "hanging" at a higher elevation as the trunk glacier deepens the main valley.

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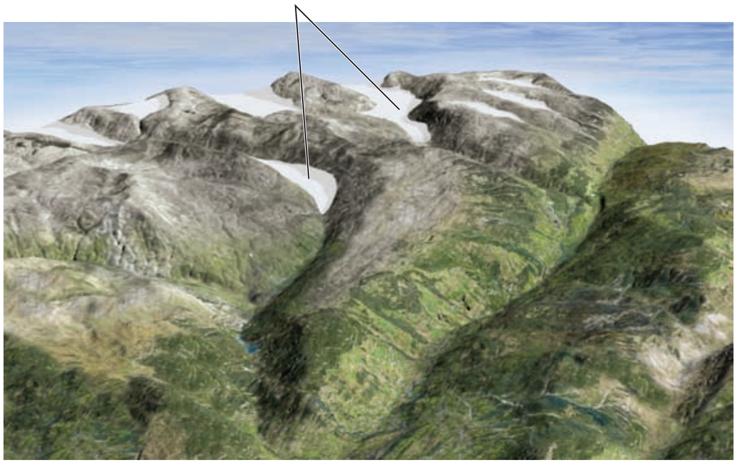
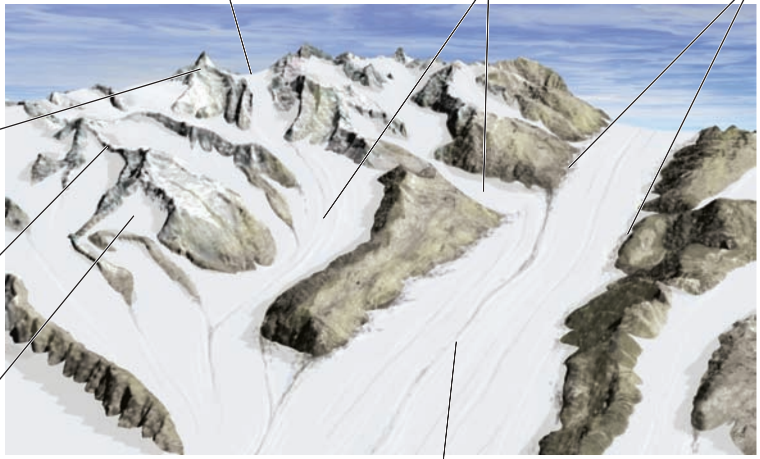
B

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.



C

Glaciation Thousands of years of accumulating snow and ice develops these new erosional forms.

Fiord Narrow, deep ocean inlet partially filling a glacial trough.

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.

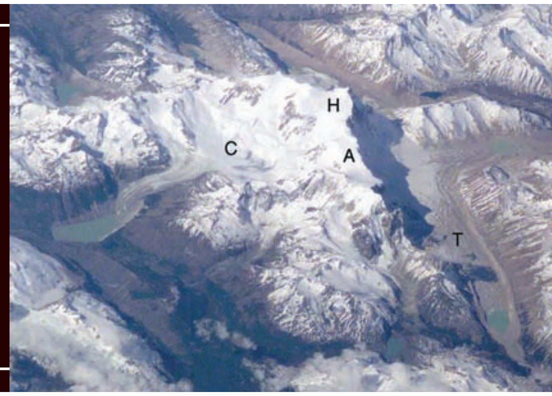
CONCEPT CHECK STOP

How do cirques develop?

What do we call the features created when glaciers deposit their rock debris?

What is a glacial trough?

What is a fiord?



Ice Sheets and Sea Ice

Learning Objectives

Define ice sheet and sea ice.

Describe the landforms created by ice sheets.

ICE SHEETS OF THE PRESENT

The ice sheets of Antarctica and Greenland are huge plates of ice, thousands of meters thick in the central areas, resting on land masses of subcontinental size. The Greenland Ice Sheet has an area of 1.7 million sq km (about 670,000 sq mi) and occupies about seven-eighths of the entire island of Greenland (Figure 14.7). The only land exposed is a narrow, mountainous coastal strip. The Antarctic Ice Sheet covers 13 million sq km (about 5 million sq mi) (Figure 14.8). 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. The Antarctic Ice Sheet is thicker than the Greenland Ice Sheet—as much as 4000 m (about 13,000 ft) at maximum. At some locations, ice sheets extend long tongues, called *outlet glaciers*, to reach the sea at the heads of fiords. Huge masses of ice break off from the floating edge of the glacier and drift out to open sea with tidal currents to become icebergs. 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.

The Greenland ice sheet

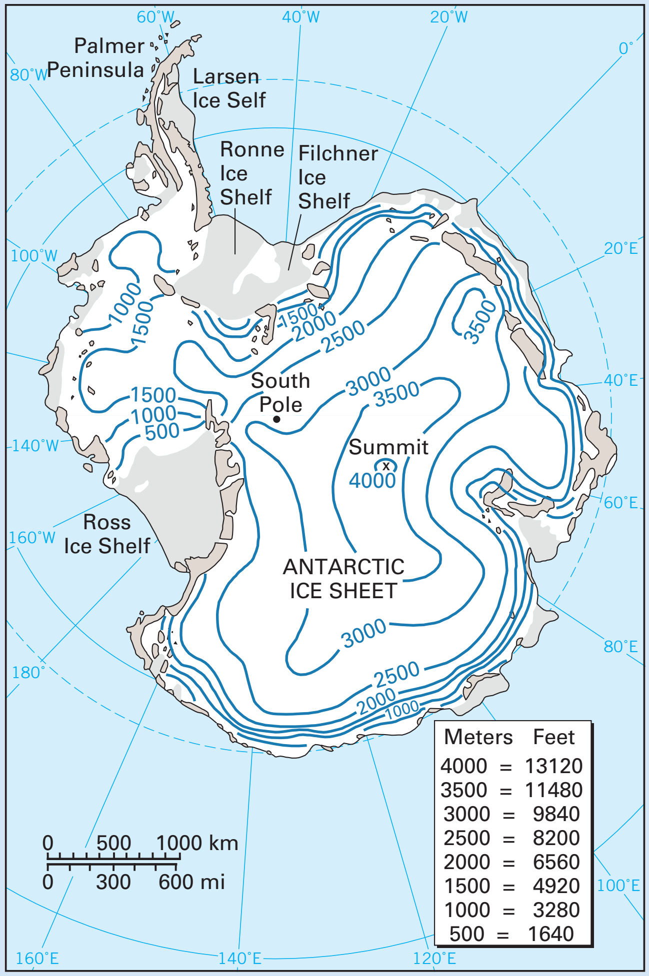
FIGURE 14.7

Contours show elevations of the ice sheet surface.

The Antarctic ice sheet and its ice shelves

FIGURE 14.8

Contours show elevations of the ice sheet surface.



SEA ICE AND ICEBERGS

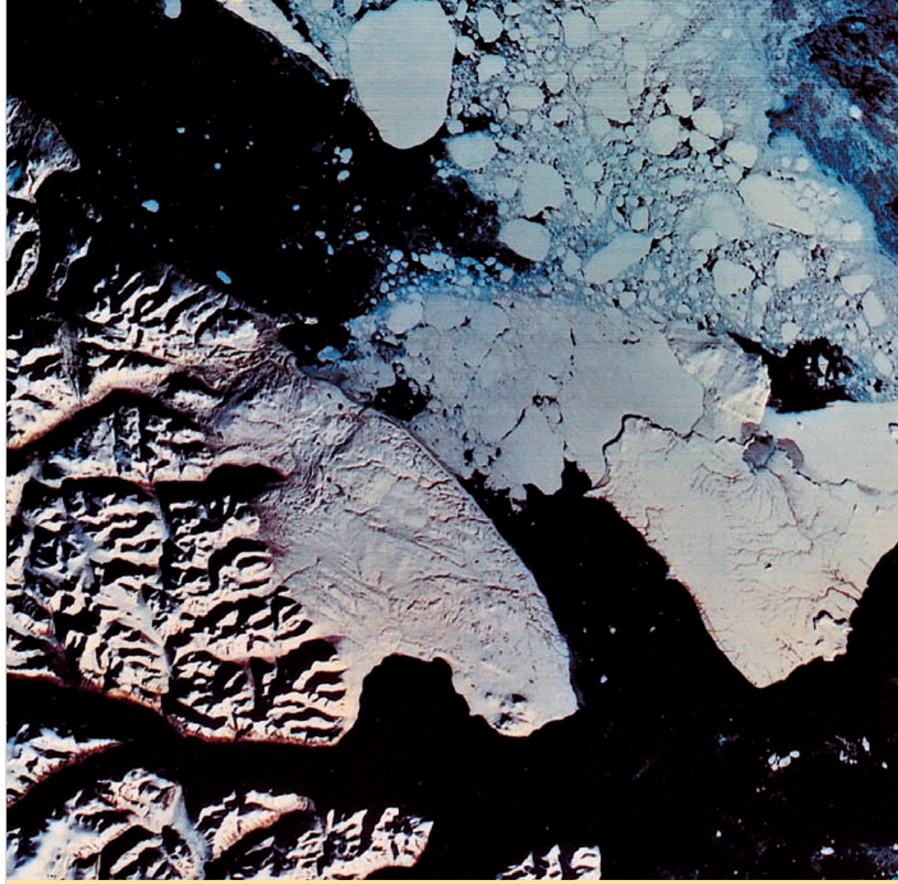
Sea ice Floating ice of the oceans formed by direct freezing of ocean water.

Iceberg Mass of glacial ice floating in the ocean that has broken off a glacier that extends into tidal water.

Free-floating ice on the sea surface takes two forms—sea ice and icebergs. **Sea ice** (FIGURE 14.9) is formed by direct freezing of ocean water. In contrast, **icebergs** have broken free from glaciers that terminate in the ocean. Another major difference between sea ice and icebergs is thickness. Sea ice is always less than 5 m (15 ft) in thickness, whereas icebergs may be hundreds of meters thick.

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 such 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 make traveling across polar sea ice on foot even more difficult. The surface zone of sea ice is composed of fresh water, while the deeper ice is salty.

When a valley glacier or tongue of an ice sheet terminates in sea water, blocks of ice break off to form icebergs (FIGURE 14.10). 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.



Sea ice FIGURE 14.9

A Landsat image of a portion of the Canadian arctic archipelago. There is an ice cap on a land mass in the center of the photo, with exposed mountainous ridges on the uncovered portions of the land mass. In the lower part of the image there is a branching glacial trough, now a water-filled fiord. In the upper left are huge chunks of free-floating sea ice.

Icebergs FIGURE 14.10

Adelie penguins socializing in the sun atop an iceberg in McMurdo Sound, Antarctica.

LANDFORMS MADE BY ICE SHEETS

Like alpine glaciers, ice sheets are very good at stripping away surface materials and eroding 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 much 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

Glacial abrasion FIGURE 14.11

A near-vertical rock outcrop on the side of Tracy Arm Fiord, Alaska, shows grooving and polishing from the passage of glacial ice.

on almost any freshly exposed hard rock surface. Sometimes the ice polishes the rock to a smooth, shining surface (FIGURE 14.11).

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 a valley glacier, scooping out a deep glacial trough.

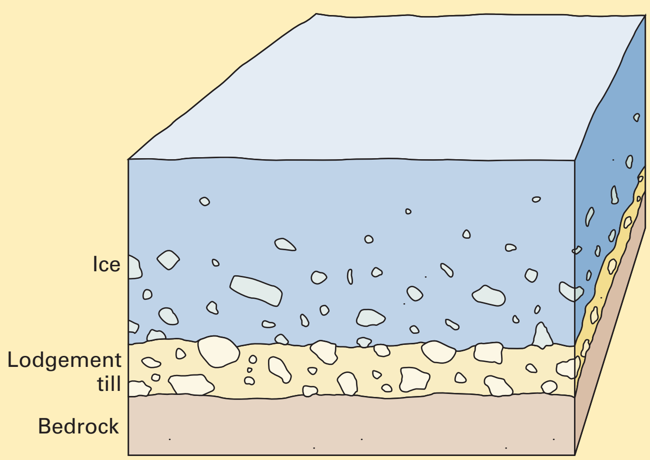
Ice sheets also resemble huge conveyor belts. Anything carried on the belt is dumped off at the end, and, if not constantly removed, will pile up in increasing quantity. Rock fragments brought within the ice are deposited at its outer edge as the ice evaporates or melts. We use the term **glacial drift** 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 an unstratified mixture of rock fragments, ranging in size from clay to boulders, that is deposited directly from the ice without water transport (FIGURE 14.12). Where till forms a thin, more or less even cover, it is referred to as *ground moraine*.

Glacial drift
General term for all varieties and forms of rock debris deposited by ice sheets.

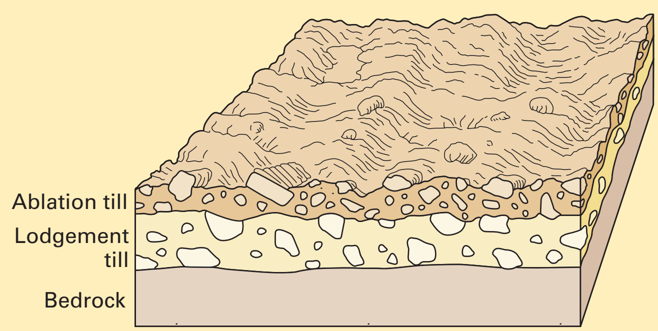
Over those parts of North America formerly covered by ice sheets, glacial drift thickness averages from 6 m (about 20 ft) over mountainous terrain, such as New England, to 15 m (about 50 ft) and more over the lowlands of the north-central United States. Over Iowa, drift thickness is from 45 to 60 m (about 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.

FIGURE 14.13 describes the form and composition of deposits left by ice sheets, including moraines, *eskers*, *drumlins*, and *kames*. *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

Glacial till FIGURE 14.12



A 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.

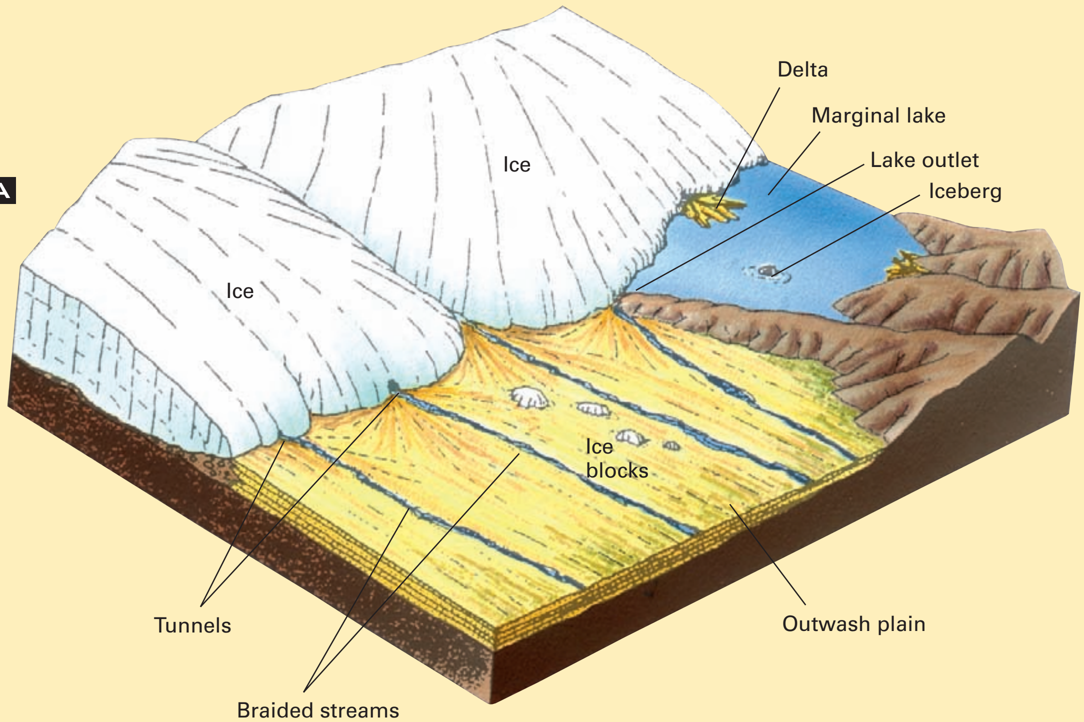


B When the overlying ice stagnates and melts, rock particles it holds in its body are lowered to the solid surface beneath, forming a layer of ablational till consisting of a mixture of sand and silt, with many angular pebbles and boulders. The layer of dense lodgment till lies below it.

Marginal landforms produced by ice sheets FIGURE 14.13

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.

A



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 stratified 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.

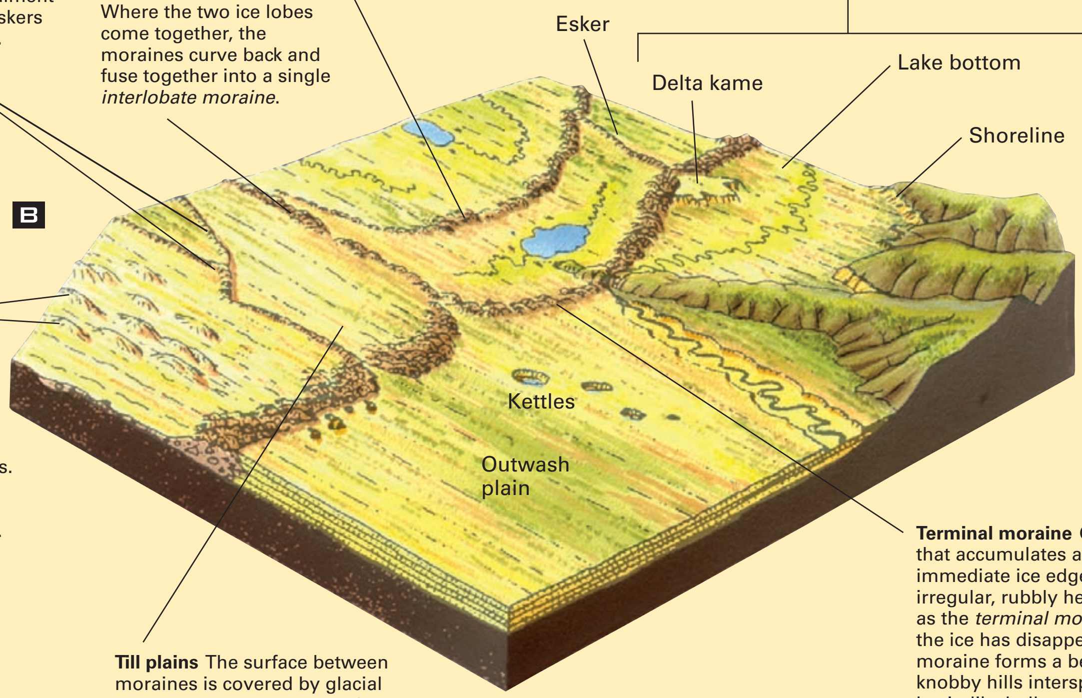
Esker The curving ridge of sand and gravel in this photo is an esker, marking the bed of a river of meltwater flowing underneath a continental ice sheet near its margin. Kettle Moraine State Park Wisconsin.

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.

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.

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. 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.

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.

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.

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.

▼ **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.

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). ▶

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. It's difficult to cultivate this till because there are countless boulders and cobbles in the clay soil. 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 knob-and-kettle 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, so it's a major source of ground water.

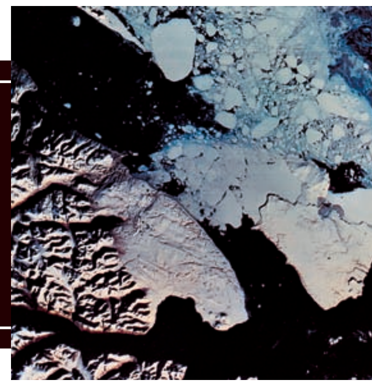
CONCEPT CHECK STOP

Give two differences between sea ice and icebergs.

What is glacial drift?

List five landforms produced by moving ice sheets.

Describe how they formed.



The Ice Age

Learning Objectives

Explain what an ice age is.

Define the Late-Cenozoic Ice Age.

Explain the possible causes of the Ice Age and glaciation cycles.

Describe Holocene environments.

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.

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

Glaciation
Single episode or time period in which ice sheets formed, spread, and disappeared.

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.

Late-Cenozoic Ice Age Or the **Ice Age** Series of glaciations, deglaciations, and interglaciations experienced during the late Cenozoic Era.

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.

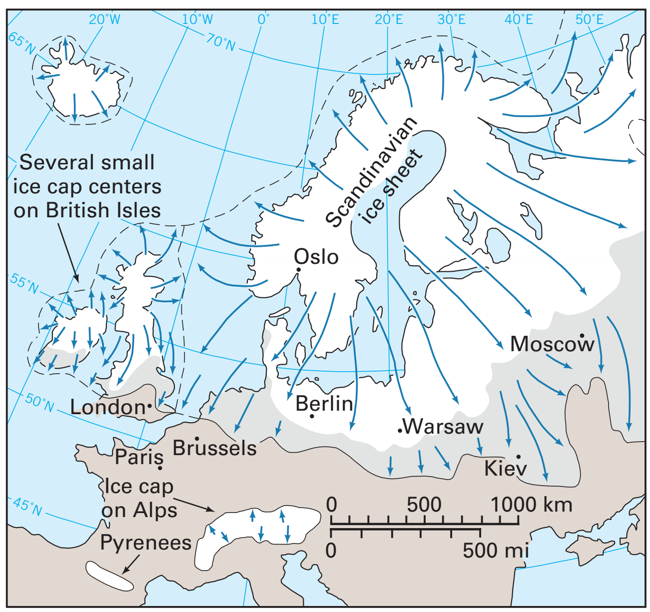
FIGURE 14.14 shows the maximum extent to which North America and Europe were covered during the last advance of the ice. Most of Canada was

Maximum glaciation in North America and Europe FIGURE 14.14

During glaciations sea level was much lower. The present coastline is shown for reference only.

A Continental glaciers of the Ice Age in North America at their maximum extent reached as far south as the present Ohio and Missouri rivers.

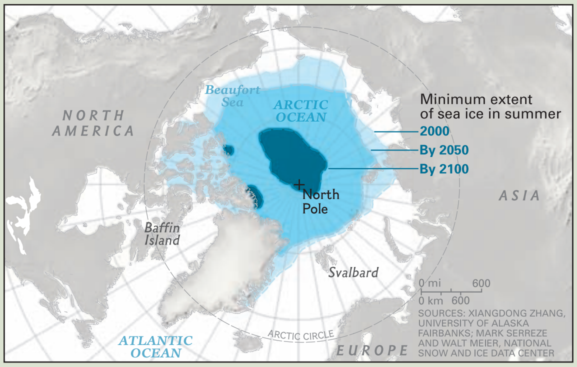
This area in southwestern Wisconsin escaped inundation, and is known as the Driftless Area.



B 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.

GLACIAL CLIMATE

The Cenozoic Era, beginning about 66 million years ago, has seen a gradually cooling climate, culminating in the recent Ice Age. By about 40 million years ago, the Antarctic ice sheet began to form, and by about 5 million years ago, the Arctic Ocean was ice-covered. Since then, the Earth has experienced alternating glacial and interglacial periods, with five major glaciations in the past 500,000 years.



◀ POLAR ICE CAP

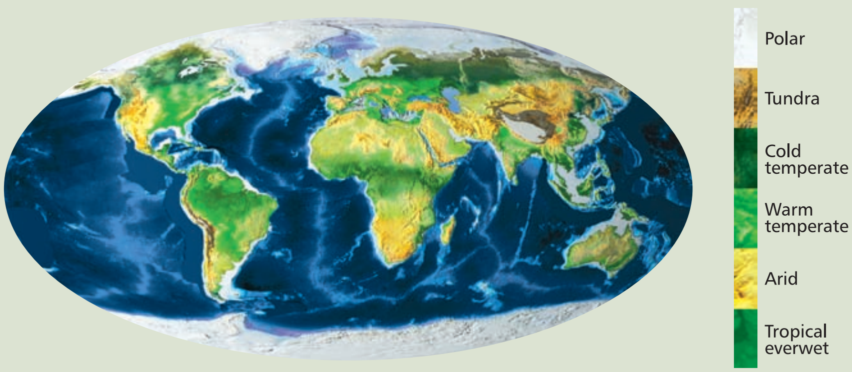
Over the last 50 years, the extent of polar sea ice has noticeably decreased. Since 1970 alone, an area larger than Norway, Sweden, and Denmark combined has melted. This trend is predicted to accelerate as temperatures rise in the Arctic and across the globe.

◀ 55 MILLION YEARS AGO

As the Indian subcontinent was approaching Asia, and South America and Africa were moving apart to widen the narrow Atlantic Ocean, the Earth was quite warm. Sea levels were higher, submerging much of southeastern North America. The climates of Canada and northern Europe were warm and moist.

▶ 5 MILLION YEARS AGO

By about 5 million years ago, ice sheets accumulated on Antarctica and Greenland, and the Arctic Ocean was covered with a floating ice cap. Sea levels fell as ice accumulated on the continents, and modern coastal land features, such as the Florida peninsula, emerged from the sea.

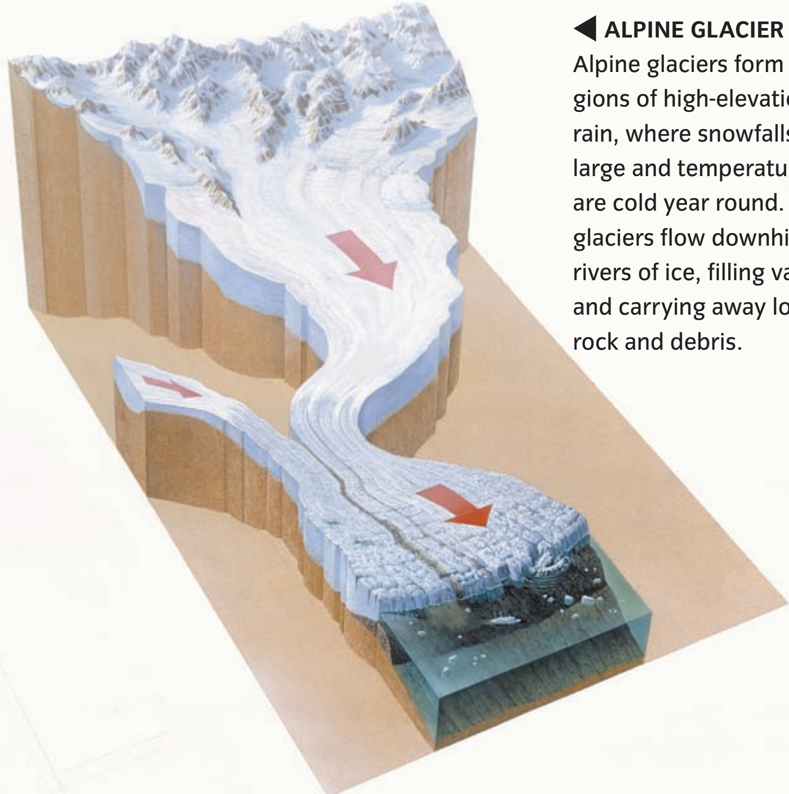


▶ RECENT ICE AGES

The Earth now oscillates between colder glacial and warmer interglacial periods. During the last glacial period, which ended about 20,000 years ago, ice sheets covered large portions of North America, Europe, and the Andes. Global sea level was about 120 m (about 400 ft) lower than present.

NATIONAL GEOGRAPHIC

Visualizing
Glacial Climates and Landforms

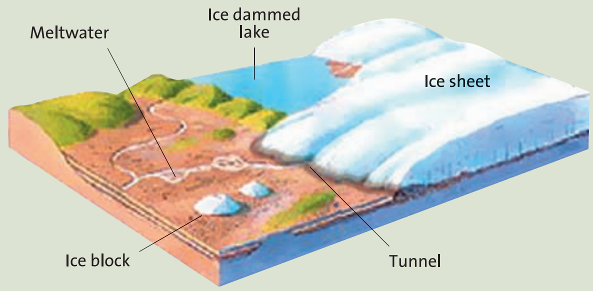


◀ ALPINE GLACIER
Alpine glaciers form in regions of high-elevation terrain, where snowfalls are large and temperatures are cold year round. The glaciers flow downhill like rivers of ice, filling valleys and carrying away loose rock and debris.

▲ ICEBERG
Icebergs are huge masses of ice that break off from glaciers flowing into ocean water. In Antarctica, some icebergs are formed by the breakup of ice shelves—massive ice sheets that extend out from parent continental glaciers but are still connected to them.

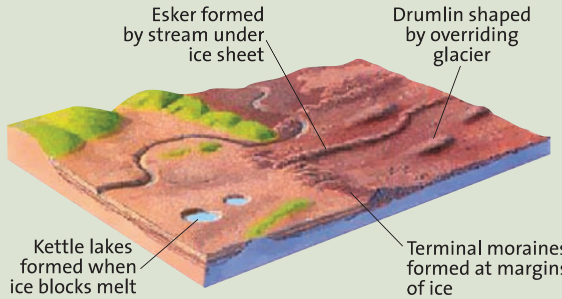
GLACIAL LANDFORMS

Glacial ice, flowing as alpine glaciers or as continental ice sheets, creates many distinctive landforms found in high-latitude and high-elevation parts of the world. Powered by gravity, the ice picks up and carries away loose rock and soil while grinding and polishing underlying bedrock. The sediment load is deposited when the ice melts at or near the terminus of the glacier.



▲ GLACIAL STAGE
Continental glaciers move across the landscape, filling river valleys and damming them with ice. The ice changes the topography as it sweeps up loose soil and regolith and grinds away at bedrock. It carries the debris to its terminus, where it is dumped in piles or washed away by meltwater.

◀ ALPINE GLACIER
Alpine glaciers are found in many mountainous regions of the world, even though the Earth's climate is presently interglacial. Pictured here is the terminus of the Moreno Glacier where it enters Lake Argentino, Patagonia. The glacier front is about 60 m (200 ft) high.



▲ POSTGLACIAL STAGE
Melting reveals a terrain of stony soils with grooved and polished bedrock formed at the bed of the continental glacier. Beyond the ice sheet's margin are plains of outwash sand and gravel.

engulfed by the vast Laurentide Ice Sheet, which then spread south into the United States.

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 14.14, 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.

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.

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.

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 Pangea 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 land-mass area to a high latitude and surrounded a polar ocean with land. 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 Pangea 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 14.15). 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.

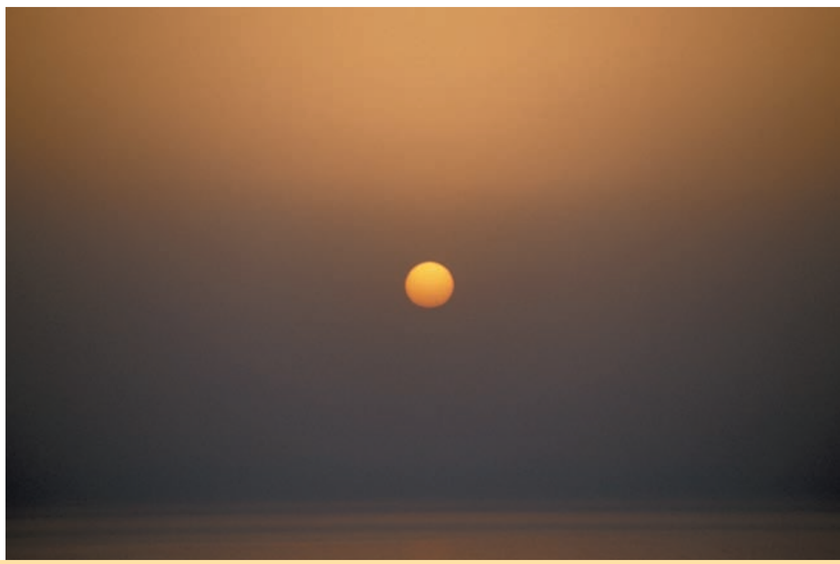
Volcanic eruption FIGURE 14.15

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.

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 14.16). 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 timescale. 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.



Solar output FIGURE 14.16

One possible cause of the Late-Cenozoic Ice Age is a reduction in solar output.

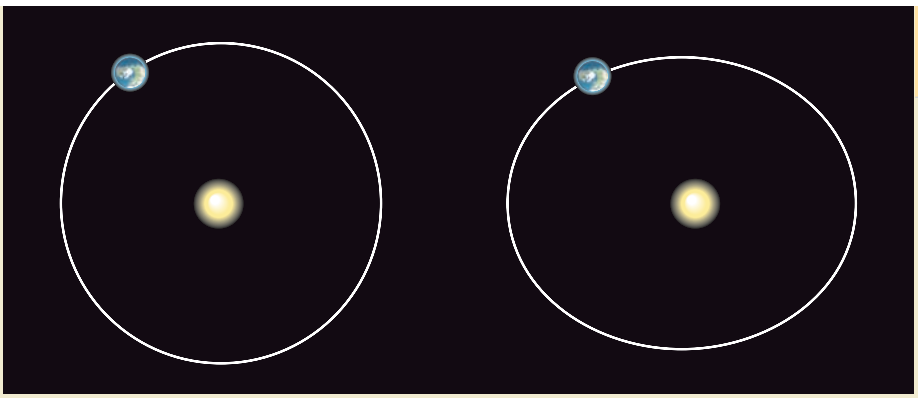
POSSIBLE CAUSES OF GLACIATION CYCLES

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 14.17). The Earth's orbit around the Sun is an ellipse, not a circle. We call the point in the orbit nearest the Sun the perihelion, and the point farthest from the Sun the aphelion. Today, the Earth is at perihelion around December 5 and aphelion around July 5. 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. This changes the Earth–Sun distance and therefore the amount of solar energy the Earth receives at each point of the annual cycle.

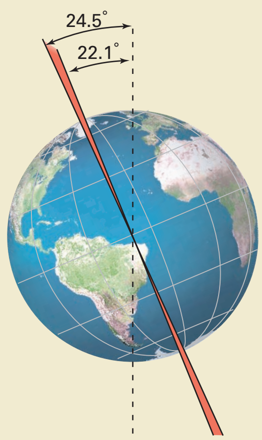
Astronomical hypothesis
Explanation for glaciations and interglaciations based on cyclic variations in the solar energy received at the Earth's surface.

The astronomical hypothesis
FIGURE 14.17

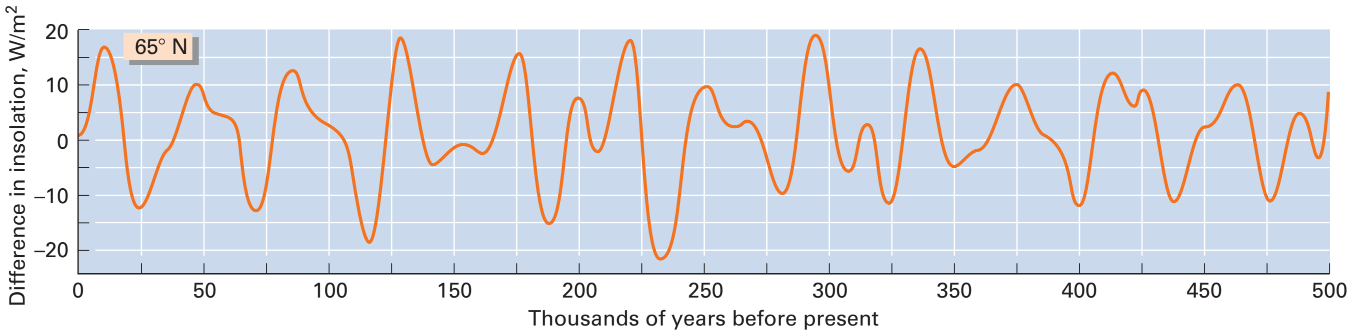


▲ The shape of the Earth's orbit around the Sun varies from nearly circular to slightly elliptical with a period of about 108,000 years.

▲ The Earth's 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 22.1° to 24.5° with a period of about 41,000 years.



The Milankovitch curve FIGURE 14.18

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 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.

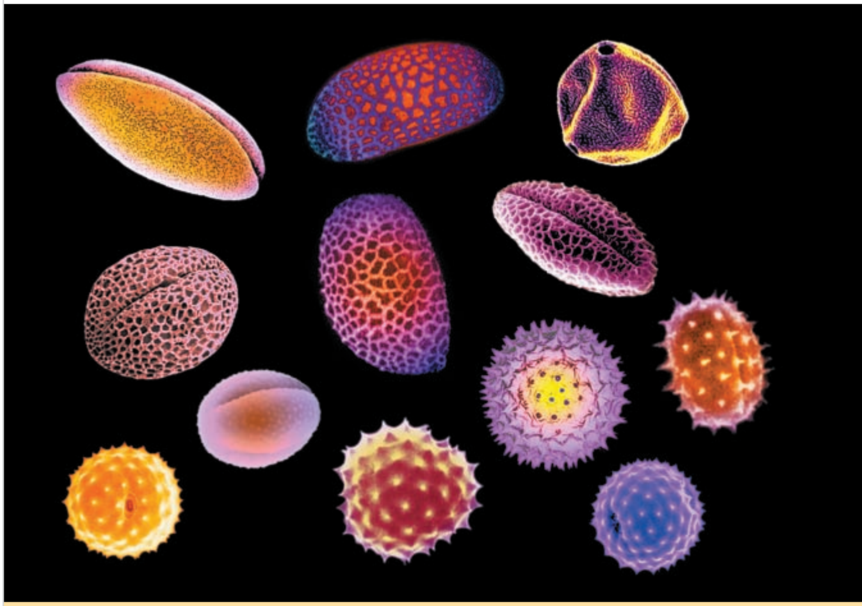
These cycles in axial rotation and solar revolution mean that the annual insolation experienced at each latitude changes from year to year. FIGURE 14.18 shows a graph of summer insolation received at 65° N latitude for the last 500,000 years as calculated from these cycles. The graph is known as the 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 cyclic insolation changes explain the cycles of glaciation within the Ice Age.

HOLOCENE ENVIRONMENTS

About 10,000 years have elapsed since the Wisconsinan Glaciation ended. We call that 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 14.19). The earliest of the three is the Boreal stage, characterized by boreal forest vegetation in midlatitude regions. There followed a general warming until the

Holocene Epoch Last epoch of geologic time, commencing about 10,000 years ago and including the present.



Pollen grains FIGURE 14.19

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 that existed nearby. (Colors shown do not reflect true colors.)

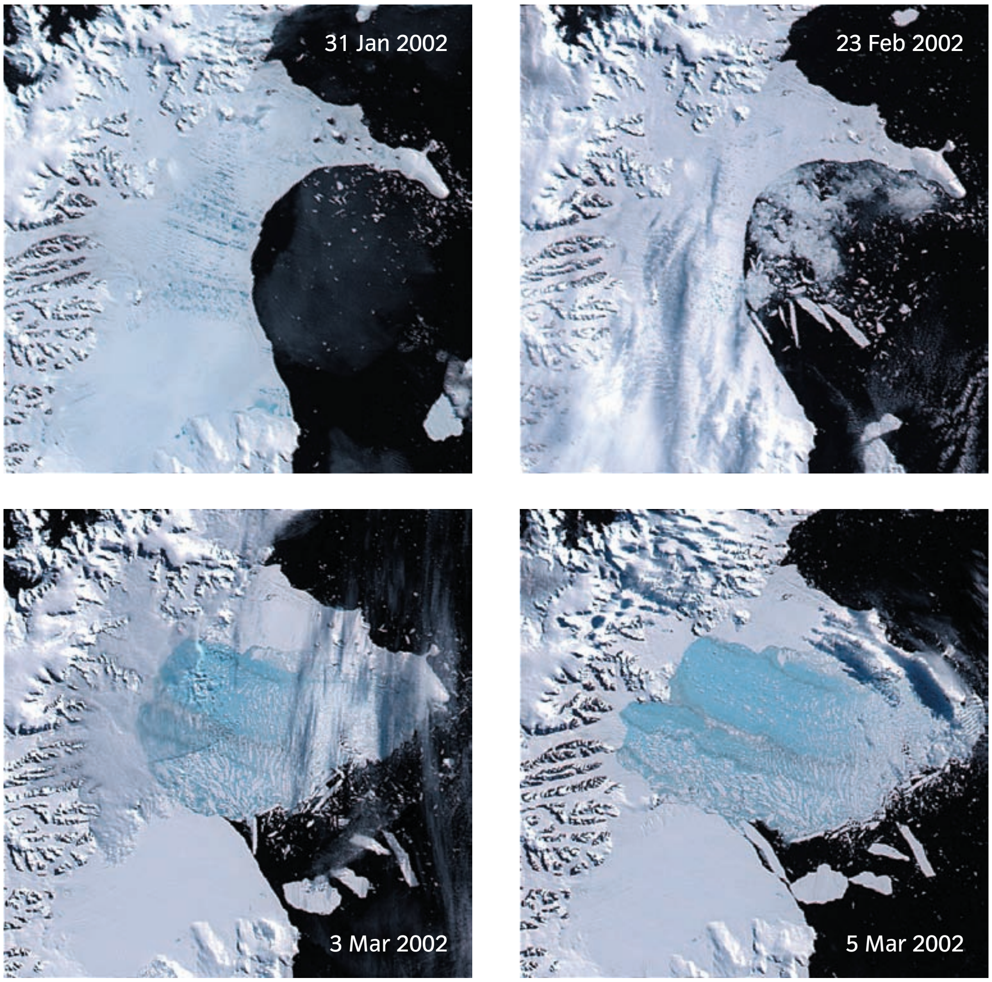
What a Geographer Sees

Ice sheets and global warming

These four satellite images document the disintegration of the Larsen B ice shelf in 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 event was the largest single event in the decline of the Larsen ice shelf, which has lost 13,500 km^2 (about 5200 mi^2) since 1974.

Geophysicists believe that the collapse was triggered as extensive meltwater ponds formed on top of the shelf. Meltwater filled fractures in the ice, creating pressure at the bottoms of these cracks, forcing them to grow.

The ponds themselves formed during the particularly warm summer in a climate that has warmed by about 2.5°C (4.5°F) since the 1940s. We don't know the exact effects that human-induced global warming will have on the Earth's ice sheets. But we hope that any changes will be slow enough for us to adapt to them.



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. How will this affect the existing continental ice sheets of Greenland and Antarctica? "What a Geographer Sees: Ice sheets and global warming" looks at how ice shelves are already responding to rising temperatures.

CONCEPT CHECK STOP

What is glaciation?

What is an ice age? In which three epochs of the Cenozoic Era did the Ice Age occur?

Give three possible causes for the Late-Cenozoic Ice Age.

Name the most established hypothesis that explains the glaciation cycles.

What is happening in this picture ?

This photo was taken by an astronaut on the Space Shuttle and shows the Finger Lakes region of New York. The long, deep, parallel basins, which now hold lakes, have been called "inland fiords." The lakes are oriented roughly in a north-south direction.

- Explain how an ice sheet could have created the basins from a set of former stream valleys. In which direction do you think the ice sheet may have been moving?

VISUAL SUMMARY

1 Glaciers

1. Glaciers form when snow accumulates to a great depth. They are plastic in their lower layers and flow outward or downhill.

2. Glaciers can erode bedrock by abrasion and plucking. They leave depositional landforms when the ice melts.

3. Alpine glaciers develop in high mountains. Ice sheets are huge plates of ice and are present today in Greenland and Antarctica.

2 Alpine Glaciers

1. Alpine glaciers flow downvalley, picking up rock debris and depositing it in moraines.

2. Through erosion, glaciers carve U-shaped glacial troughs, which can become fiords if later submerged by rising sea level.

3 Ice Sheets and Sea Ice

1. The Antarctic Ice Sheet includes ice shelves—great plates of floating glacial ice.

2. Icebergs form when glacial ice breaks into chunks. Sea ice, which is much thinner and more continuous, is formed by direct freezing of ocean water and accumulation of snow.

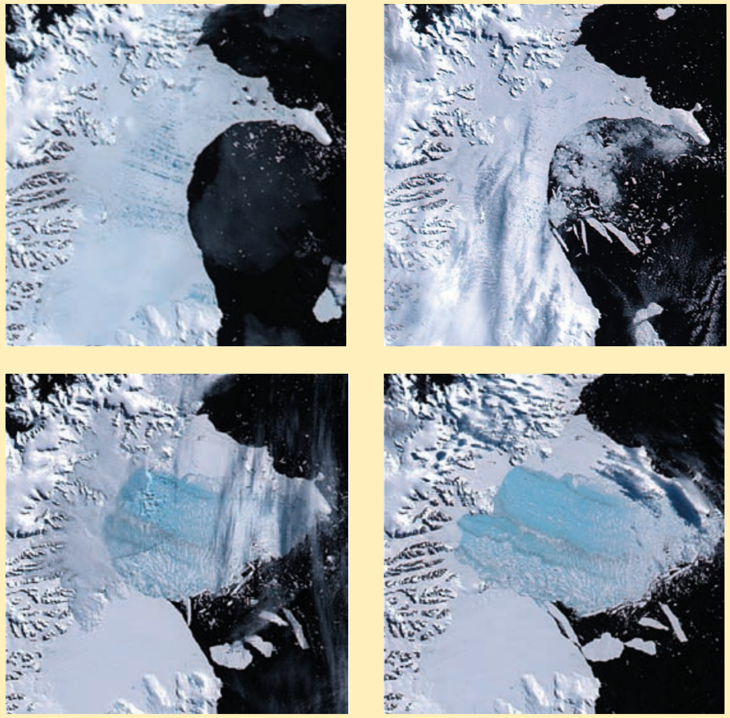
3. Moving ice sheets create many types of landforms, including moraines, outwash plains, eskers, till plains, and drumlins.

4 The Ice Age

1. 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.

2. Plate tectonics, increased volcanic activity, and a reduction in the Sun's energy output are possible causes of the Ice Age.

3. Individual cycles of glaciation seem strongly related to cyclic changes in Earth–Sun distance and axial tilt.



KEY TERMS

- **alpine glacier** p. 419
- **ice sheet** p. 419
- **glacial trough** p. 421
- **fiord** p. 424
- **sea ice** p. 426
- **iceberg** p. 426
- **glacial drift** p. 427
- **glaciation** p. 430
- **Late-Cenozoic Ice Age** p. 431
- **astronomical hypothesis** p. 436
- **Holocene Epoch** p. 437

CRITICAL AND CREATIVE THINKING QUESTIONS

1. How does a glacier form? What factors are important? Why does a glacier move?

2. What are some typical features of an alpine glacier? Sketch a cross section along the length of an alpine glacier and label it.

3. What is a glacial trough, and how is it formed? What is its basic shape? In what ways can a glacial trough appear after glaciation is over?

4. What are moraines? How are they formed? What types of moraines are there?

5. What is an ice sheet? Identify the landforms and deposits associated with stream action at or near the front of an ice sheet.

6. Identify the landforms and deposits associated with deposition underneath a moving ice sheet.

7. Identify the landforms and deposits associated with lakes that form at ice sheet margins.

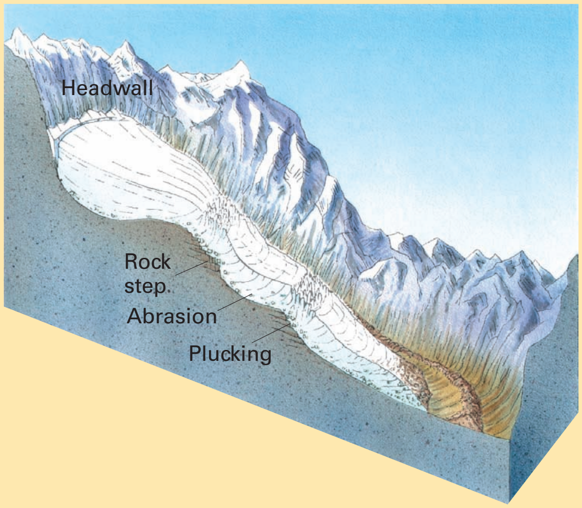
8. At some time during the latter part of the Pliocene Epoch, the Earth entered an ice age. Describe the nature of this ice age and the cycles that occur within it. What explanations are proposed for causing an ice age and its cycles? What cycles have been observed since the last ice sheets retreated?

SELF-TEST

1. What condition must be met for a glacier to begin flowing downhill?

a. Snow compacts into granular ice.
b. Snow compacts into hard crystalline ice.
c. The ice mass must become so thick that the bottom layers become plastic.
d. Evaporation and melting must occur over several years.

2. The diagram shows a cross section of an alpine glacier. Label the following regions: (a) cirque, (b) firn field, (c) lateral moraine, and (d) zone of ablation.



3. Which regions of the glacier, as shown in the diagram, move most quickly? What might cause an alpine glacier to surge?

4. _______________ produces grooved and polished bedrock surfaces that mark the former path of movement of glacial ice.

a. Glacial plucking
b. Glacial abrasion
c. Glacial deposition
d. Glacial erosion

5. Where two cirque headwalls intersect from opposite sides, a jagged, knife-like ridge called a(n) _______________ is formed.

a. arête
b. tarn
c. horn
d. col

6. A ridge or pile of rock debris left by glacial action that marks the terminus of a glacier is called a _______________.

a. medial moraine
b. recessional moraine
c. terminal moraine
d. lateral moraine

7. Of the following locations, which is not covered with an ice sheet?

a. North Pole
b. South Pole
c. Greenland
d. Antarctica

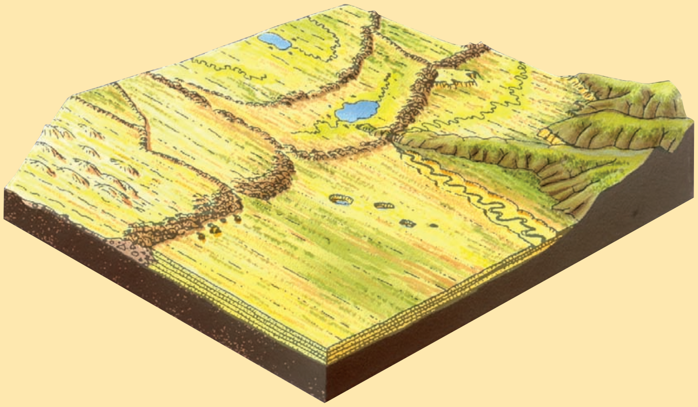
8. _______________ are bodies of land ice that have broken free from glaciers that terminate in the ocean.

a. Bergs
b. Icebergs
c. Sea ice
d. Pack ice

9. A succession of glaciations regularly interrupted by warmer interglacial periods constitutes a(n) _______________.

a. glacial period
b. freezing epoch
c. ice age
d. interstadial

10. The diagram shows some of the landforms produced by continental glaciers. Label the following features: (a) drumlins, (b) eskers, (c) kettles, and (d) the outwash plain.



11. Closed basins in nonglaciated regions that experienced cooler and moister conditions during glacial periods sometimes filled with water to form _______________ lakes.
    a. marginal
    b. glacial
    c. pluvial
    d. proglacial

12. Agriculture is sometimes difficult in formerly glaciated terrains because _______________.
    a. the climate is too cold to sustain crops
    b. glacial activity scraped away almost all of the soil
    c. the topography is too variable for farming
    d. glacial till is often stony and hard to cultivate

13. What may have caused the Earth to enter into an Ice Age in the late Cenozoic Era?
    a. volcanic activity
    b. plate tectonics
    c. decreased solar output
    d. all of the above

14. The most likely explanation for the cyclical nature of glaciations and interglaciations during the Pliocene and Pleistocene epochs involves _______________.
    a. the changing distance between the Earth and Sun
    b. the changing tilt of the Earth's axis of rotation
    c. both a and b
    d. none of the above

15. The elapsed time span of about 10,000 years since the Wisconsinan Glaciation ended is called the _______________.
    a. Holocene Epoch
    b. Miocene Epoch
    c. Paleocene Epoch
    d. Pleistocene Epoch

Global Soils

15

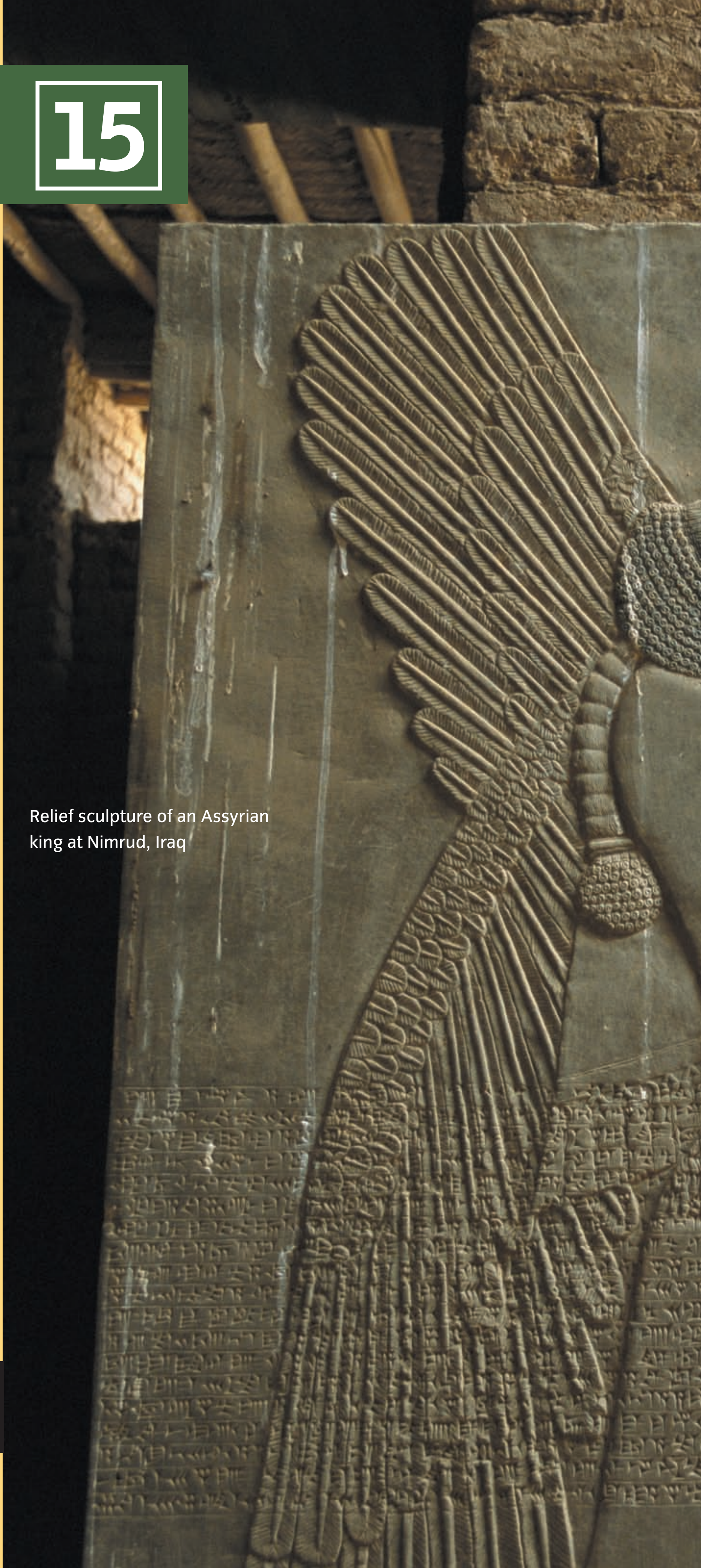
What causes a mighty civilization to collapse after flourishing for thousands of years? Conquest by an invading empire may seem the most obvious answer, but that's not always the case. The ancient Sumerian civilization, for example, was defeated by a much stealthier enemy—the soil under its feet.

The Sumerian culture developed thousands of years ago, cradled between the Tigris and Euphrates rivers that flow out across the deserts of modern-day Iraq and the Persian Gulf.

Between about five millennia B.C. and 3000 B.C., the evolving culture established itself. The Sumerians developed the first written language, built the first cities, and produced highly crafted pottery, jewelry, and ornate weapons of copper, silver, and gold. They also built a vast irrigation system to support their agricultural base, exploiting the nearby Tigris and Euphrates rivers.

But in about 2400 B.C. their croplands began to deteriorate. The problem was that each year a small amount of salt was being added to the soil from irrigation water. Over time, the salt content was high enough to affect crops, so wheat and grain yields seriously declined. As the Sumerian civilization withered in the south, political control passed to the rising northern power of Babylon. In their quest for water the Sumerians unknowingly destroyed their own land.

The great Babylonian civilization was similarly doomed. Over time, their irrigation systems became clogged with silt, ultimately leading to their downfall. Problems with irrigation systems have plagued desert populations for centuries. Today, Pakistan, Mexico, and Israel suffer similarly, highlighting the soil's vital role in nourishing us.



Relief sculpture of an Assyrian king at Nimrud, Iraq

NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

- **The Nature of the Soil** p. 446

- **Soil Development** p. 452

- **The Global Scope of Soils** p. 457

The Nature of the Soil

LEARNING OBJECTIVES

Describe the soil layer.

Define soil color, texture, acidity and alkalinity, and structure.

Define primary and secondary minerals.

Explain the important role of soil moisture.

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 (**FIGURE 15.1**). 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.

Soil Natural terrestrial surface layer containing living matter and supporting, or capable of supporting, plants.

Soil and agriculture FIGURE 15.1

North American prairies are famous for their fertile soils. This farm in Grand Coulee, near Regina, Saskatchewan, specializes in growing crop seeds.

You can find matter in all three states—solid, liquid, and gas—in soil. Because the solid, liquid, and gaseous matter are 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.

Parent material Inorganic material base from which soil is formed.

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 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. **Parent material** may come from the underlying *bedrock* below the soil layer (**FIGURE 15.2**). 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.

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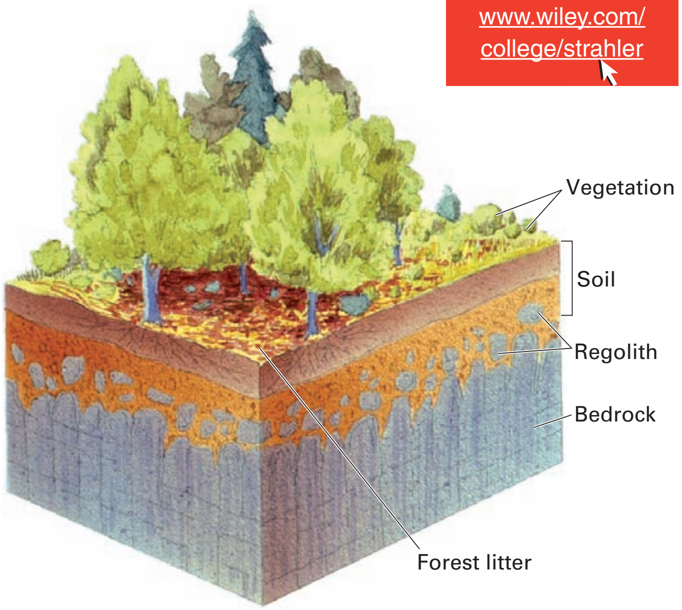


A cross section through the land surface
FIGURE 15.2

In this cross section, vegetation and forest litter lie atop the soil. Below is regolith, produced by the breakup of the underlying bedrock.

SOIL COLOR AND TEXTURE

Color is the most obvious feature of a soil. Some color relationships are quite simple. For example, Midwest prairie soils are black or dark brown in color because they contain many humus particles (FIGURE 15.3A). And the red or yellow soils of the Southeast are created by the presence of iron-containing oxides (FIGURE 15.3B).

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 (FIGURE 15.3C). In the cold, moist climate of the boreal forest, a pale, ash-gray layer near the top of the soil is created when organic matter and colored minerals are washed downward, leaving only pure, light-colored mineral matter behind.

A 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 1900's technology.

B Agricultural fields on the flank of Cedar Mountain, Culpeper County, Virginia. The ancient soils of this region are highly productive with proper treatment. The red-brown color of the soil is caused by iron oxides.

C 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.

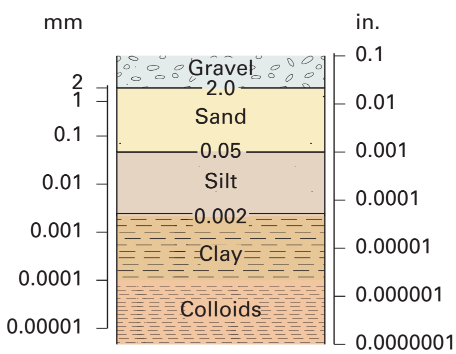
Soil color FIGURE 15.3

Soil texture
Descriptive property of the mineral portion of soil based on varying proportions of sand, silt, and clay.

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 15.4). The finest soil particles, which are included in the clay grade, are called *colloids*. When we talk about soil texture, we don't include gravel and larger particles because they don't play an important role in soil processes.

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.

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 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.



Mineral particle sizes FIGURE 15.4

Size grades are named sand, silt, and clay (which includes colloids). Gravel isn't included when discussing soil texture. Size grades are defined using the metric system, and each unit on the scale represents a power of ten. English equivalents are also shown.

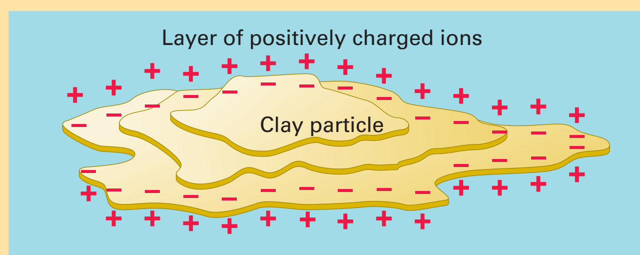
SOIL COLLOIDS

Soil colloids
Extremely small mineral or organic particles that can remain suspended in water indefinitely.

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. If you look at mineral colloids under a microscope, you will find that they have thin, plate-like bodies. 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 15.5 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.

Bases Positively charged plant nutrient ions.



A colloid particle FIGURE 15.5

Colloid surfaces tend to be negatively charged because of their molecular structure. They attract and hold positively charged ions.

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 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 15.6). 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 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 silicate 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.

Secondary minerals Minerals derived by chemical alteration of the original silicate minerals found in rock (primary minerals).

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.

Soil structure FIGURE 15.6

This soil shows a granular structure. The grains are called peds. They form when the soil dries and clay minerals shrink and crack.

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 15.7).

Sesquioxide of iron (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

Bauxite mine FIGURE 15.7

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.

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. 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.

The *wilting point* is the water storage level below which 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.

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, loss, and storage of soil water. Water held in storage is recharged during precipitation but depleted by evapotranspiration. Monitoring these values on a monthly basis provides a soil-water budget for the year.

CONCEPT CHECK **STOP**

Which characteristics do we use to describe soil?

What are primary and secondary minerals? Which are most important in determining soil fertility?

What processes affect soil moisture?

Soil Development

Learning Objectives

Explain soil horizons and soil profiles.

Describe the soil-forming processes: enrichment, removal, translocation, and transformation.

Explain the influence of soil temperature, land configuration, and animals and plants on soil development.

How do soils develop their distinctive characteristics? Let's turn to the processes that form soils and soil layers.

SOIL HORIZONS

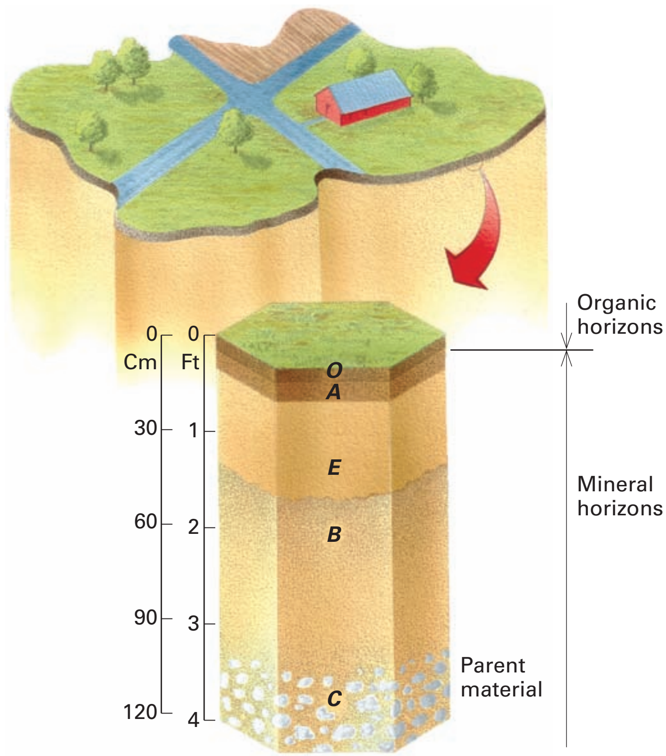
Soil horizon Distinctive layer of soil, more or less horizontal, set apart from other layers by differences in physical or chemical composition.

Most soils have distinctive horizontal layers that differ in physical composition, chemical composition, organic content, or structure (FIGURE 15.8). We call these layers **soil horizons**. They develop through interactions between climate, living organisms, and the land surface, over time. In some time periods, certain ions, colloids, and chemical compounds are removed from the soil. In others they accumulate. This removal or accumulation is normally produced by water seeping through the soil profile from the surface to deeper layers. Horizons often have different colors.

Soil profile Display of soil horizons on the face of a freshly cut vertical exposure through the soil.

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 15.9, displays the horizons on a cross section through the soil.

There are two types of soil horizon: 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.

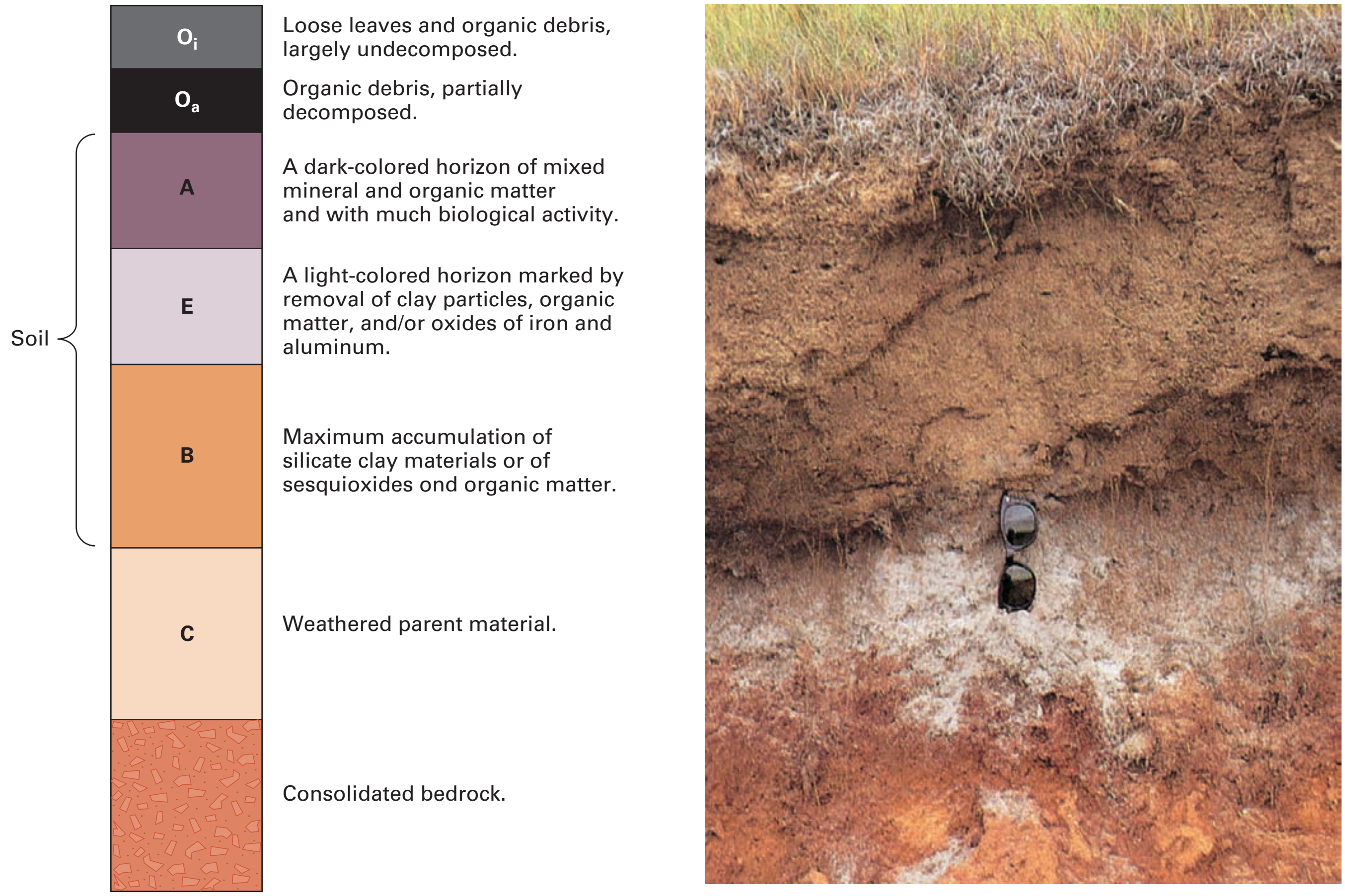


Soil horizons FIGURE 15.8

A column of soil will normally show a series of horizons, which are horizontal layers with different properties.

There are four main mineral horizons. Soil scientists limit the term *soil* to the *A*, *E*, and *B* horizons, which plant roots can readily penetrate. The *A horizon* is rich in organic matter, downwashed 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-seeping 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



A A sequence of horizons that might appear in a forest soil developed under a cool, moist climate.

B 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.

Forest soil profile FIGURE 15.9

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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-FORMING PROCESSES

There are four classes of soil-forming processes: soil enrichment, removal, translocation, and transformation. They are described in more detail in the process diagram, "Soil formation."

In *soil enrichment*, matter—organic or inorganic—is added to the soil. In *removal* processes, material is either eroded away from the soil, or leached from the soil by seeping water and taken to the ground water. *Translocation* describes the movement of materials upward or downward within the soil. **Eluviation** describes the downward movement of

Eluviation Downward transport of fine particles, carrying them out of the upper soil horizons.

Soil formation mechanisms—enrichment, removal, translocation, and transformation

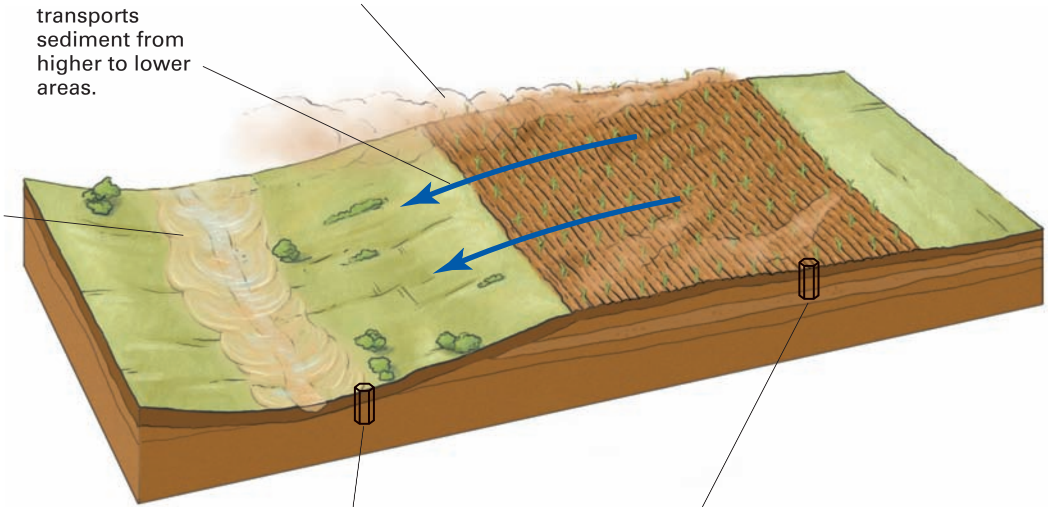
A ENRICHMENT—Adds Soil Material

Inorganic enrichment adds mineral material in three ways—

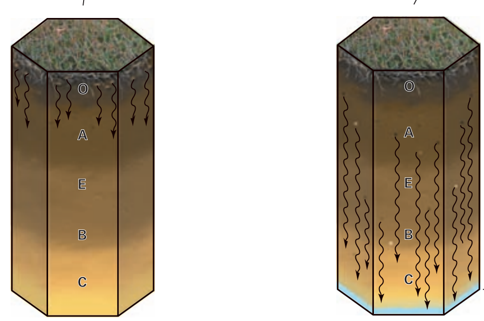
1. Wind carries fine material that accumulates on soil surface.
2. Overland flow transports sediment from higher to lower areas.
3. Stream flooding deposits fine mineral particles on floodplain soil surfaces.

B REMOVAL—Loss of Soil Material

Surface erosion Wind and water loosen and carry sediment away from the uppermost soil layer.



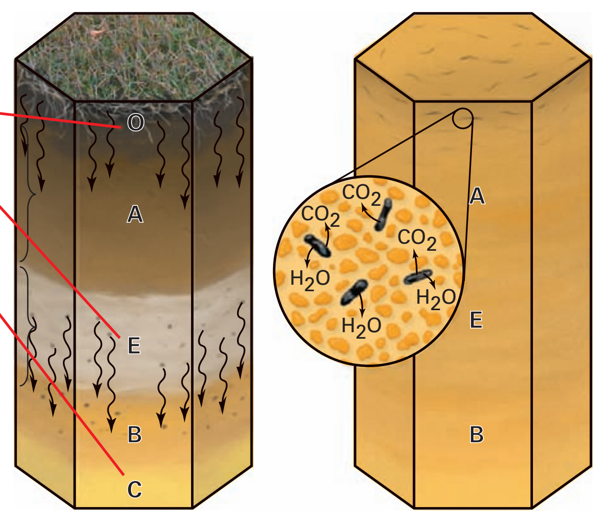
▶ **Organic enrichment adds humus** Occurs when humus from the *O* horizon (brown speckles) is carried downward to enrich the *A* horizon.



◀ **Leaching** Seeping water dissolves soil materials, moving them to deeper horizons or into ground water. Leaching is a major soil removal process. *Decalcification* is the leaching of calcium carbonate out of the soil.

C TRANSLOCATION moves soil material within horizons

Usually occurs from one soil horizon to another.
Fine particles—particularly clays and colloids—are translocated downward, a process called *eluviation*. This leaves grains of sand or coarse silt, 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*. Other translocation processes include *calcification*—the build-up of calcium carbonate that has been leached from upper layers—and *salinization*, the upward wicking of salt-laden groundwater.



D TRANSFORMATION alters soil material within horizons

An example is conversion of minerals from primary types (like feldspars) to secondaries (like clays). Another example is decomposition of organic matter to produce humus, called *humification*. In warm, moist climates, humification can decompose organic matter completely to yield carbon dioxide and water, leaving virtually no organic matter in the soil.

Illuviation Accumulation in a lower soil horizon of materials brought down from upper horizons.

material, while **illuviation** is the accumulation of that material in lower layers.

The soil profile shown in FIGURE 15.9 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 translocation of calcium carbonate is another important process. In moist climates, a large amount of surplus soil water moves downward to the ground-water 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, calcium carbonate is leached and carried down to the *B* horizon, where it is deposited in crystalline form, a process called *calcification*.

The last process of translocation occurs 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 this 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. This is exactly what happened to the ancient Sumerian civilization described in the chapter opener.

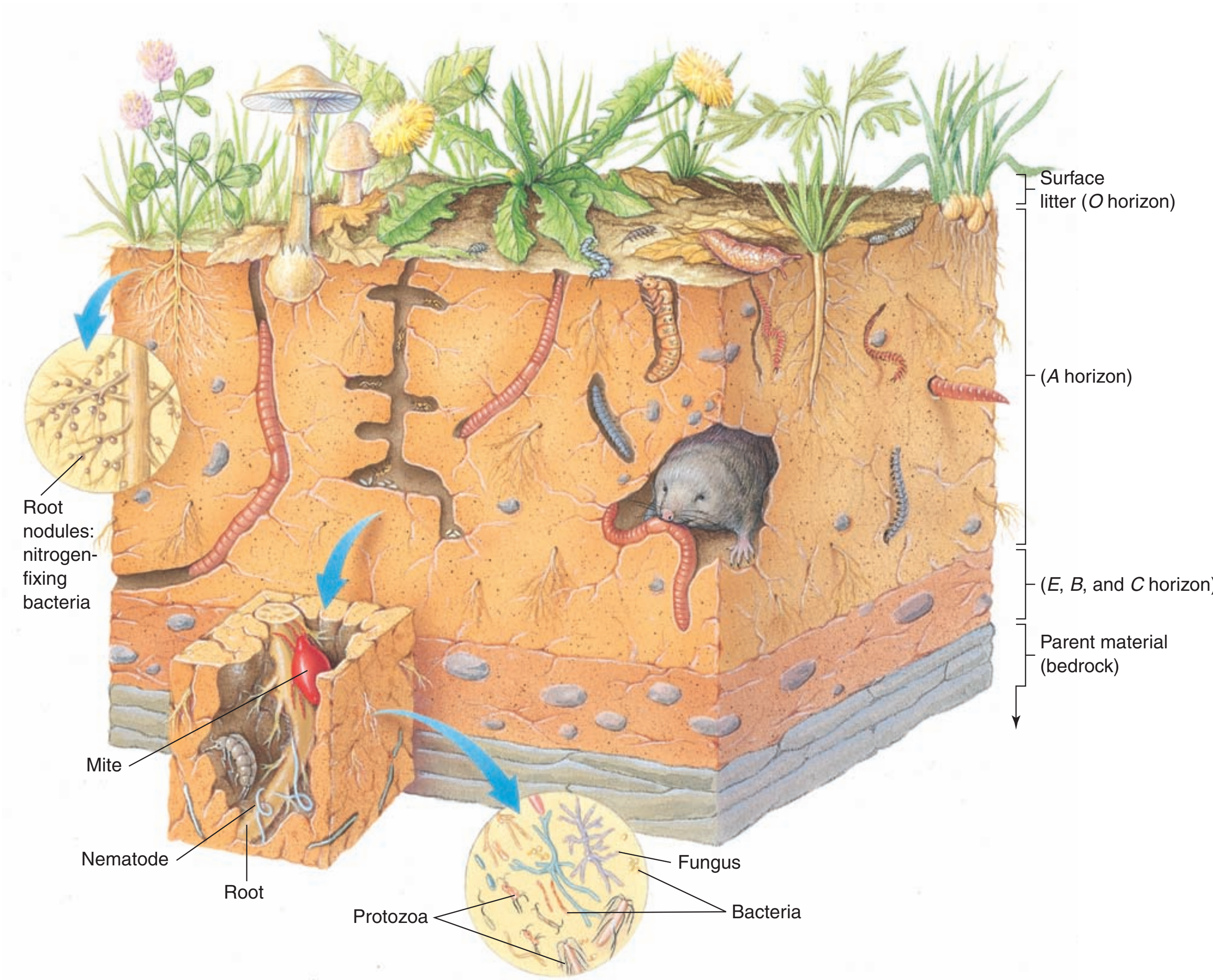
SOIL TEMPERATURE AND OTHER FACTORS

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, providing a healthy environment for plant roots.



Soil organisms FIGURE 15.10

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.)

Organisms living in the soil include many species—from bacteria to burrowing mammals (FIGURE 15.10). 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 tube-like openings larger.

Human activity also influences the physical and chemical nature of the soil. Large areas of agricultural 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.

CONCEPT CHECK **STOP**

What is a soil horizon?

Name the four processes of soil formation.

What other factors influence soil development?

The Global Scope of Soils

Learning Objectives

Describe the 11 soil orders.

Explain the effect of global climate change on agriculture.

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. Soil 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 11 **soil orders** summarized in TABLE 15.1. We'll also mention a few important suborders that make up the second classification level.

Soil orders Eleven soil classes that form the highest category in soil classification.

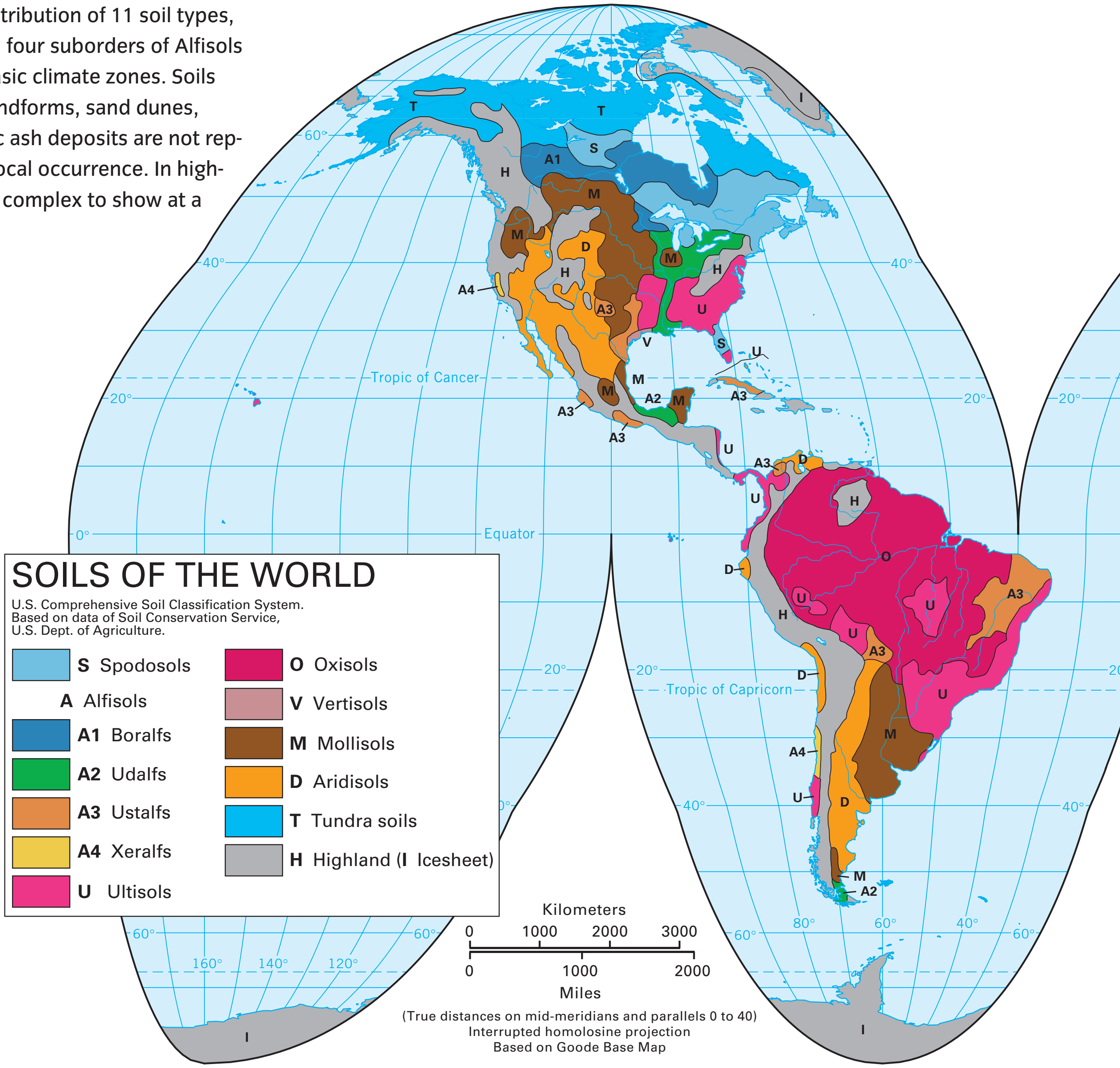
There are three groups of soil orders, as shown in TABLE 15.1. The largest group includes seven

Soil Orders TABLE 15.1

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.
Andisols	Soils with weakly developed horizons, having a high proportion of glassy volcanic parent material produced by erupting volcanoes.

Soils of the world FIGURE 15.11

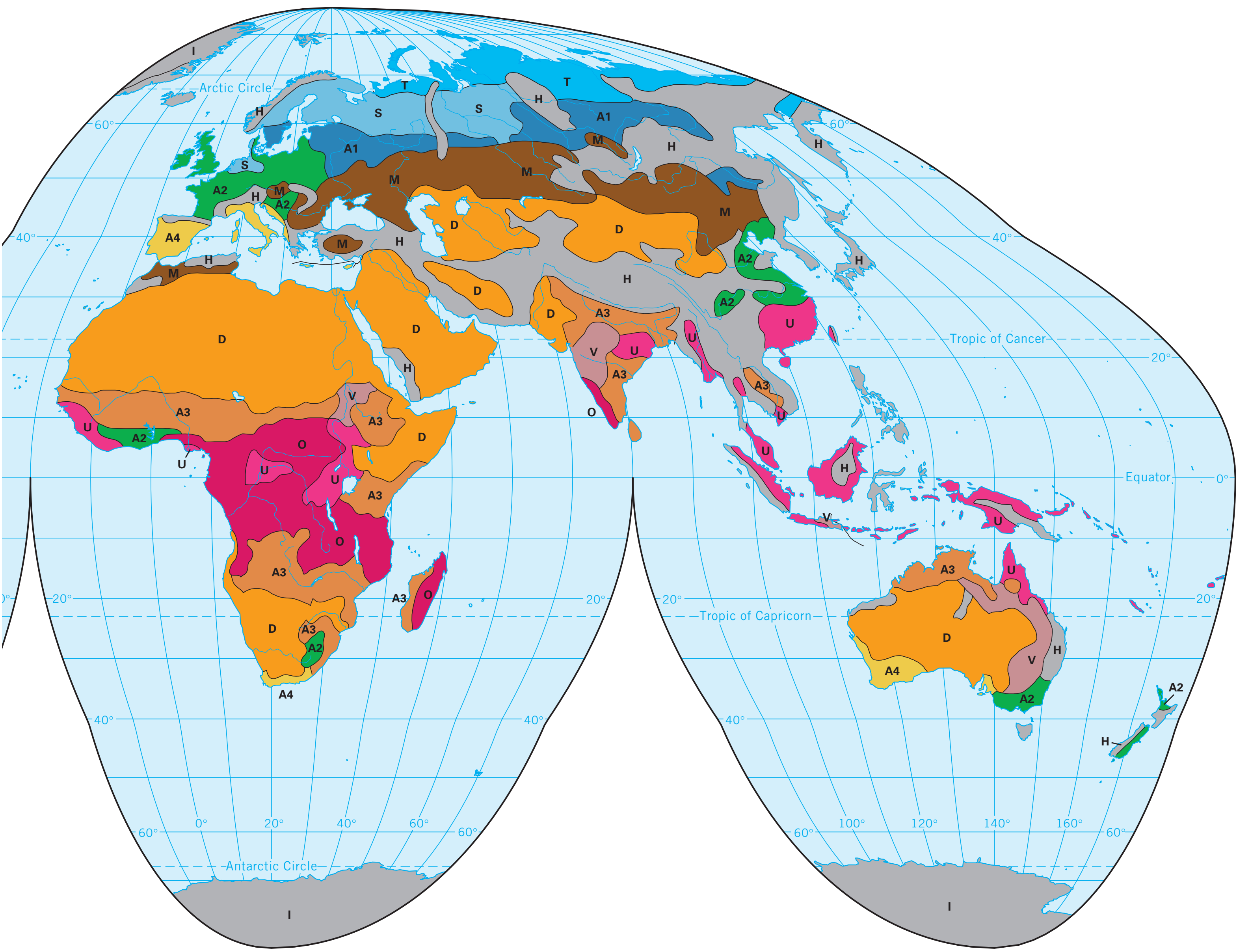
The map shows the general distribution of 11 soil types, including seven soil orders and four suborders of Alfisols that correspond well to four basic climate zones. Soils found on floodplains, glacial landforms, sand dunes, marshlands, bogs, and volcanic ash deposits are not represented because they are of local occurrence. In highlands, the soil patterns are too complex to show at a global scale.



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 three soil orders with poorly developed horizons or no horizons. FIGURE 15.11 is a map of world soil orders. Let's look at the soil orders in more detail.

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.

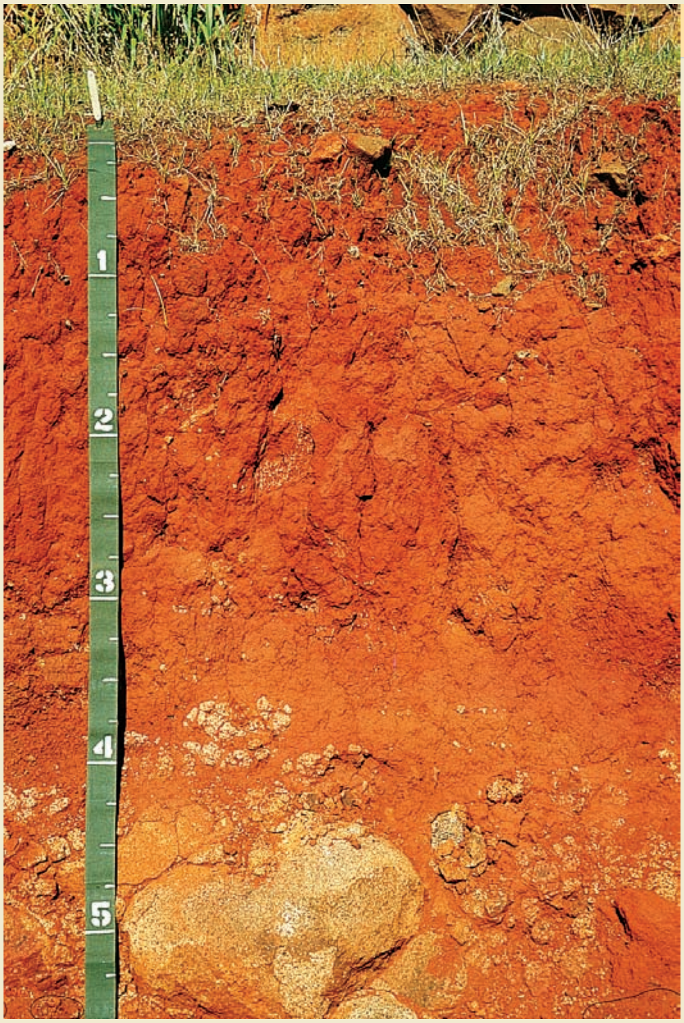


Oxisols *Oxisols* have developed in the moist climates of the equatorial, tropical, and subtropical zones on land surfaces that have been stable over long periods of time.

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 15.12 shows a soil profile for an Oxisol in Hawaii.

Oxisols FIGURE 15.12

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 a red, yellow, and yellowish-brown color. 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.



A 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.

B An Oxisol in Hawaii Sugarcane is being cultivated here.

Ultisols *Ultisols* are similar to the Oxisols, but have a subsurface clay horizon (FIGURE 15.13). They originate in closely related environments. In a few areas, the Ultisol profile contains a subsurface horizon of sesquioxides (FIGURE 15.14). 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.

Soil profile for an Ultisol FIGURE 15.13

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.

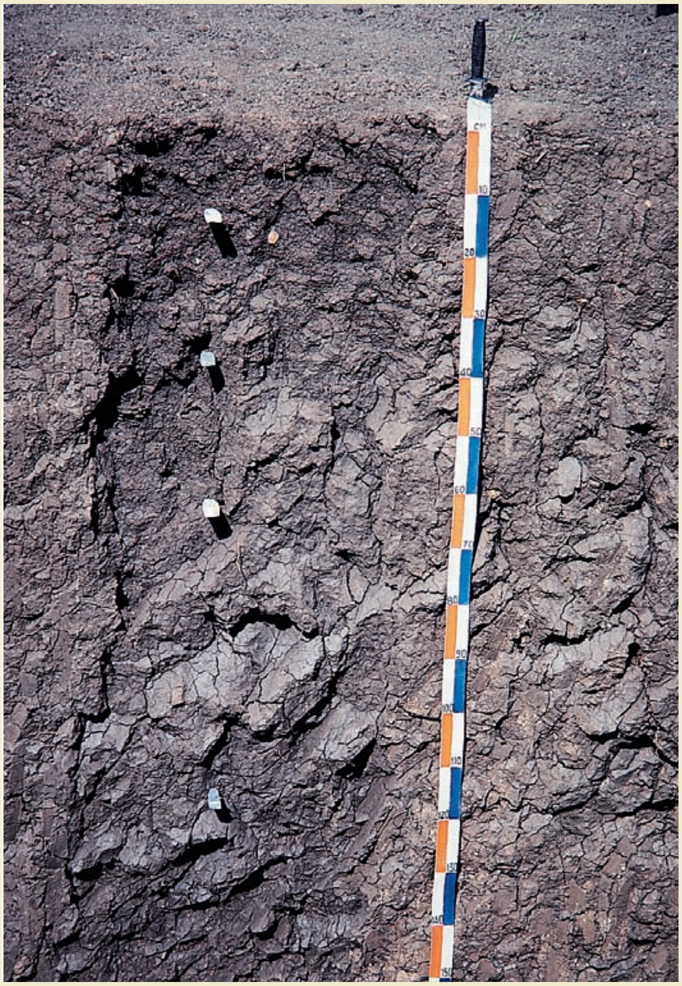
Before the advent of modern agricultural technology, both Oxisols and Ultisols of low latitudes were cultivated for centuries using a primitive "slash-and-burn" technique that is still widely practiced. Without fertilizers, these soils can sustain crops on freshly cleared areas for only two or three years, at most, before the nutrient bases are exhausted and the garden plot must be abandoned. For sustained high-crop yields, we need to use substantial amounts of lime and fertilizers. Ultisols are also vulnerable to devastating soil erosion, particularly on steep hill slopes.

Laterite FIGURE 15.14

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.

Vertisols

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 15.15). 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. Because Vertisols require a particular clay 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.



A **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.

B **Vertisol in Texas** On drying, Vertisols develop deep vertical cracks.

Vertisols FIGURE 15.15

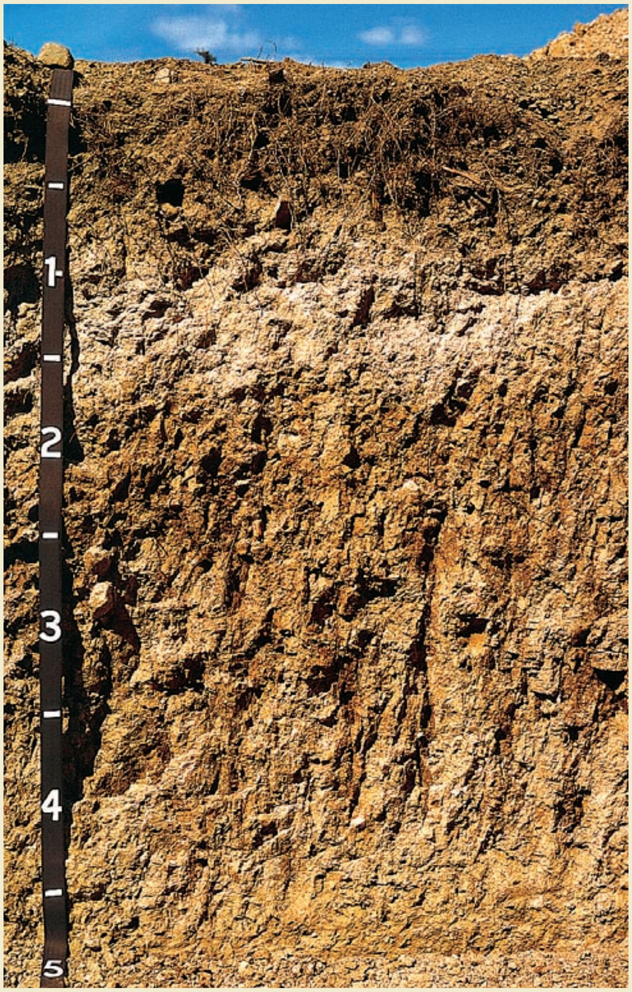
Vertisols have a high base status and are particularly rich in calcium and magnesium nutrients with a moderate content of organic matter. The soil retains large amounts of water because of its fine texture, but much of this water is held tightly by the clay particles and is not available to plants. The 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.

ALFISOLS AND SPODOSOLS

The *Alfisols* are soils characterized by a clay-rich horizon produced by illuviation (FIGURE 15.16).

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.

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

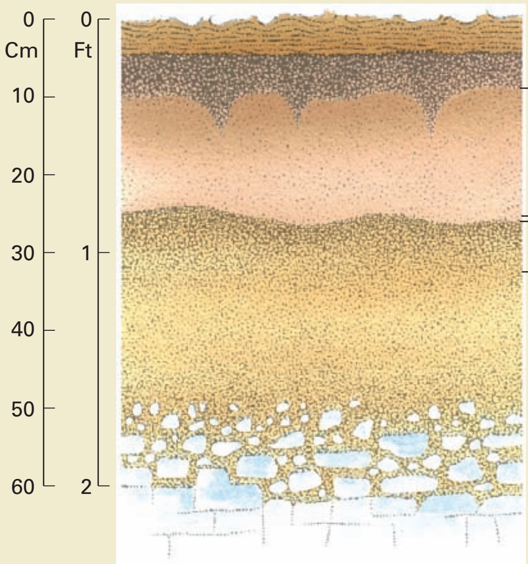


A Udalf from Michigan Udalfs are a suborder of Alfisols closely associated with the moist continental climate in North America, Europe, and eastern Asia. The *E* horizon is the lighter layer below the top darker plow layer.

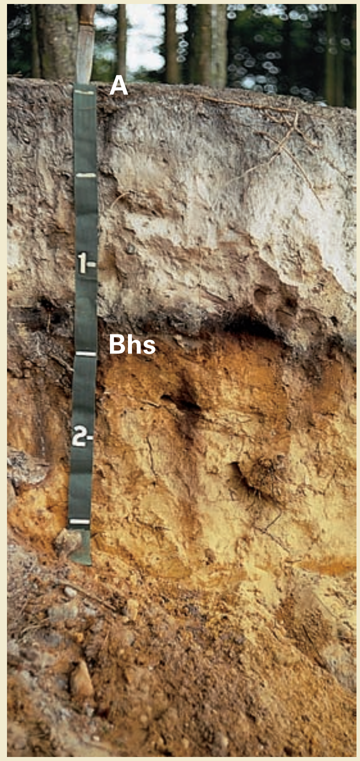
B Ustalf from Texas Ustalfs are a suborder of Alfisols that range from the subtropical zone to the equator and are often associated with the wet-dry tropical climate ③ in Southeast Asia, Africa, Australia, and South America. This Ustalf, however, is from Texas.

Alfisols FIGURE 15.16

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. Above the *B* 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.



A 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.



B 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.

Spodosol profile FIGURE 15.17

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.

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 (FIGURE 15.17).

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.

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 15.18A). Most Histosols go by 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 bogs are used extensively to cultivate cranberries. Sphagnum 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.

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 (FIGURE 15.18B). Histosols are also found in low latitudes, where poor drainage has favored thick accumulations of plant matter.

A **A Histosol from Minnesota** This soil consists almost entirely of a deep layer of weathered peat.

B **A Histosol in cultivation** Garden crops cultivated on a Histosol of a former glacial lakebed, Southern Ontario, Canada.

Histosols FIGURE 15.18

ENTISOLS, INCEPTISOLS, 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. Entisols can be found anywhere from equatorial to arctic latitude zones.

Inceptisols are soils with weakly developed horizons, usually because the soil is quite young. These areas occur within some of the regions shown on the world map as Ultisols and Oxisols.

Entisols of the subarctic and tropical deserts and arctic Inceptisols are some of the poorest soils. In contrast, Entisols and Inceptisols of floodplains and delta plains in warm and moist climates are among the most highly 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 15.19). 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.

Fertile inceptisols FIGURE 15.19

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.

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.

We haven't shown Andisols 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 mountains and islands that surrounds the great Pacific Ocean. Andisols are also found on the island of Hawaii, where volcanoes are presently active.

MOLLISOLS

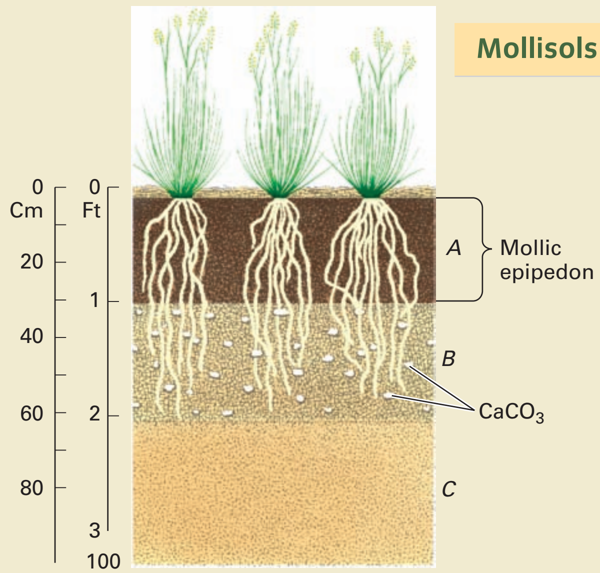
Mollisols are grassland soils that occupy vast areas of semiarid and subhumid climates in midlatitudes. They are unique in having a very thick, dark brown to black surface horizon called a *mollic epipedon* (FIGURE 15.20).

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 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. *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 (FIGURE 15.20B). *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 (FIGURE 15.20C). *Ustolls* are Mollisols of the semiarid subtype of the dry midlatitude climate ⑨, with a substantial soil-water shortage in the summer months (FIGURE 15.20D). 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 FIGURE 15.20



A 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.

B Boroll A Mollisol of cold climate regions. This example is from Russia.

C Udoll A Mollisol of moist midlatitude climates. This example is from Argentina.

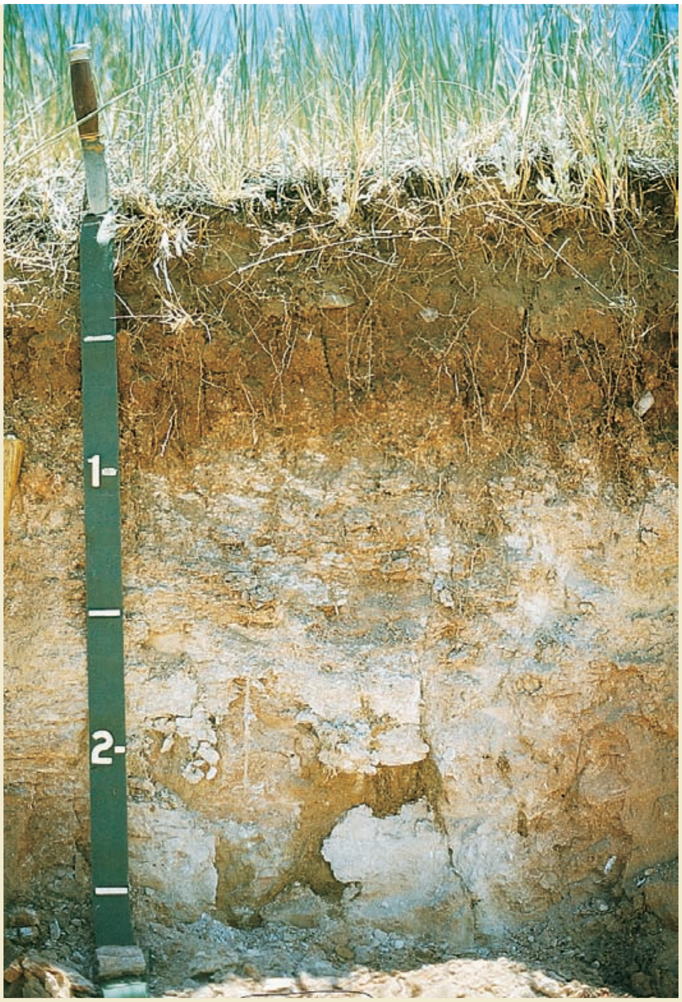
D Ustoll A Mollisol from a midlatitude semiarid climate. This example is developed on loess.

DESERT AND TUNDRA SOILS

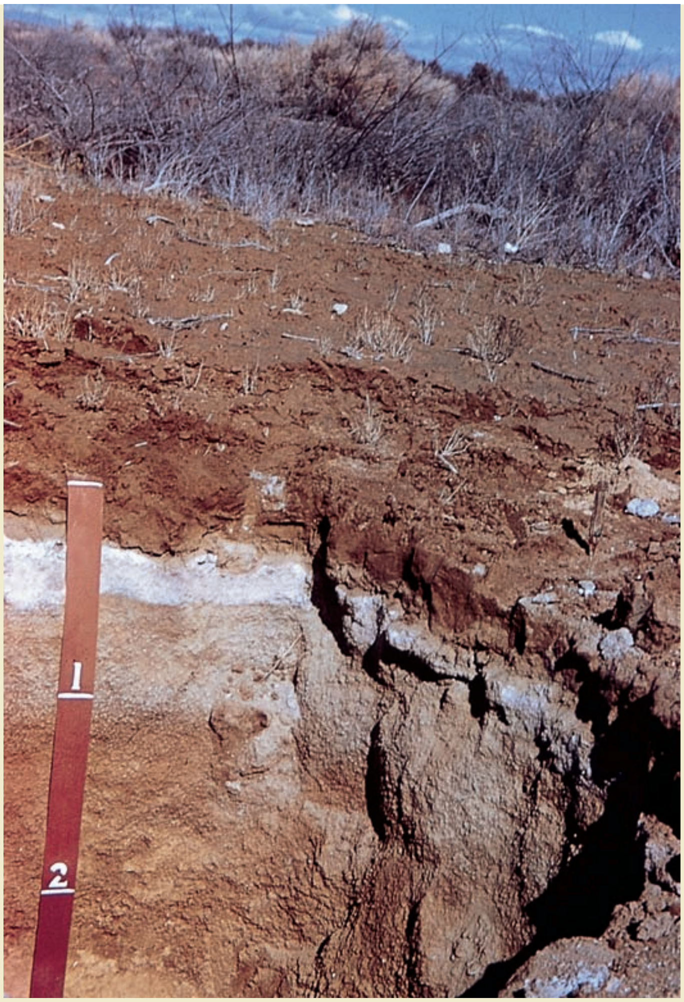
Desert and tundra soils are soils of extreme environments. *Aridisols* characterize the desert climate and are dry for long periods of time. Because the climate supports only very sparse vegetation, the soils don't contain much humus, and they are pale ranging from gray to red (FIGURE 15.21). As you might expect, they are low in organic matter and high in salts. The Aridisols are closely correlated with the arid subtype of the dry tropical ④, dry subtropical ⑤, and dry midlatitude ⑨ climates.

Most Aridisols are used for nomadic grazing, just as they have been through the ages. That's because without much rainfall, it's difficult to cultivate crops without irrigation. But in some cases Aridisols can be highly productive, as described in "What a Geographer Sees: Irrigated Aridisols."

Tundra soils are poorly developed because they are formed on very recent parent material, left behind by glacial activity during the Ice Age. The cold tundra temperatures have also restricted soil development. We usually find Inceptisols, with weakly developed horizons, in tundra regions.



A **Aridisol from Colorado** Carbonate accumulations are visible as white blotches and patches in this Aridisol, subclass Argid, from Colorado.



B **Salic horizon** The white layer close to the surface in this Aridisol profile in the Nevada desert is a salic horizon.

Aridisols FIGURE 15.21

The soil horizons of Aridisols are often weakly developed, but there may be important subsurface horizons of accumulated calcium carbonate (petrocalcic horizon) or soluble salts (salic horizon). The salts, mostly containing sodium, make the soil very alkaline.

Irrigated Aridisols

This oblique air photo shows an Aridisol soil in the broad floodplain of the Colorado River, near Parker, Arizona, being used successfully for cotton farming.

That may seem surprising, since Aridisols are associated with dry climates and can't usually support much vegetation. But locally, where there are water supplies from mountain streams or ground water, Aridisols can actually be highly productive.

Great irrigation systems in the Imperial Valley of the United States, the Nile Valley of Egypt, and the Indus Valley of Pakistan make Aridisols fertile. But these irrigation systems still suffer from salt buildup and waterlogging.

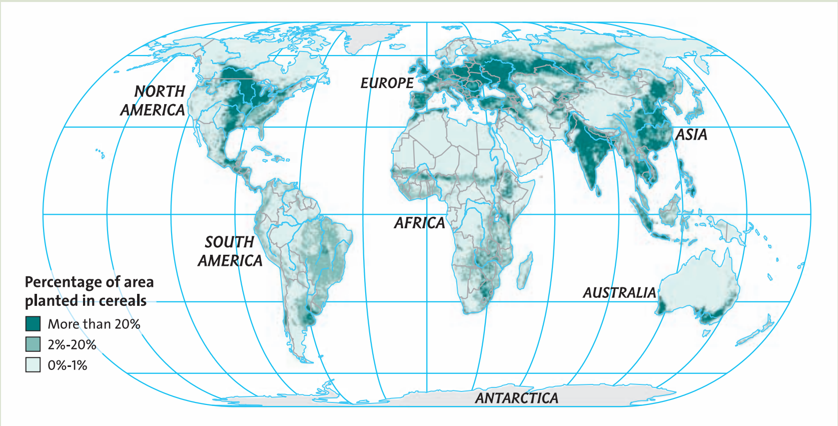
- **A** The gray and brown fields are fallow, and display typical Aridisol colors.
- **B** The cotton fields are vibrant green.
- **C** Looking closely, you can see that the grid of fields is marked out by a network of canals. This abundant supply of water coupled with plenty of sunlight makes for very good crop yields.

Tundra soils are mostly formed from primary minerals, ranging in size from silt to clay, that are broken down by frost action and glacial grinding. We often find layers of peat between mineral layers. The tundra soil lies on top of perennially frozen ground (permafrost). Because the annual summer thaw affects only a shallow surface layer, soil water can't easily drain away. So the soil is saturated with water over large areas. As the shallow surface layer repeatedly freezes and thaws, plant roots are disrupted. So, only small, shallow-rooted plants can maintain hold.

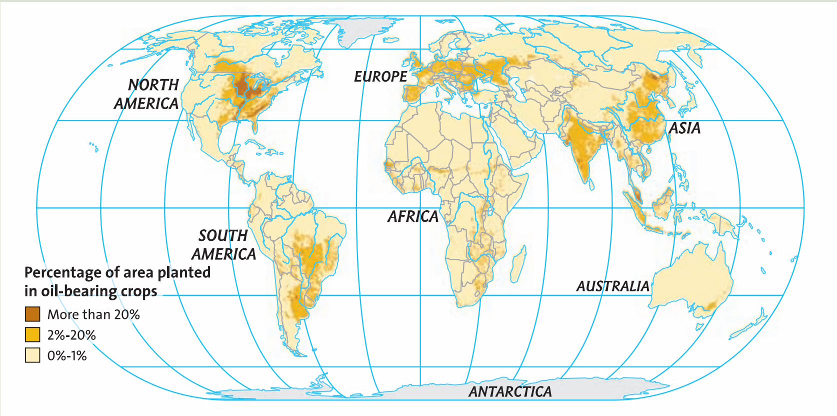
▼ **WHEAT** Wheat is among the most important of the cereal grains. Shown here is a harvest in progress in western Washington.

HARVEST OF THE LANDS AND OCEANS

Feeding the human species requires extensive use of land for domesticated plants and animals as well as the harvesting of coastal and deep ocean waters.



▲ **CEREALS** Cereal grains, including barley, maize, millet, rice, rye, sorghum, and wheat, are agricultural staples that contribute more calories and protein to the human diet than any other food group.



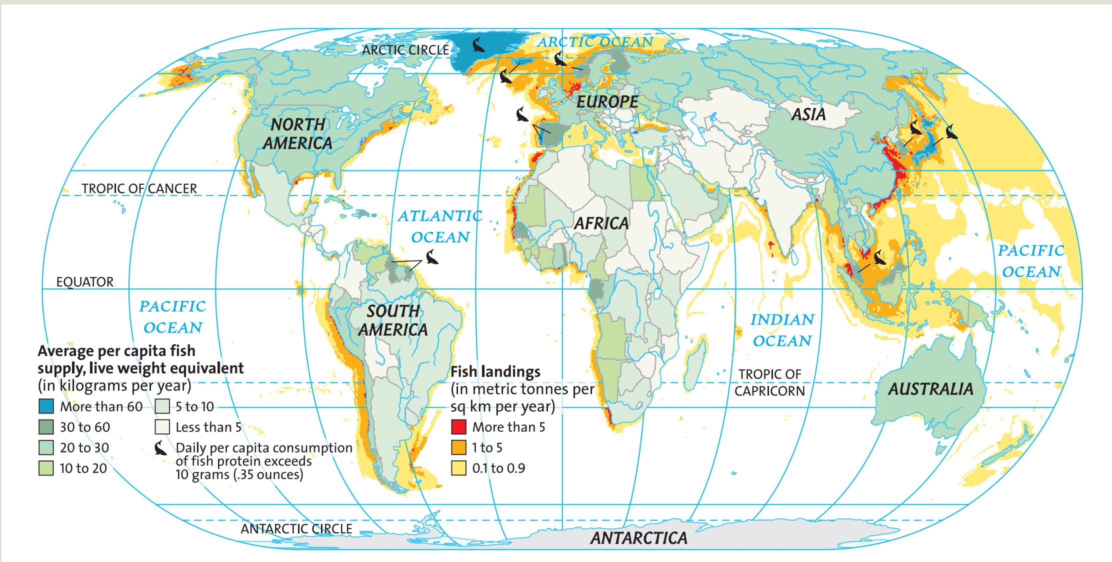
▲ **OIL-BEARING CROPS** Major oil-bearing crops—soybeans, groundnuts, rapeseed, sunflower, and oil palm fruit—account for 10 percent of the total calories available for human consumption.

▶ **SOYBEAN** Soybeans provide oil as well as plant protein. They are the leading agricultural export of the United States.

NATIONAL GEOGRAPHIC

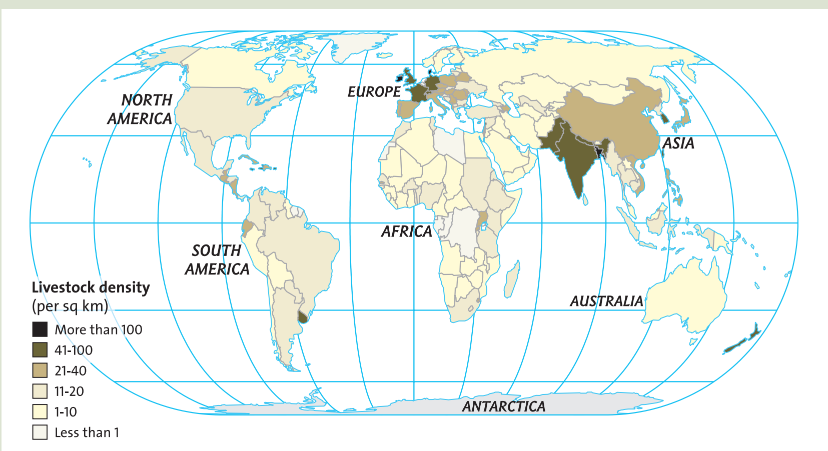
Visualizing
Global Agriculture

▶ **FISH** Fish no longer provide an inexhaustible source of protein for humans and livestock. Many ocean fisheries are at or beyond their limit of harvest. A japanese fisherman unloads a fresh catch of mackerel from a net.



◀ **FISHERIES AND AQUACULTURE** Fish is a vital source of protein for much of the world. Yet the world's primary fisheries are under stress from overfishing and environmental degradation. Aquaculture now accounts for more than 30 percent of total fish production.

▼ **ANIMAL PRODUCTS** Consumption of meat, milk, and eggs is unequal across the globe. Wealthier industrialized nations consume 30 percent more meat than developing nations.



▼ **SHEEP SHEARING** Animal products include wool and leather, in addition to meat and milk. A woman in Poland shears a sheep by hand.

GLOBAL CLIMATE CHANGE AND AGRICULTURE

Global climate change is predicted to increase global temperatures and summer droughts, change rainfall patterns, and produce more extreme events. How will this affect agriculture?

Scientists think that the immediate impact on crop yields will be positive. As temperatures begin to rise, it will shorten the length of time needed to grow crops. But then the situation will change, and the impact of even higher temperatures and more frequent droughts will be negative.

Another factor to take into account is the rising level of carbon dioxide. As CO_2 in the atmosphere increases, it will help fertilize plants—counteracting the bad effects of higher temperatures and droughts—and help to improve crop yields. On the other hand, higher CO_2 will help the weeds grow faster, too.

So what will be the overall effect of these different changes? It will vary for different regions and different crops. For example, studies cited in the Intergovernmental Panel on Climate Change Report predict that yields of corn, wheat, and rice in Egypt will decrease, while wheat yields in Australia and rice yields in Asia will increase.

But it's not enough to ask whether food production will increase or decrease in the future. Keep in mind that, so far, agricultural production has expanded to meet the expanding needs of the world's population. The important question is whether future production will be able to keep pace with this ever growing demand. Most studies predict that with a global climate change of more than 2.5°C (4.5°F), demand will exceed supply and food prices will rise.

It's obvious that global climate change will have a significant impact on agriculture. Let's hope that our species is smart enough to adapt to the changes and provide an abundance of food for all.

CONCEPT CHECK **STOP**

Name the 11 soil orders.

Which soils are found in desert and tundra climates?

How will rising temperatures and CO_2 levels affect crop yields?

What is happening in this picture ?

Galway, Ireland

This bog in Galway, Ireland, has been trenched, revealing its soil profile. The soil blocks, seen to the sides of the trench, are drying for use as fuel. What gives the soil its dark color? What is its soil order? What is the common name of this soil?

VISUAL SUMMARY

1 The Nature of the Soil

1. The soil layer is a complex mixture of solid, liquid, and gaseous components.
2. Soil texture refers to the proportions of sand, silt, and clay in the soil. Colloids, the finest soil particles, help retain nutrient ions, or bases, that are used by plants. Soils show a wide range of pH values.
3. In soils, primary minerals are chemically altered to secondary minerals, which include oxides and clay minerals. Evapotranspiration removes soil water while precipitation recharges it.

2 Soil Development

1. Most soils possess distinctive horizontal layers called horizons.
2. Horizons develop through enrichment, removal, translocation, and transformation.
3. Soil temperatures, the configuration of the land, and the presence of plants and animals all influence soil development.

3 The Global Scope of Soils

1. Global soils are classified into 11 soil orders. Oxisols, Ultisols, and Vertisols are low-latitude soils.
2. Alfisols are found in moist climates from equatorial to subarctic zones. Spodosols are found in cold, moist climates.
3. Histosols have a thick upper layer formed almost entirely of organic matter.
4. Entisols are composed of fresh parent material and have no horizons. The horizons of Inceptisols are only weakly developed. Andisols are weakly developed soils occurring on young volcanic deposits.
5. Mollisols have a thick upper layer rich in humus. They are soils of midlatitude grasslands.
6. Aridisols are soils of arid regions, marked by horizons of carbonate minerals or salts. Tundra soils are largely wet, cold Inceptisols.

KEY TERMS

- **soil** p. 446
- **parent material** p. 446
- **soil texture** p. 448
- **soil colloids** p. 448
- **bases** p. 448
- **secondary minerals** p. 449
- **soil horizon** p. 452
- **soil profile** p. 452
- **eluviation** p. 453
- **illuviation** p. 455
- **soil orders** p. 457

CRITICAL AND CREATIVE THINKING QUESTIONS

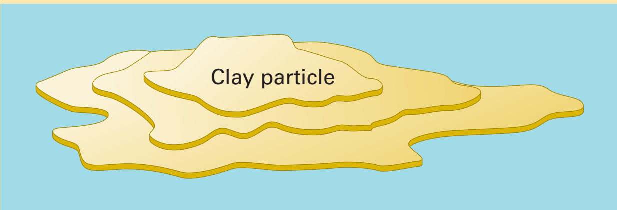
1. Which important factors condition the nature and development of the soil?
2. Soil color, soil texture, and soil structure are used to describe soils and soil horizons. Identify each of these terms, showing how they are applied.
3. Explain the concepts of acidity and alkalinity as they apply to soils.
4. What is a soil horizon? How are soil horizons named? Provide two examples.
5. Identify four classes of soil-forming processes and describe each.
6. Name three soil orders that are especially associated with low latitudes. For each order, provide at least one distinguishing characteristic and explain it.
7. Compare Alfisols and Spodosols. What features do they share? What features differentiate them? Where are they found?
8. Where are Mollisols found? How are the properties of Mollisols related to climate and vegetation cover? Name four suborders within the Mollisols.
9. Examine the world soils map (Figure 15.11) and identify three soil types that are found near your location. Develop a short list of characteristics that would help you tell them apart.
10. Clay particles and clay mineral colloids play an important role 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?

SELF-TEST

1. Soil scientists use the term ______________ to describe finely divided, partially decomposed organic matter in soils.
a. colloid
b. peat
c. organic residue
d. humus

2. The term ______________ describes all forms of mineral matter that are suitable for transformation into soil.
a. regolith
b. weathered rock
c. parent material
d. bedrock

3. Label the charge of this clay particle. Give examples of plant nutrients that will be attracted to the particle's charged surface.

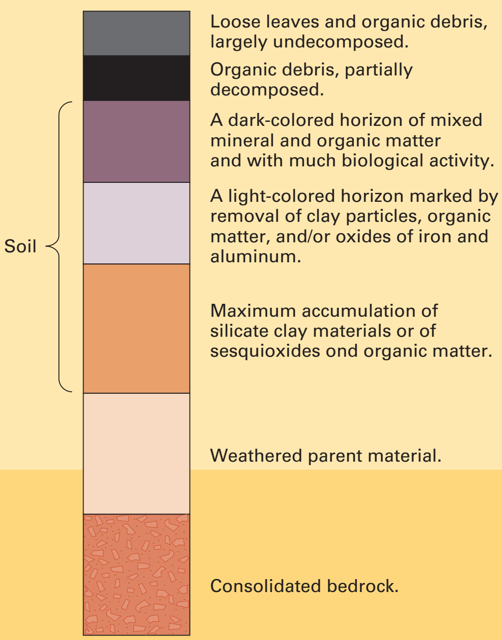


4. High soil acidity is typical of ______________ climates.
a. cold, humid
b. cold, dry
c. warm, humid
d. warm, dry

5. Soils with ______________ lack soil structure peds.
a. low clay content
b. high clay content
c. high sand content
d. low sand content

6. Surplus water stored in the soil usually ______________.
a. evaporates
b. transpires
c. undergoes evapotranspiration
d. percolates down to the ground-water zone

7. The diagram shows a sequence of horizons that could be found in forest soil. Label the following horizons: "A," "B," "C," "E," "O_a," and "O_i." What is the term given to such diagrams, which display the horizons on a cross section through the soil?



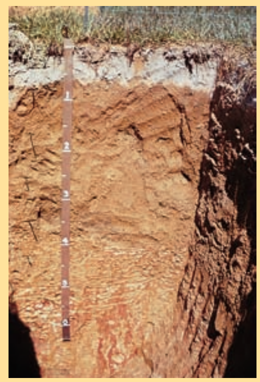
8. Two processes of ______________ that operate simultaneously are eluviation and illuviation.
a. relocation
b. soil enrichment
c. leaching
d. translocation

9. In ______________ climates organic matter accumulates in soils while in comparison, it is relatively scarce in ______________ climates.
a. cold, warm
b. dry, wet
c. warm, cold
d. wet, dry

10. __________, soils of the desert climate, are dry for long periods of time.
a. Spodosols
b. Mollisols
c. Vertisols
d. Aridisols

11. Tundra soils fall largely into the order of ______________, soils with weakly developed horizons that are usually associated with a moist climate.
a. Spodosols
b. Andisols
c. Inceptisols
d. Histosols

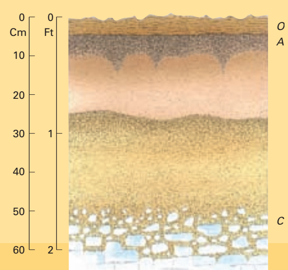
12. Which soil, shown here, is usually reddish to yellowish and is quite closely related to the Oxisols in outward appearance and environment of origin?



13. __________ typically form under grass and savanna vegetation in subtropical and tropical climates with a pronounced dry season.
a. Vertisols
b. Spodosols
c. Entisols
d. Aridisols

14. __________ are soils in which more than half of the parent mineral matter is volcanic ash. This soil has a high carbon content, so it appears very dark in color.
a. Oxisols
b. Andisols
c. Alfisols
d. Entisols

15. The soil profile shown here has a unique property—a dense layer of iron and aluminum oxides and organic matter. Identify the soil and describe where it may have formed.



Biogeographic Processes

16

The Galápagos Islands may be small in size, but their impact on the world has been huge. That's because they inspired a theory that changed our understanding of biological diversity.

Lying west of Ecuador in South America, the islands are named after the giant tortoises that inhabit them. The tortoise shells reminded the sixteenth-century Spanish explorers who discovered the islands of a kind of saddle they called a "galápago"—and the name stuck for both the animals and the region.

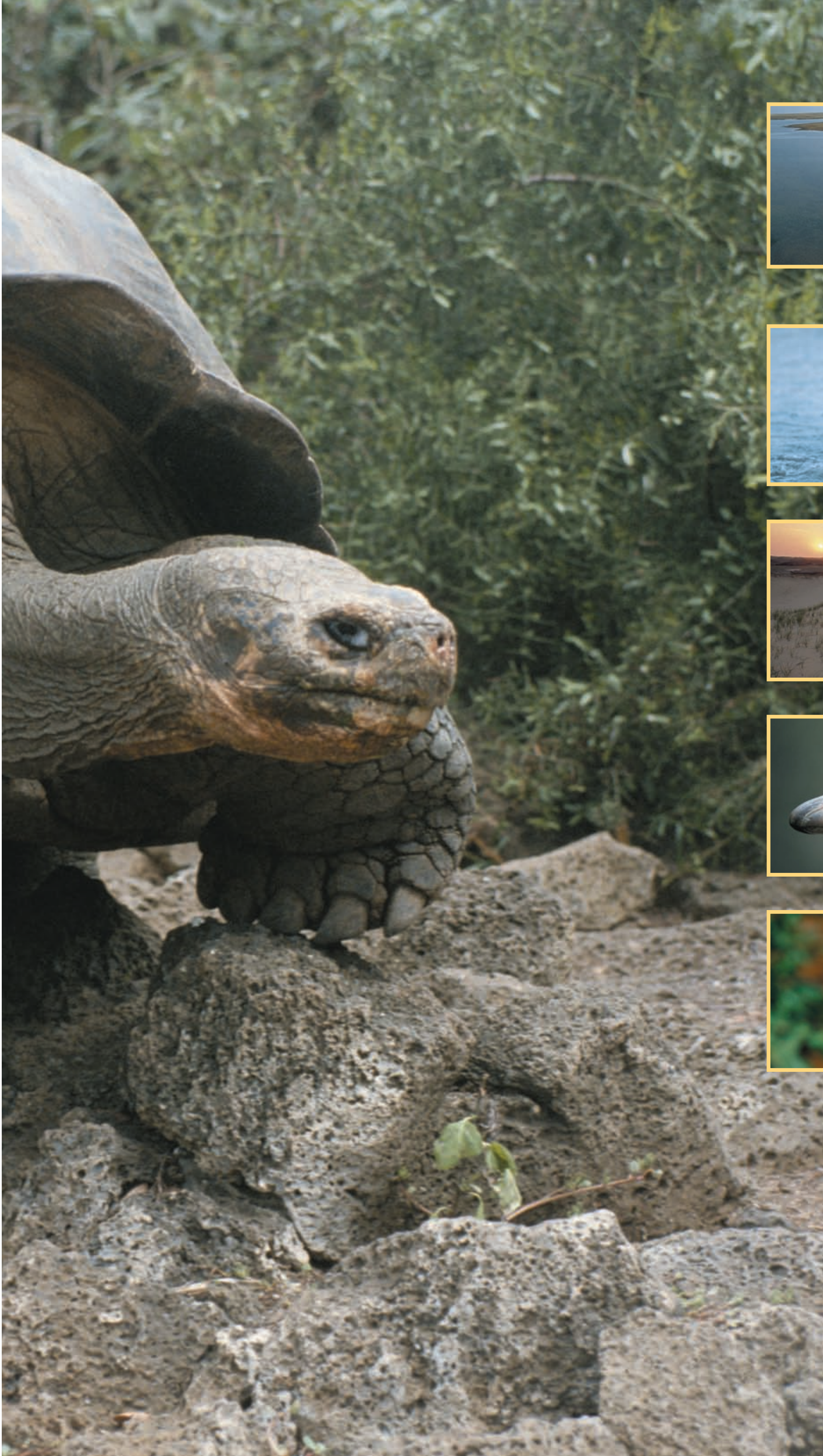
The islands' remarkable birds and animals inspired the young naturalist Charles Darwin who visited the islands in 1835. Impressed by "the amount of creative force displayed on these small, barren and rocky islands," he proposed that the life-forms could have evolved from common ancestors through natural selection.

Humans have influenced the islands. As many as 250,000 giant tortoises inhabited the islands when they were discovered. Today only about 18,000 are left. This is mainly because eighteenth- and nineteenth-century pirates used the animals—which can survive for several months without food and water—as a source of fresh meat on their whaling ships, turning them on to their backs so that they couldn't move. The tortoises' diluted urine was also used as drinking water. Goats introduced to the island by humans have also destroyed the tortoises' food supply.

The tortoises are part of the Earth's large, diverse, and constantly changing biological realm, which includes millions of species of organisms found from the ocean's abyssal depths to the land's highest peaks.

NATIONAL GEOGRAPHIC

A Galapagos tortoise ambles over rocky terrain.



CHAPTER OUTLINE

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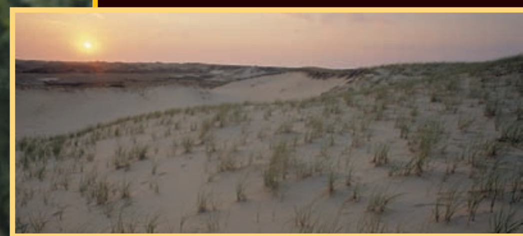
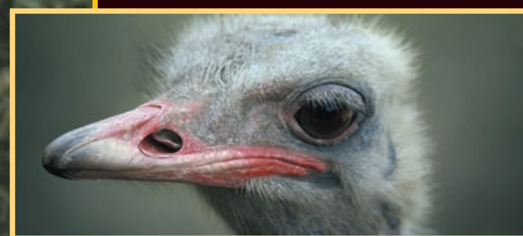
■ Ecological Biogeography p. 487



■ Ecological Succession p. 497



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Energy and Matter Flow in Ecosystems

Learning Objectives

Describe food webs.

Explain photosynthesis and respiration.

Describe the carbon and nitrogen cycles.

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 attempts to identify and describe 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.

Biogeography The study of the distribution patterns of organisms over space and time and of the processes that produced these patterns.

Ecosystem Group of organisms and the environment with which they interact.

Before we turn to those processes, we must begin by understanding 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 16.1). 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

Ecosystems FIGURE 16.1

A Tundra The caribou, a large grazing mammal, is one of the important primary consumers of the tundra ecosystem. Alaska's North Slope.

B 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.

C 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 travel single-file across the savanna plains of the Savuti region, Botswana.

of these balances are robust and self-regulating, but some are quite sensitive and can be easily upset or destroyed.

THE FOOD WEB

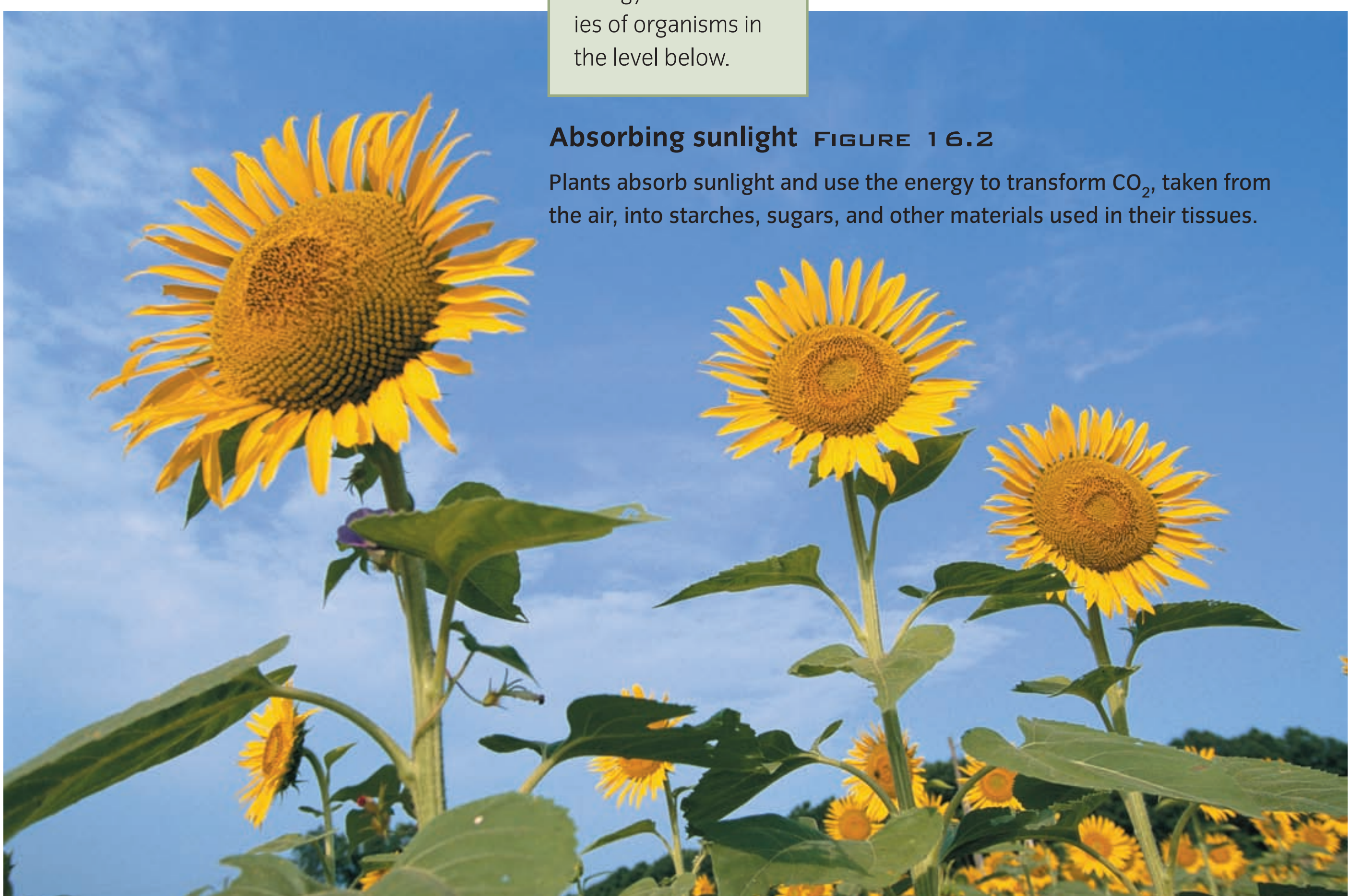
Energy is transferred through an ecosystem in steps, making up a *food chain* or a **food web**. At the bottom of the chain are the *primary producers*, which absorb sunlight and use the light energy to convert carbon dioxide and water into carbohydrates (long chains of sugar molecules) and eventually into other biochemical molecules, by *photosynthesis* (FIGURE 16.2). 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 process diagram: "The food web" looks at the producers, consumers, and decomposers of a salt marsh ecosystem.

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.

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 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.

Food web (food chain) Organization of an ecosystem into levels through which energy flows as the organisms at each level consume energy from the bodies of organisms in the level below.



Absorbing sunlight FIGURE 16.2

Plants absorb sunlight and use the energy to transform CO_2, taken from the air, into starches, sugars, and other materials used in their tissues.

Process Diagram

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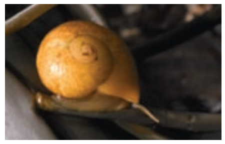
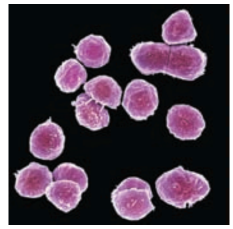
Higher level consumers Still higher levels of feeding occur in the salt-marsh ecosystem as marsh hawks and owls consume the smaller animals below them in the food web. In most ecosystems there are about four levels of consumers.

Secondary consumers At the next level are the secondary consumers (the mammals, birds, and larger fishes), which feed on the primary consumers.



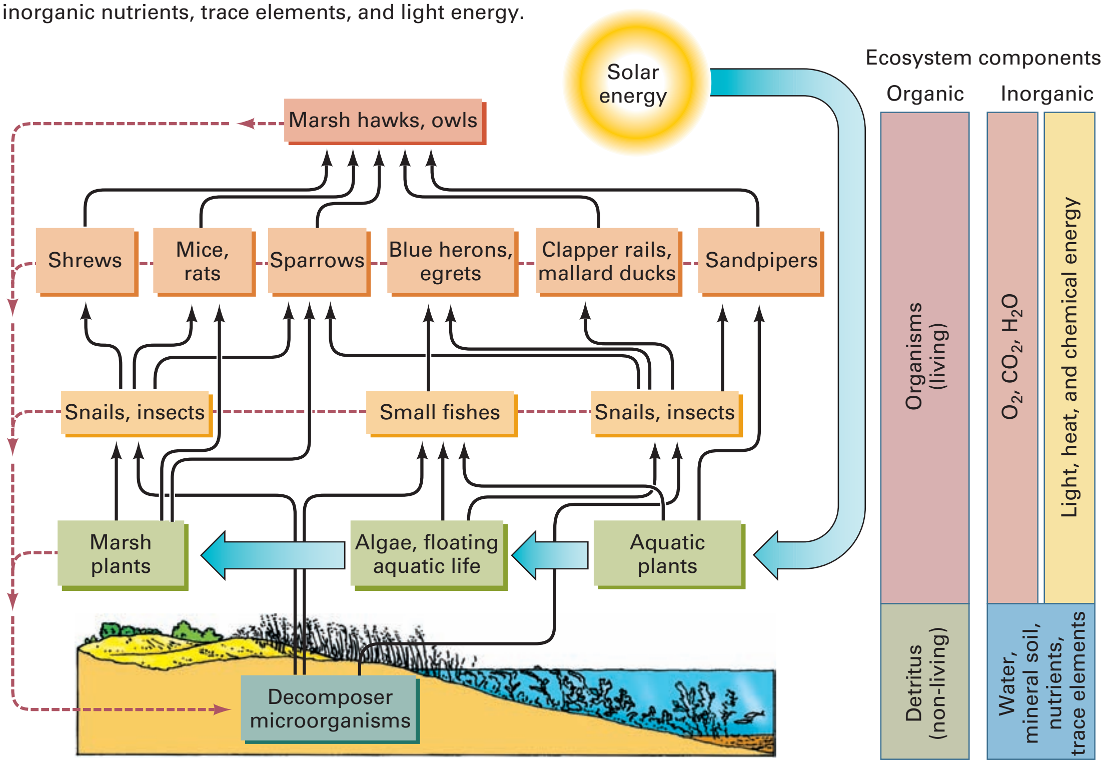
Primary consumers The lowest level of consumers are the primary consumers (the snails, insects and fishes).

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.



Decomposers Microscopic organisms and bacteria feed on detritus, or decaying organic matter, from all levels of the web.

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.



The food web

PHOTOSYNTHESIS AND RESPIRATION

Photosynthesis
Production of carbohydrate from water and carbon dioxide, using light energy.

Simply put, **photosynthesis** is the production of carbohydrate (FIGURE 16.3). 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 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:

$$H_2O + CO_2 + \text{light energy} \longrightarrow \text{—CHOH—} + O_2$$

Oxygen gas molecules (O_2) are a byproduct 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:

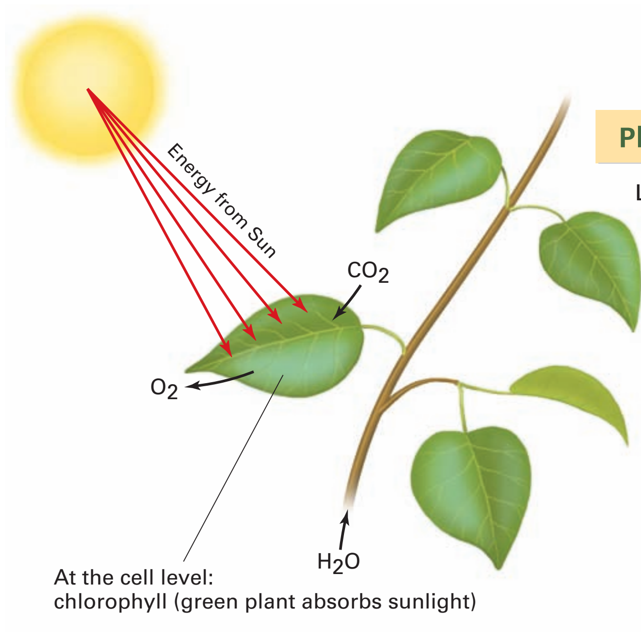
$$\text{—CHOH—} + O_2 \longrightarrow CO_2 + H_2O + \text{chemical energy}$$

As with photosynthesis, the actual reactions involved aren't 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 that synthesized carbohydrate remaining after respiration has broken down sufficient carbohydrate to power the plant:

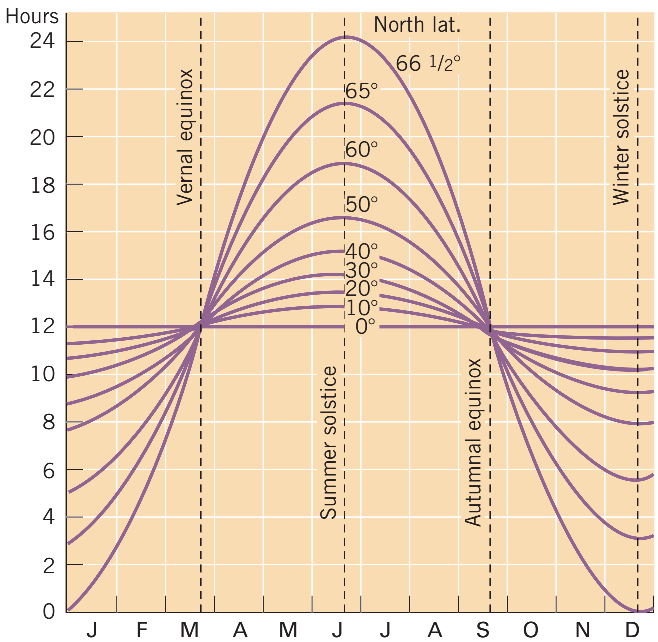
$$\text{Net photosynthesis} = \text{Gross photosynthesis} - \text{Respiration}$$

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



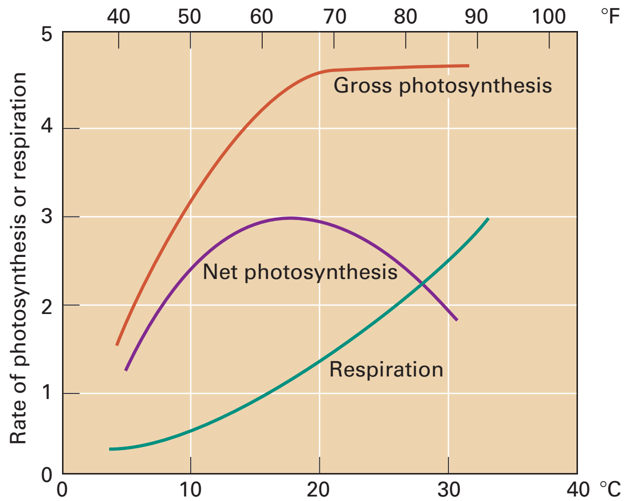
Photosynthesis FIGURE 16.3

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.



Day-length variation FIGURE 16.4

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.



Temperature and energy flow FIGURE 16.5

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.

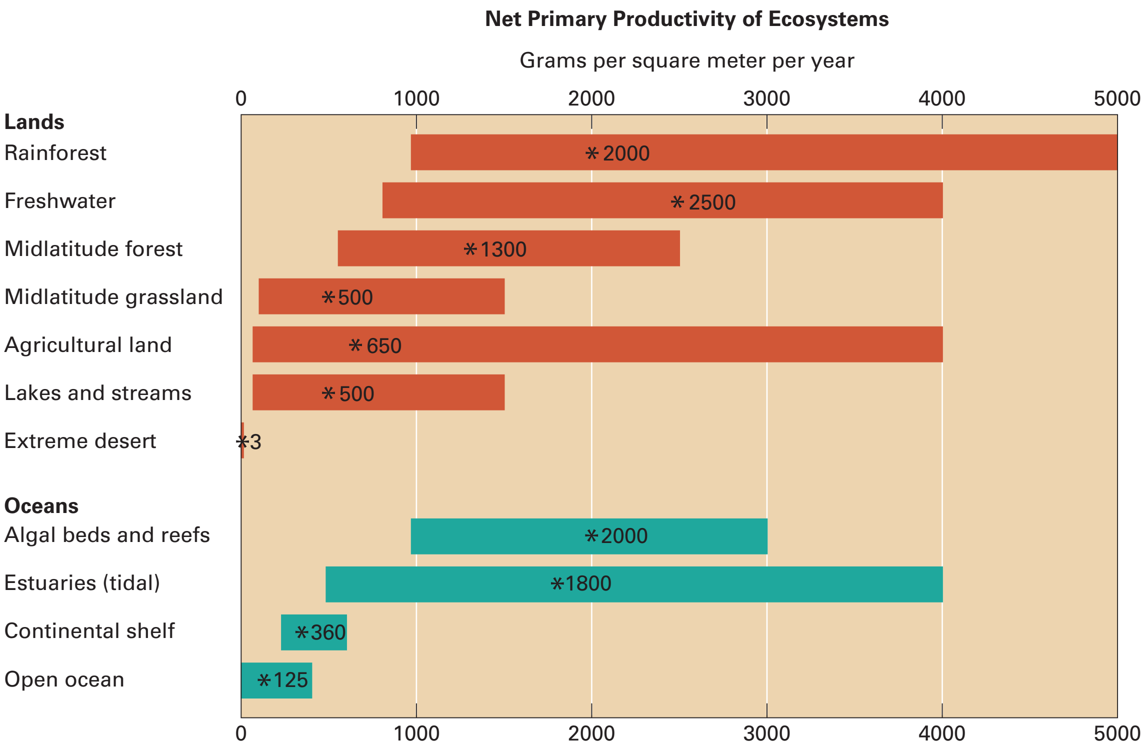
summer sunlight for maximum net photosynthesis. Once the intensity of light is high enough for maximum net photosynthesis, the duration of daylight becomes an important factor in determining the rate at which the products of photosynthesis build up in plant tissues (FIGURE 16.4). The rate of photosynthesis also increases as air temperature increases, up to a limit (FIGURE 16.5).

NET PRIMARY PRODUCTION

Plant ecologists measure the accumulated net production by photosynthesis in terms of the **biomass**, which is 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.

Biomass Dry weight of living organic matter in an ecosystem within a designated surface area.

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 pro-



Net primary production of ecosystems

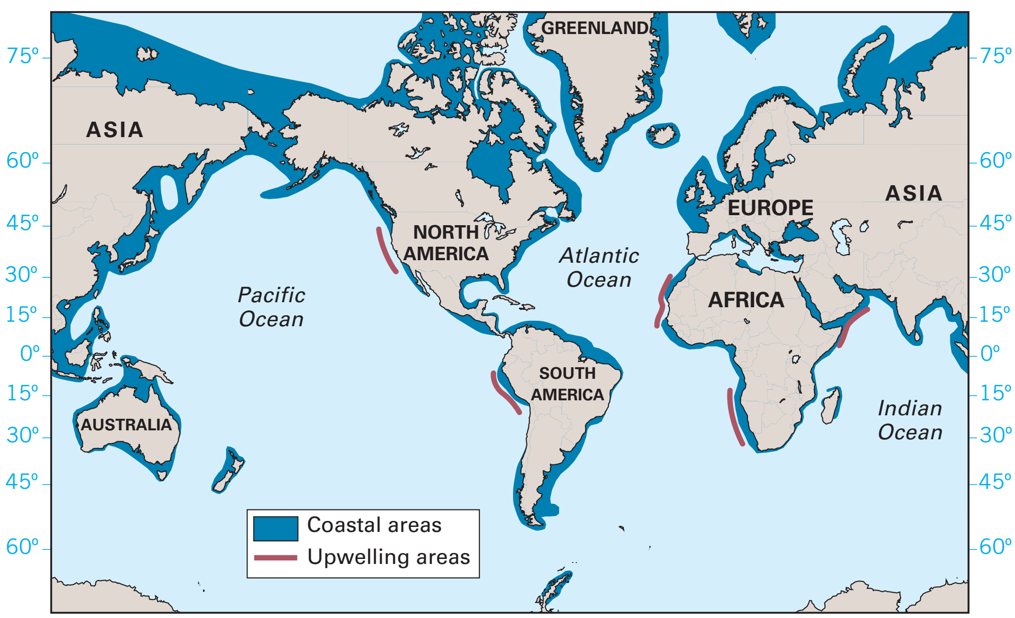
FIGURE 16.6

Freshwater swamps and marshes are most productive on land, and algal beds and reefs are most productive in the ocean.

duction 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, for example by burning wood for fires.

FIGURE 16.6 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 16.7). Upwelling zones are also highly productive.



Distribution of world fisheries

FIGURE 16.7

Coastal areas and upwelling areas together supply over 99 percent of world production.

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 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 reformed 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*).

Carbon cycle
Biogeochemical cycle in which carbon moves through the biosphere.

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 16.8 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.

Plants remove carbon dioxide for photosynthesis. Carbon dioxide also leaves the atmospheric pool to enter the oceans, where it is used in photosynthesis by phytoplankton, which build skeletal structures of calcium carbonate. These skeletons settle to the ocean floor to accumulate as layers of sediment. This is an enormous carbon storage pool, but it's not available to organisms until it's later released by rock weathering. Organic compounds synthesized by phytoplankton also settle to the ocean floor and eventually are transformed into the hydrocarbon compounds making up petroleum and natural gas. Humans exploit the fossil fuels petroleum, natural gas, and coal for energy.

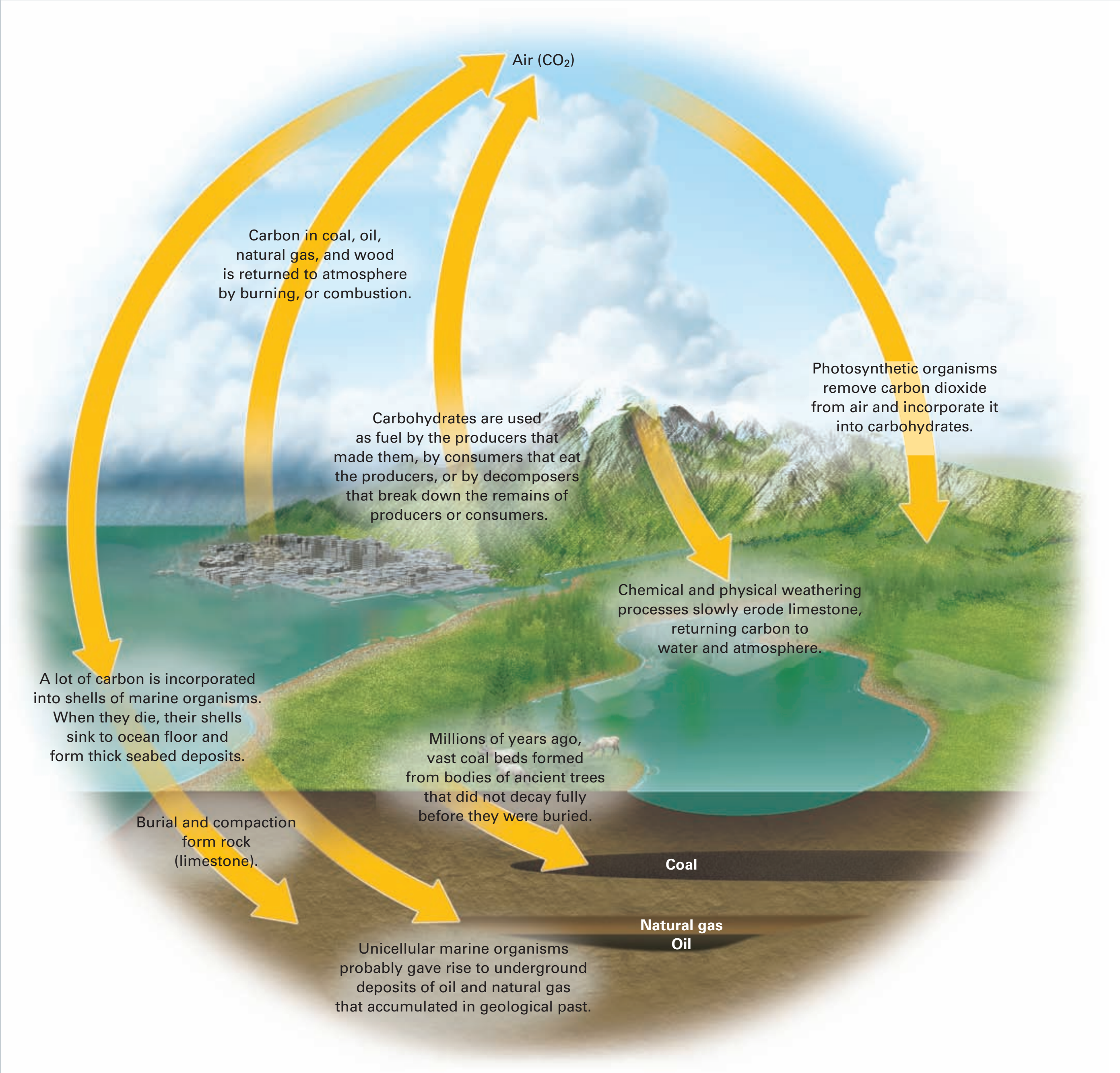
We are currently significantly affecting the carbon cycle by burning fossil fuels. CO_2 is being released to the atmosphere at a rate far beyond that of any natural process. Another important human impact lies in changing the Earth's land covers—for example, in clearing forests or abandoning agricultural areas. What happens to the extra carbon that fossil fuel burning liberates? About half is taken up by the atmosphere. A small amount is absorbed by the oceans. But the rest must be flowing into the biosphere.

Ecosystems cycle carbon in photosynthesis, respiration, decomposition, and combustion. By applying the logic of budgeting, we know that the amount of terrestrial biomass must be increasing to account for the added carbon. 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 about 25 percent from 1970 to 1990. A century ago, only a small portion of New England was forested. Now only a small portion is cleared.

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 16.9 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 fix nitrogen. 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.



The carbon cycle FIGURE 16.8

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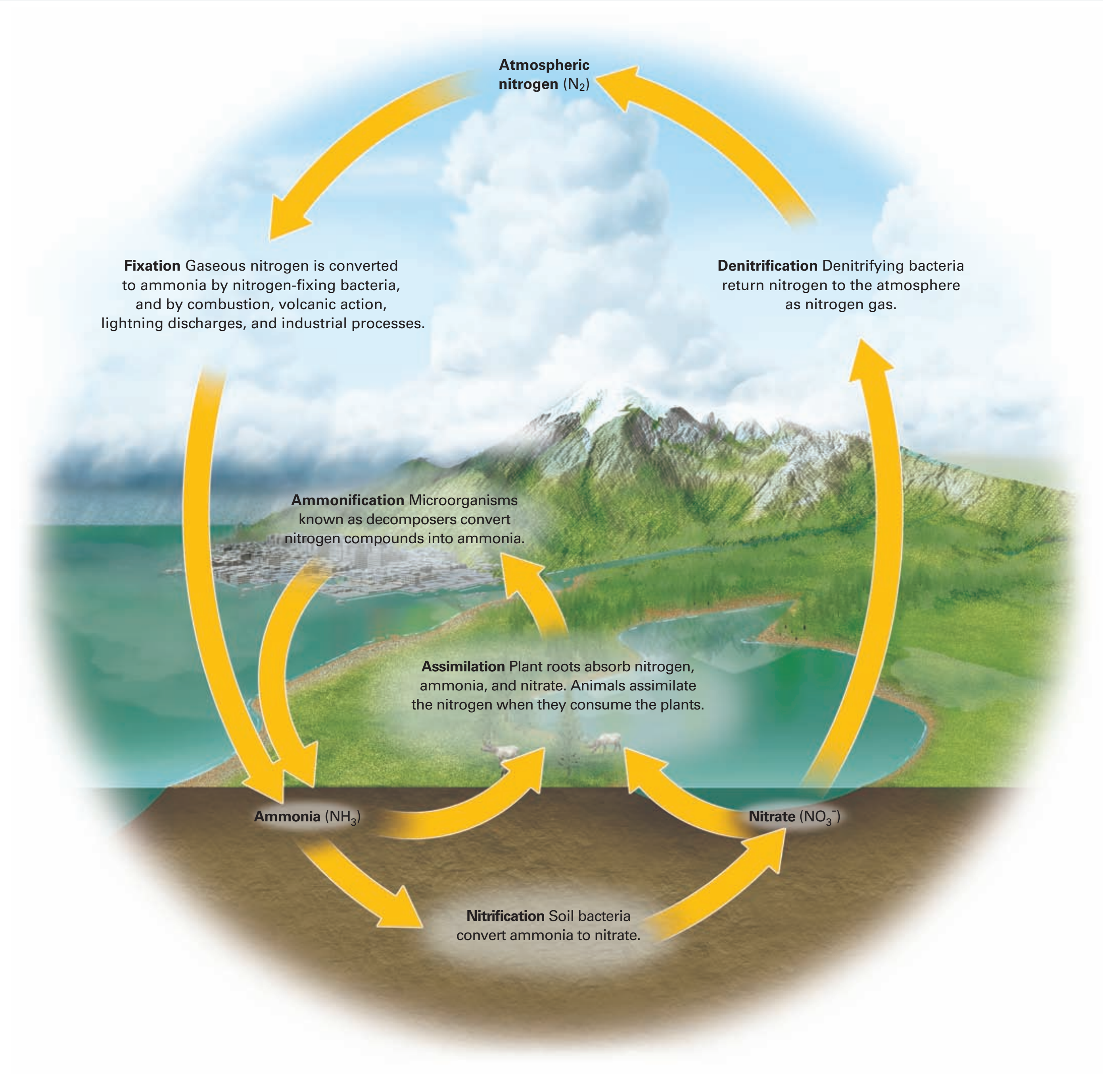
Carbon moves through the cycle as a gas, as a liquid, and as a solid. In the gaseous portion of the cycle, carbon moves largely as carbon dioxide (CO_2), which is a free gas in the atmosphere and a dissolved gas in fresh and saltwater. In the sedimentary portion of its cycle, we find carbon in carbohydrate molecules in organic matter, as hydrocarbon compounds in rock (petroleum, coal), and as mineral carbonate compounds such as calcium carbonate ($CaCO_3$).



The nitrogen cycle FIGURE 16.9

The five steps of the nitrogen cycle are nitrogen fixation, nitrification, assimilation, ammonification, and denitrification.

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Other soil bacteria convert nitrogen from usable forms back to N_2, in a process called *denitrification*, completing the organic portion of the nitrogen cycle.

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. Much of this nitrogen is carried from the soil into rivers and lakes and ultimately reaches the ocean, polluting water. 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.

CONCEPT CHECK STOP

What is a food web? What levels make up the food web?

Define photosynthesis. What is the name of the process that converts the end products of photosynthesis back to the starting products?

Name two important biogeochemical cycles. What are the biggest storage pools in each of these cycles?

Ecological Biogeography

LEARNING OBJECTIVES

Define habitat.

Explain the physical factors that influence plant and animal distribution.

Describe interactions between species.

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 well as a set of characteristic adaptations that it exploits to obtain the energy it needs to live.

Habitat Subdivision of the environment according to the needs and preferences of organisms or groups of organisms.

Let's start by looking at the relationship between organisms and their physical environment. FIGURE 16.10 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.

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 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. Let's now turn to each of the environmental factors that help determine where organisms, as individuals and species, are found.

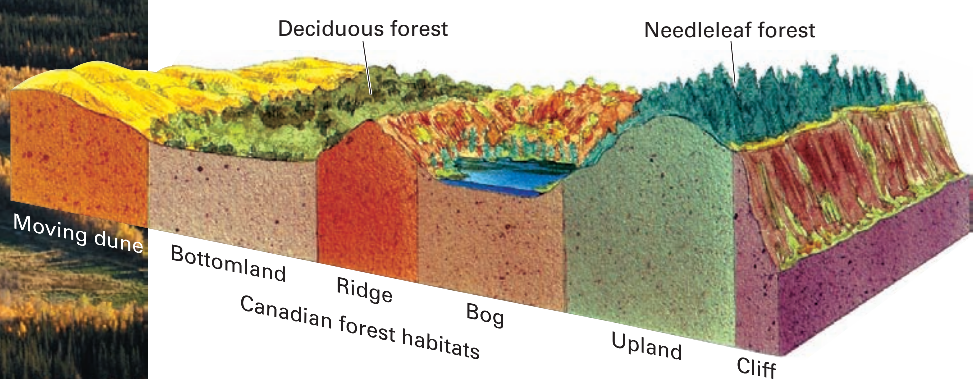
WATER NEED

Plants and animals have adapted to cope with the abundance or scarcity of water in a variety of ways. Plants that are adapted to drought conditions are called *xerophytes.* ("Xerophyte" comes from the Greek roots xero-, meaning "dry," and phyton, meaning "plant.")

Some xerophytes have a thick layer of wax or waxlike material on leaves and stems, helping them to seal water vapor 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 (FIGURE 16.11A).

Habitats of the Canadian boreal forest

FIGURE 16.10



B Habitats of the Canadian boreal forest are quite varied and include moving dune, bottomland, ridge, bog, upland, and cliff.

A This aerial view of the Mackenzie River shows some of the boreal forest habitats shown in part B. 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.

A This clump of prickly pear cactus (*Opuntia*) is in the San Pedro Valley, Arizona.

B This Californian live oak holds most of its tough, waxy leaves through the dry season. Such hard-leaved evergreen trees and woody shrubs are called sclerophylls.

C This 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.

Organisms adapted to water scarcity

FIGURE 16.11

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.

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 and the moist continental climate ⑩, have a yearly cycle with one season in which water is unavailable to plants because of lack of precipitation or because the soil water is frozen. This season alternates with one in which there is abundant water. Plants adapted to such regimes are called *tropophytes*, from the Greek word *trophos*, meaning "change" or "turn." Tropohytes drop their leaves at the close of the moist season, becoming dormant during the dry or cold season. When water is again available, they leaf out and grow at a rapid rate. Trees and shrubs that shed their leaves seasonally are termed *deciduous*, while *evergreen* plants retain most of their leaves in a green state through one or more years.

The Mediterranean climate ⑦ also has a strong seasonal wet-dry alternation, with dry summers and wet winters. Plants in this climate are often xerophytic and characteristically have hard, thick, leathery leaves (FIGURE 16.11B). Plants that hold their leaves through a dry or cold season have the advantage of being able to resume photosynthesis rapidly when growing conditions become favorable, whereas the deciduous plants must grow a new set of leaves.

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.

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, spending their days in cool burrows in the soil and their nights foraging for food (FIGURE 16.11C).

TEMPERATURE

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 also limiting lower and upper temperatures for these individual functions 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. A large number of tropical plant species cannot survive below-freezing temperatures for more than a few hours. We only find a few plants and animals in the severely cold arctic and alpine environments of high latitudes and high altitudes. At the other end of the spectrum, this explains why an equatorial rainforest contains such a diverse array of plants and animals. In plants, ice crystals can grow inside cells in freezing weather, disrupting cell 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 16.12A). 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 16.12B). 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 16.12C).

OTHER CLIMATIC FACTORS

Light also helps determine local plant distribution patterns. Some plants are adapted to bright sunlight, whereas others require shade (FIGURE 16.13). The amount of light available to a plant will depend in large part on the plant's position. Tree crowns in the upper

A 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.

B A heavy coat and a thick layer of body fat insulate this Alaskan brown bear, allowing the mammal to maintain a constant body temperature.

C 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.

Temperature adaptations FIGURE 16.12

layer of a forest receive maximum light but correspondingly reduce the amount available to lower layers. In extreme 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 leaf canopy is completed. Other low plants in the same habitat require shade and do not appear until the leaf canopy is well developed.

Sun-loving and shade-loving plants FIGURE 16.13

A California poppies and desert dandelions thrive in bright sun.

B Cow parsnip prefers the deep shade in the Mount Hood National Forest, Oregon.

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. This means that, although frost in these regions shortens the growing season for plants, the rate of plant growth in the short frost-free summer is greatly accelerated by the prolonged daylight.

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 will trigger such activities as mating and reproduction.

Wind is also an important environmental factor in the structure of vegetation in highly exposed positions, as described in "What a Geographer Sees: The flag-shaped tree."

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) can all affect ecosystems. In a much broader sense, geomorphic factors include the entire sculpting of the landscape by erosion, transportation, and deposition, by streams, waves, wind, and ice.

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 can penetrate the soil and be held there. 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.

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.

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

The flag-shaped tree

Where winds are strong and blow from a constant direction, you can find trees that have been deformed in quite curious ways. This photograph shows a tree above a broad plain in Tierra del Fuego, Argentina, with branches skewed to the left.

A geographer would recognize that the tree has adapted to wind conditions. Wind causes excessive drying, damaging the exposed side of the plant and killing its leaves and shoots. Trees of high-mountain summits can be even more distorted, with trunks and branches bent to near-horizontal, facing away from the prevailing wind direction.

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 16.14). 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

Forest fire FIGURE 16.14

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.

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 (FIGURE 16.15).

Tree throw FIGURE 16.15

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.

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 16.16). Both populations suffer from lowered growth rates than they would have had if only one species was 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.

Competition FIGURE 16.16

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.

Predation and *parasitism* are other negative interactions between species. Predation occurs when one species feeds on another (FIGURE 16.17). 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.

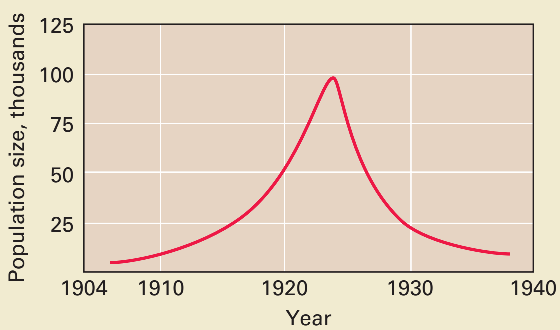
Although we tend to think that predation and parasitism are always negative—benefiting one species at the expense of the other—in some cases it works out well for the prey or host populations too, in the long run. A classic example is the rise and fall of the deer herd on the Kaibab Plateau north of the Grand Canyon in Arizona (FIGURE 16.18). Predation and parasitism will also remove the weaker individuals, improving the attacked species' genetic composition.

Predation FIGURE 16.17

This giant anteater enjoys a lunch of Brazilian termites.

Rise and fall of the Kaibab deer herd FIGURE 16.18

A 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.



B This graph plots the population size of the deer herd in the Kaibab National Forest, Arizona. The herd grew from about 4,000 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.

A third type of predation 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*, a fourth type of negative interaction, occurs when one plant species produces chemical toxins that inhibits others.

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 (FIGURE 16.19). 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 to survive.

Symbiosis
Positive interaction between species that is beneficial to at least one of the species and does not harm the other.

Commensalism FIGURE 16.19

This Australian orchid depends on a eucalyptus tree for support.

CONCEPT CHECK STOP

Define habitat.

Which physical environmental factors influence plant and animal distribution?

Name the different types of negative interaction between species.

What is symbiosis? Name three types of symbiotic relationship.

Ecological Succession

LEARNING OBJECTIVES

Describe ecological succession.

Define primary succession and secondary succession.

Explain old-field succession.

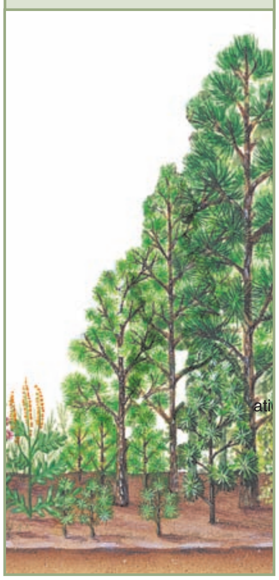
Explain how autogenic succession can be interrupted.

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 humans, 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.

Ecological 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, clear cutting, or other agents.



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 animals 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 16.20). 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.

Dune succession FIGURE 16.20

A 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.

B 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.

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 16.21).

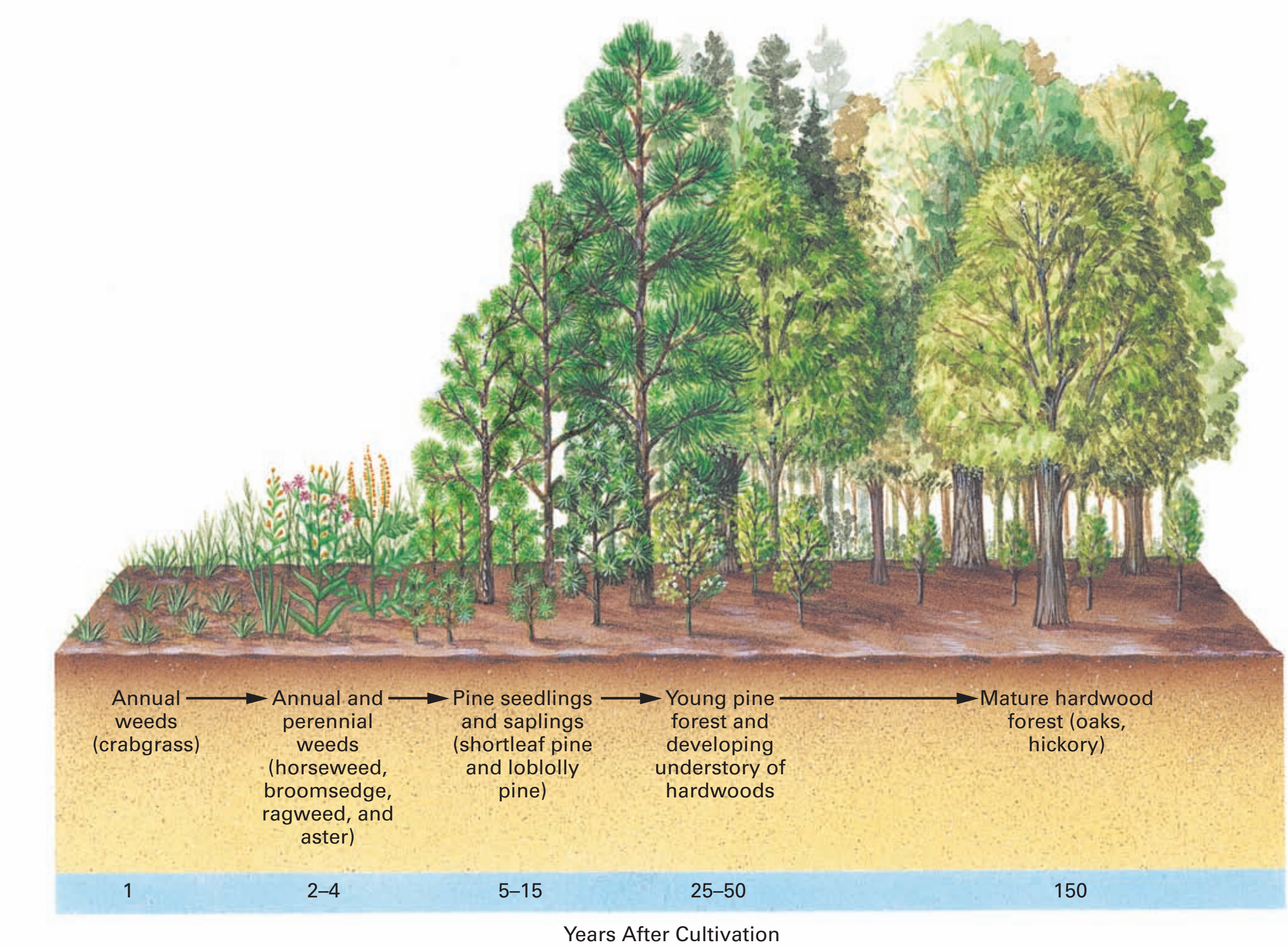
SUCCESSION, CHANGE, AND EQUILIBRIUM

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.

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.

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.



Old-field succession in the Southeast U.S. FIGURE 16.21

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.

CONCEPT CHECK STOP

Define ecological succession.

What is the difference between primary and secondary succession? Give examples of surfaces on which these two types of succession can occur.

What is autogenic succession? What factors can limit it?

Historical Biogeography

LEARNING OBJECTIVES

Explain evolution and natural selection.

Contrast speciation and extinction.

Describe species distribution patterns.

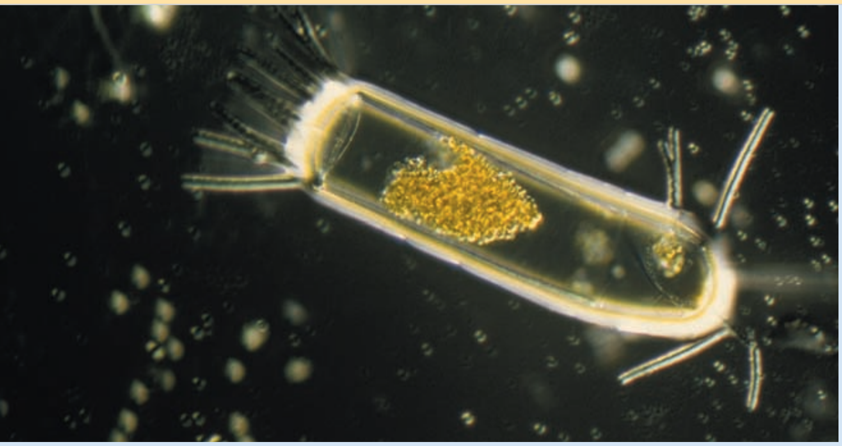
So far, we've assumed that all the successional species are ready and available to colonize new space. But when we think of changes on continental and global scales, taken over longer spans of time, not all species are available. On this scale, other processes are more important in determining the spatial patterns we observe, which we'll turn to now. *Historical biogeography* focuses on how spatial distribution patterns arise over space and time through four key processes: evolution, speciation, extinction, and dispersal.

EVOLUTION

Evolution The creation of diversity of life-forms through the process of natural selection.

An astonishing number of organisms exist on Earth, each adapted to the ecosystem in which it carries out its life cycle (FIGURE 16.22). About 40,000 species of microorganisms, 350,000 species of plants, and 2.2 million

Diversity of life-forms on Earth FIGURE 16.22



A 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.

B Fungus A stinkhorn fungus on the floor of a Costa Rican rainforest. Fungi are plants without chlorophyll that gain their nutrition from dead and decaying organic matter.

C 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.

D 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.

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 itself has acted on organisms to create this diversity. You've probably heard of Sir Charles Darwin, whom we mentioned in the chapter opener. His monumental 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 go on and propagate.

Natural selection Selection of organisms by environment in a process similar to selection of plants or animals for breeding by agriculturalists.

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. Recombination describes the process by which an offspring receives two slightly different copies, or *alleles*, of each gene from its parents.

Species A collection of individual organisms that are capable of interbreeding to produce fertile offspring.

Mutations change the nature of species through time. But just what is a species? For our purposes here, 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 16.23).

Red and white oaks FIGURE 16.23

Although similar in general appearance, these two species are easily separated.

A Red oak Red oak acorns have a flat cap and stubby nut, with pointed bristle tips on the leaf lobes.

B White oak White oak acorns have a deeper cap and a pointed nut, with rounded leaf-lobe tips.

SPECIATION

Speciation
The process by which species are differentiated and maintained.

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.

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 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. For example, plate tectonics 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 16.24). 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, as mentioned at the beginning of the chapter, and they inspired his ideas about evolution. The giant tortoises that we met in the chapter opener are another example of allopatric speciation. 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.

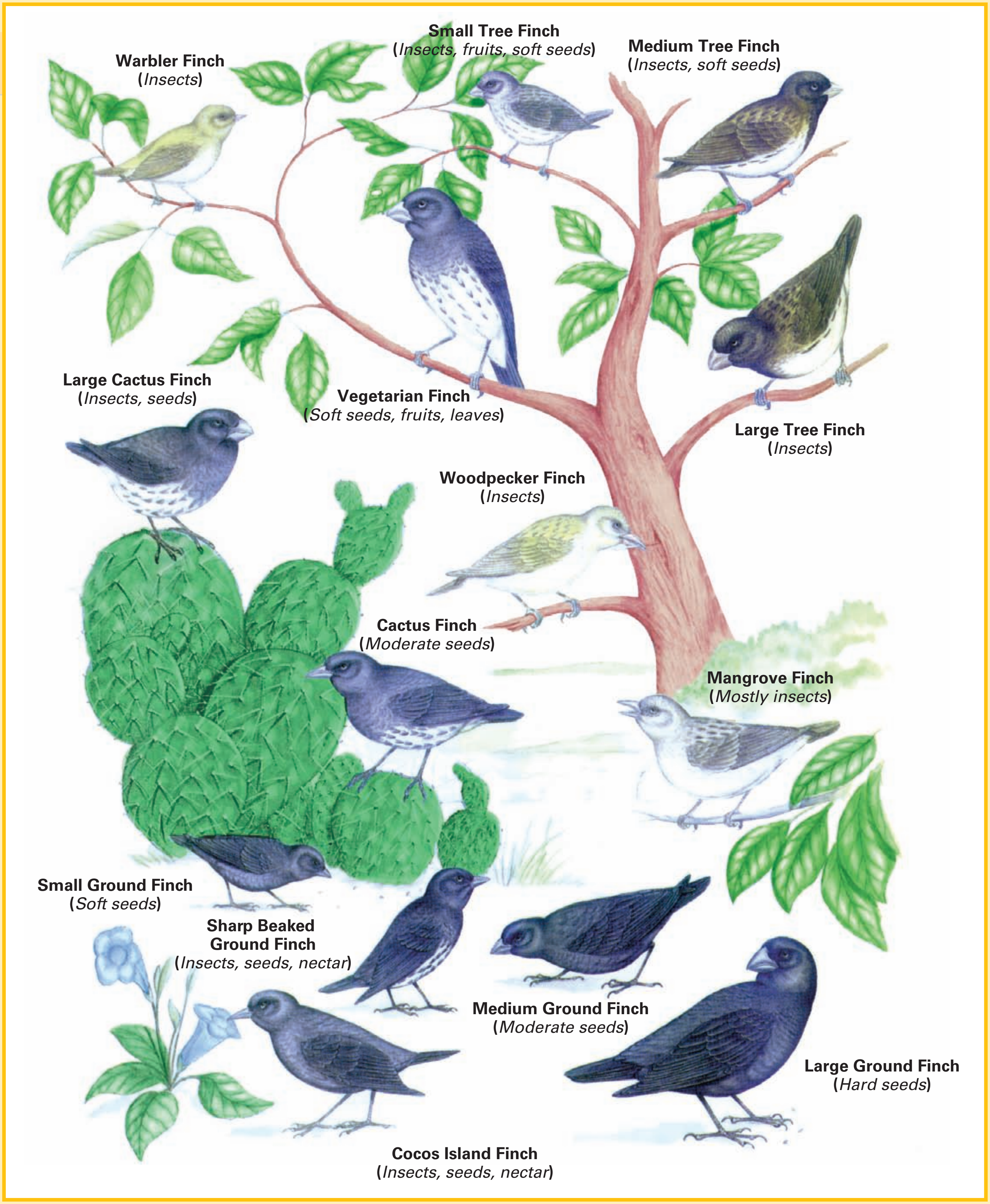
Allopatric speciation of Galápagos finches
FIGURE 16.24

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.

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. We think that about 70 to 80 percent of higher plant species 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.


Small Tree Finch
(Insects, fruits, soft seeds)
Medium Tree Finch
(Insects, soft seeds)
Warbler Finch
(Insects)
Large Cactus Finch
(Insects, seeds)
Vegetarian Finch
(Soft seeds, fruits, leaves)
Large Tree Finch
(Insects)
Woodpecker Finch
(Insects)
Cactus Finch
(Moderate seeds)
Mangrove Finch
(Mostly insects)
Small Ground Finch
(Soft seeds)
Sharp Beaked
Ground Finch
(Insects, seeds, nectar)
Medium Ground Finch
(Moderate seeds)
Large Ground Finch
(Hard seeds)
Cocos Island Finch
(Insects, seeds, nectar)

Some extinctions occur very rapidly, particularly those induced by human activity, such as in the classic example of the passenger pigeon (FIGURE 16.25). Rare but extreme events can also cause extinctions. Strong evidence suggests that the Earth was struck by a meteorite about 65 million years ago, wiping out the dinosaurs and many other groups of terrestrial and marine organisms (FIGURE 16.26).

Passenger pigeon FIGURE 16.25

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.

Chicxulub crater FIGURE 16.26

When a huge 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.

DISPERSAL

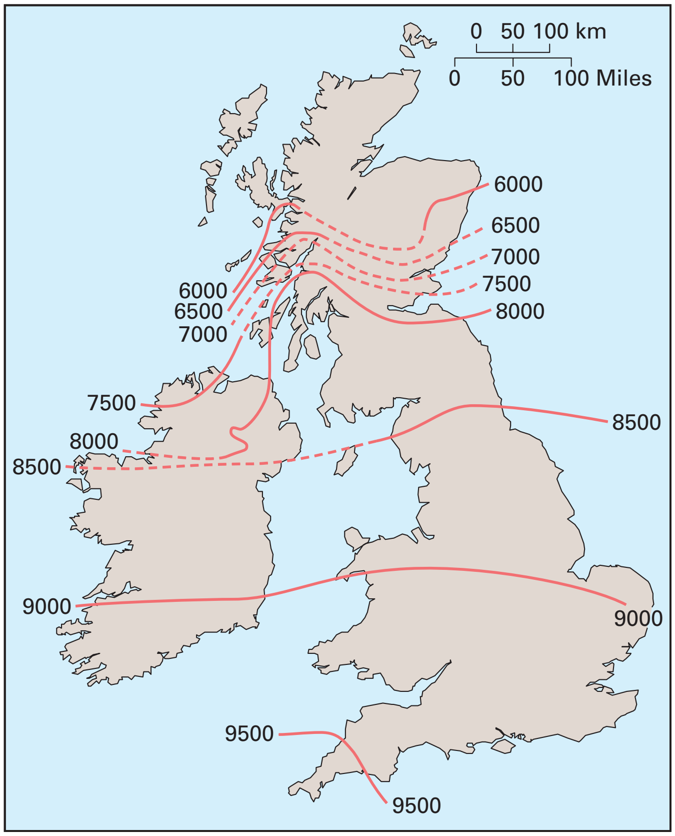
Nearly all types of organisms can move from an origin location to new sites. Often this *dispersal* is confined to one life stage, as in the dispersal of higher plants as seeds. Even for animals, there is often a developmental stage when the animals are more likely to move from one site to the next.

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 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 16.27).

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 16.28). 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 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.

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.



Diffusion of oaks FIGURE 16.27

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 border 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.

Dispersal FIGURE 16.28

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.

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 16.29A).

In contrast to endemics are *cosmopolitan species*, which are distributed very widely (FIGURE 16.29B). 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.

Endemic and cosmopolitan species FIGURE 16.29

A **Endemic** 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.

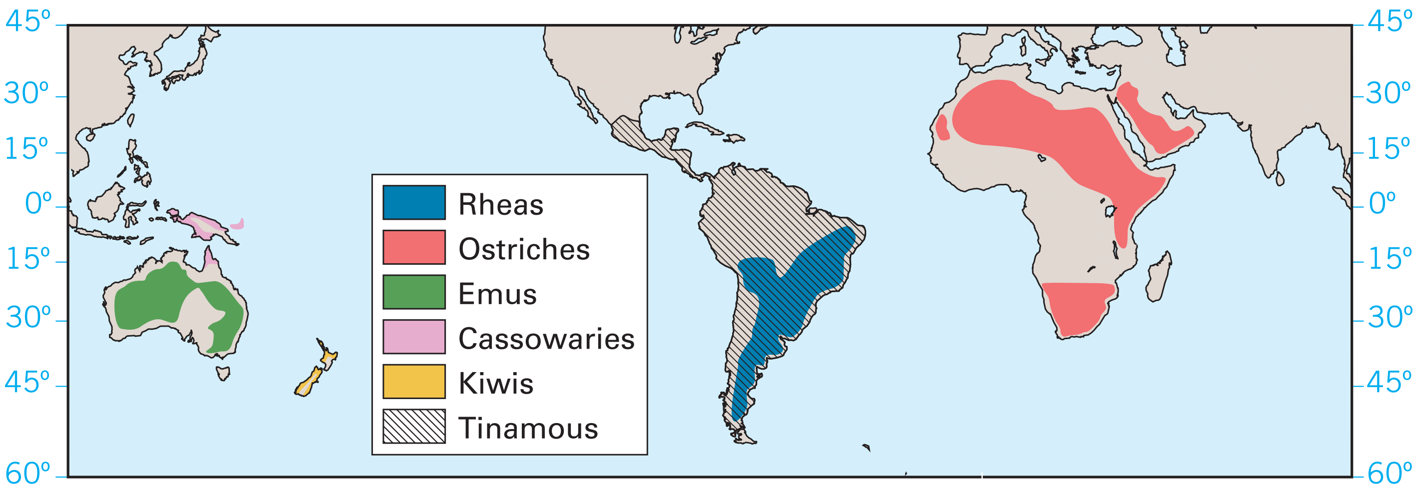
B Shown here are two cosmopolitan species—the peregrine falcon (*Falco peregrinus*) and the human (*Homo sapiens*). Both are found widely over the globe. The human on the left, a scientist, is attaching a band to the leg of the bird as part of a study of how the falcon is affected by chemical contamination.

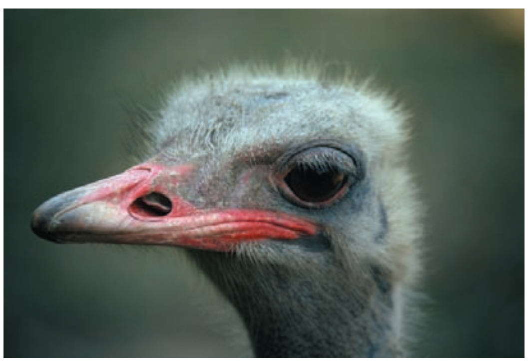
BIOGEOGRAPHIC REGIONS

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 16.30, also fits the distribution of many other ancient families of plants and animals. This reflects their common ancestry on the southern supercontinent Gondwana, before it split apart. 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.

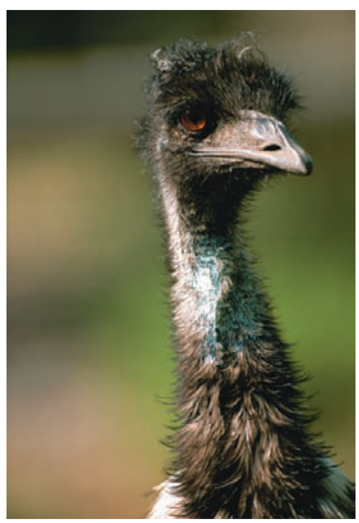
Disjunct distribution FIGURE 16.30

A 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.





B **Ostrich** The ostrich is restricted to Africa and the Middle East, although it was formerly found in Asia.



C **Emu** The emu inhabits most of Australia and is commonly encountered in the wild.

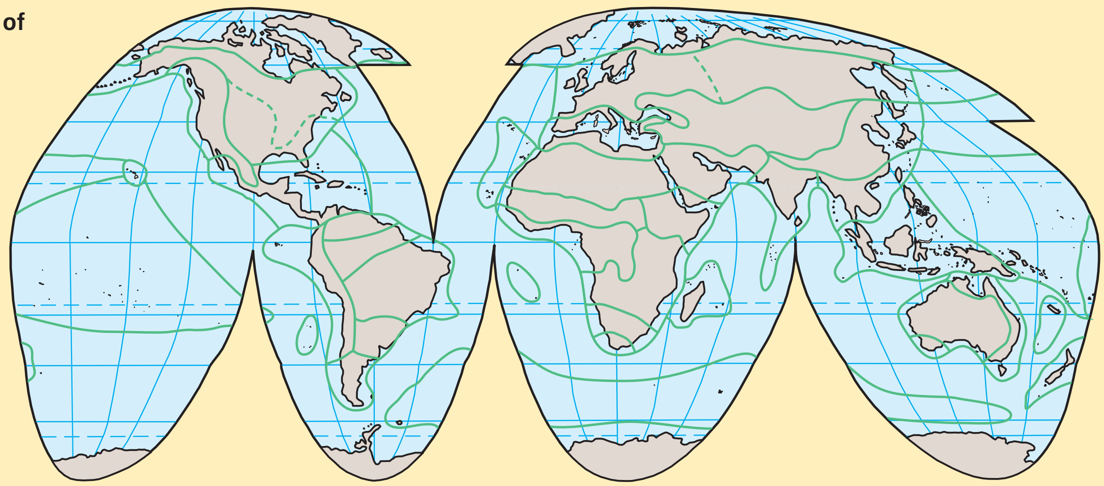
D **Cassowary** The cassowary hails from New Guinea and northeastern Australia. It is a rainforest dweller.

We can define *biogeographic regions* 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 16.31** shows the major biogeographic regions for plants and animals.

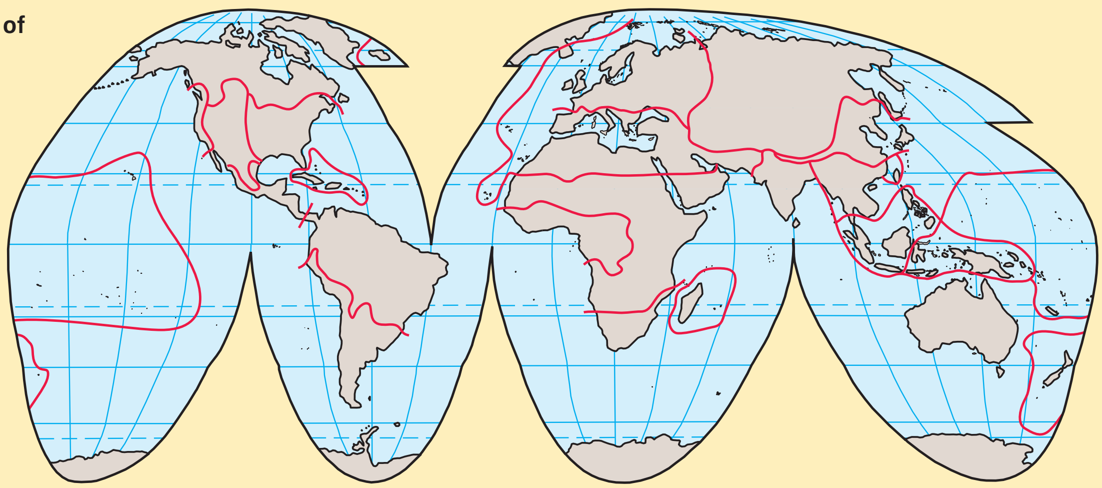
Biogeographic regions FIGURE 16.31

Note that many of the boundaries on the two maps are very close, indicating that at the global scale, plants and animals have similar and related histories of evolution and environmental affinity.

A Biogeographic regions of land plants.



B Biogeographic regions of land animals.



CONCEPT CHECK STOP

Define evolution. What are the two sources of variation?

What is speciation? Name the four key processes that lead to speciation.

What is the difference between allopatric speciation and sympatric speciation? Give an example of each.

What term describes the distribution pattern of ratite birds? How was this pattern created?

Biodiversity

Learning Objectives

Explain the impact of human activity on biodiversity.

Define hotspots.

Today, **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 face extinction, according to the International Union for Conservation of Nature and Natural Resources (Figure 16.32).

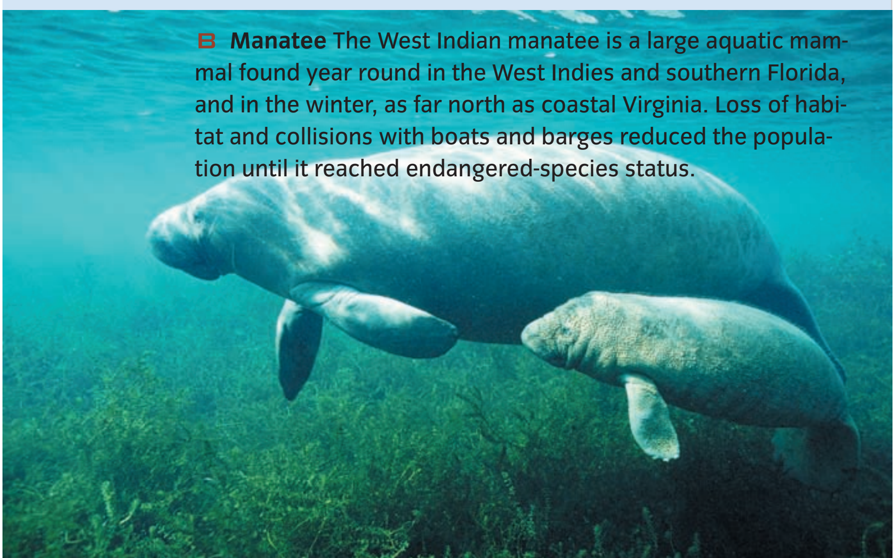
> **Biodiversity** The variety of biological life on Earth or within a region.

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 may become extinct without ever being described.

Endangered species

Figure 16.32

A 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.



B 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.

How has human activity created extinctions? We're monopolizing the world's resources—altering habitats along the way. We've doubled the natural rate of nitrogen fixation, used more than half of the Earth's supply of surface water, and transformed more than 40 percent of the land surface.

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. And as humans learned to use fire, large areas became subject to periodic burning.

Biodiversity is not uniform over the Earth's surface. Tropical and equatorial regions have more species and more variation in species composition between different habitats. We call geographic areas where biodiversity is especially high *hotspots*. The Visualizing feature locates and discusses some of these hotspots. If we want to preserve global biodiversity, we must protect them.

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, that web will thin, with unknown consequences for both the human species and continued life on Earth.

CONCEPT CHECK STOP

How has human activity created extinctions?

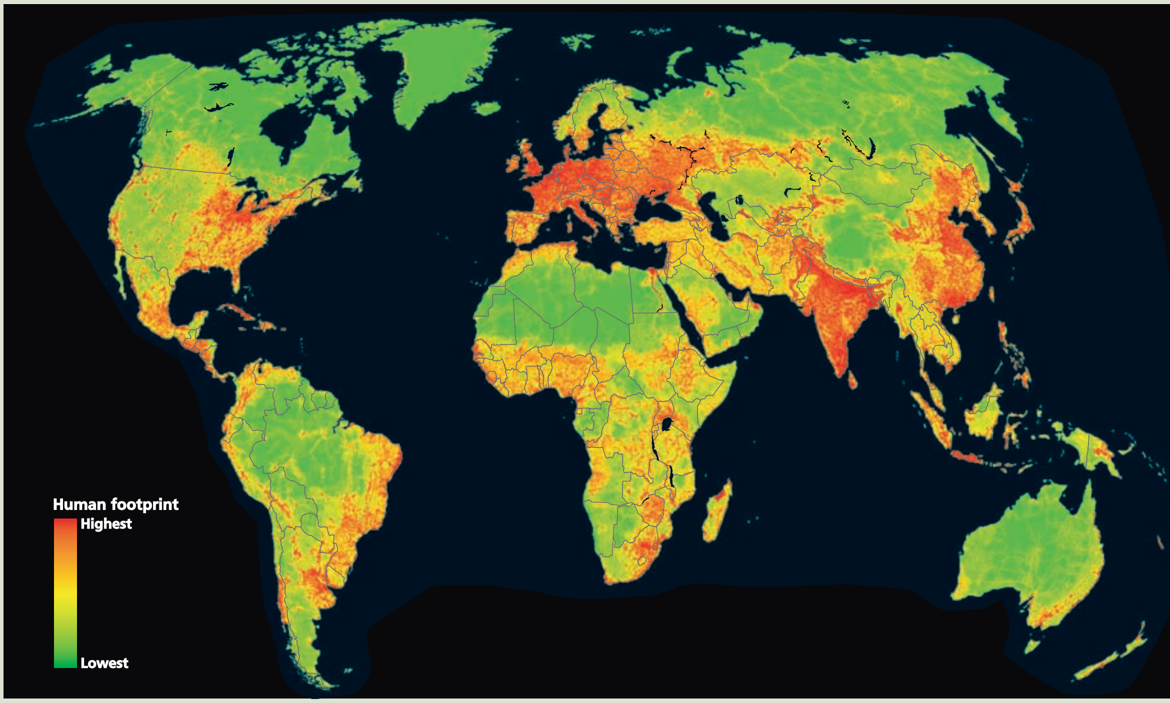
What are hotspots?

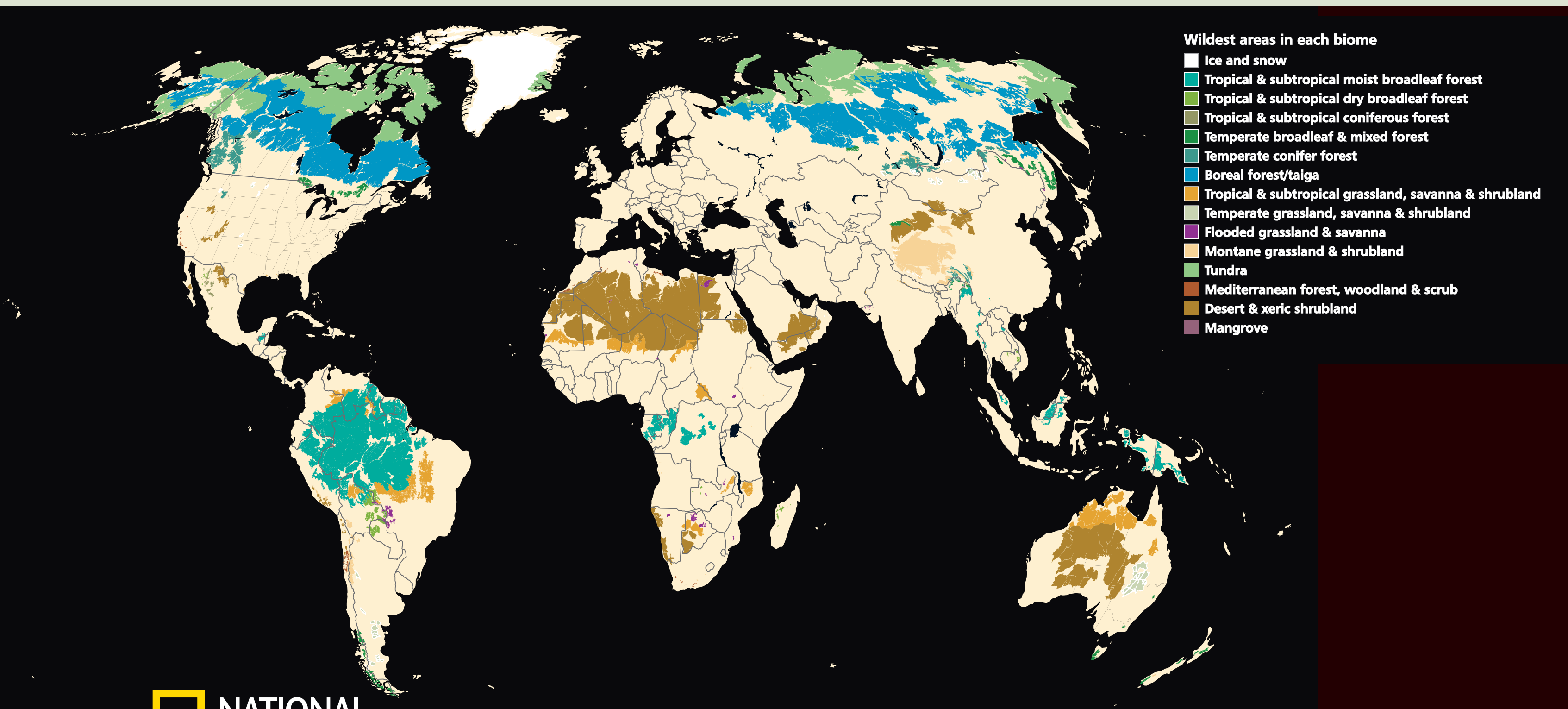
HUMAN FOOTPRINT

The human species has altered vast areas of the globe to support its activities, leaving little untouched.

▶ **HUMAN FOOTPRINT** Human influence is felt in all parts of the planet. We consume 40 percent of the Earth's net primary productivity, 35 percent of oceanic shelf productivity, and 60 percent of freshwater runoff. Nearly 75 percent of habitable surface area is disturbed by human use.

▼ **WILDERNESS** Wilderness is defined as terrestrial, freshwater, or marine area that is mostly intact in terms of habitat, faunal assemblages, and biological processes. Low human impact and population density are defining factors.





NATIONAL GEOGRAPHIC

BIODIVERSITY

Functioning ecological systems require a resilient web of interacting organisms.

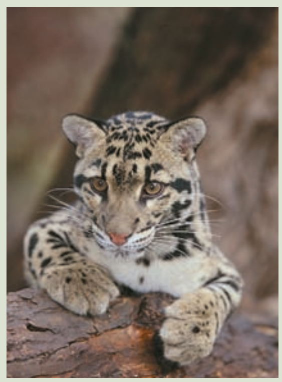
▶ BIODIVERSITY HOTSPOTS

Conservation International identified 34 "hotspots," defined as habitat holding at least 1500 endemic plant species and having lost 70 percent of its original extent.

1. Bering Sea
2. Southeastern U.S. streams and rivers
3. Amazon River and flooded forests
4. Rift Valley lakes
5. Eastern Himalayan broadleaf and conifer forests
6. Sulu-Sulawesi Seas

▶ BERING SEA

The Bering Sea is one of the world's most diverse marine environments, including polar bears, seals, sea lions, walruses, whales, enormous populations of sea birds, and more than 400 species of fish, crustaceans, and mollusks.



◀ EASTERN HIMALAYAN FORESTS

Snaking across the lowlands and foothills of the Himalaya, this ecoregion supports a remarkable diversity of plants and animals, including endangered mammals such as the clouded leopard, Himalayan black bear, and golden langur, as well as many endemic bird species.

◀ THREATS TO BIODIVERSITY

More than 60 percent of vascular plants and 40 percent of nonfish vertebrates are endemic to only 7.5 percent of Earth's land surface. The greatest threats to biodiversity—habitat loss and fragmentation, invasion of nonnative species, pollution, and unsustainable exploitation—are all caused by human activity.

What is happening in this picture ?

The Chisos Mountains of Big Bend National Park

In this scene we can pick out two quite distinct biotic communities on the mountain. The left, south-facing slope supports a community of low shrubs, while the north-facing slope is covered in piñon pine and juniper.

- What has caused this extreme difference?

VISUAL SUMMARY

1 Energy and Matter Flow in Ecosystems

1. The food web of an ecosystem details how food energy flows from primary producers through consumers and on to decomposers.
2. 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.
3. Biogeochemical cycles consist of active pools and storage pools linked by flow paths. The carbon cycle and the nitrogen cycle are important biogeochemical cycles.

2 Ecological Biogeography

1. A community of organisms occupies a particular environment or habitat. Environmental factors influencing the distribution patterns of organisms include moisture, temperature, light, and wind.

2. Geomorphic (landform) factors affect both the moisture and temperature environment of the habitat. Soil, or edaphic, factors can also limit the distribution of organisms or affect community composition.

3. Species interactions include competition, predation and parasitism, herbivory, and allelopathy. Positive interactions are symbiotic.

3 Ecological Succession

1. Ecological succession comes about as ecosystems change in predictable ways through time.

2. Primary succession occurs on new soil substrate, while secondary succession occurs on disturbed habitats.

3. Succession is opposed by natural disturbances and limited by local environmental conditions.

4 Historical Biogeography

1. Life has attained its astonishing diversity through evolution. Natural selection acts on variation to produce populations that are progressively better adjusted to their environment. Variation arises from mutation and recombination.

2. Speciation is the process by which species are differentiated and maintained. It includes mutation, natural selection, genetic drift, and gene flow. Geographic isolation enhances speciation.

3. 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.

4. Species expand and contract their ranges by dispersal.

5. Endemic species are found in one region or location and nowhere else. Cosmopolitan species are widely dispersed and nearly universal. Disjunction occurs when one or more closely related species appear in widely separated regions.

5 Biodiversity

1. Biodiversity is rapidly decreasing.

2. Humans disperse predators, parasites, and competitors widely, disrupting long-established species. Hunting, burning, and habitat alteration have exterminated many species.

3. We must protect hotspots where diversity is greatest.

KEY TERMS

- **biogeography** p. 478
- **ecosystem** p. 478
- **food web (food chain)** p. 479
- **photosynthesis** p. 481
- **biomass** p. 482
- **carbon cycle** p. 484
- **habitat** p. 488
- **symbiosis** p. 496
- **ecological succession** p. 497
- **evolution** p. 500
- **natural selection** p. 501
- **species** p. 501
- **speciation** p. 502
- **biodiversity** p. 509

CRITICAL AND CREATIVE THINKING QUESTIONS

1. What is a food web or food chain? What are its essential components? How does energy flow through the food web of an ecosystem? Use the salt marsh ecosystem to provide examples to illustrate your answers.

2. Diagram the global carbon cycle. Suppose atmospheric carbon dioxide concentration doubles. What will be the effect on the carbon cycle? How will flows change? Which pools will increase? Decrease?

3. What is a habitat? Select three distinctive habitats for plants and animals that occur nearby and with which you are familiar. Organize a field trip (real or imaginary) to visit the habitats. Compare their physical environments and describe the basic characteristics of the ecosystems found there.

4. Describe how organisms adapt to arid environments. How do animals cope with variation in temperature?

5. How does the ecological factor of light affect plants and animals? How does wind affect plants?

6. How do geomorphic and edaphic factors influence the habitat of a community?

7. Contrast the terms used to describe interactions among species. Provide an example of positive predation.

8. Describe ecological succession using the terms *sere*, *seral stage*, *pioneer*, and *climax*. How do primary succession and secondary succession differ? Draw a timeline illustrating either dune succession or old-field succession. Between the stages, indicate the environmental changes that occur.

9. Explain Darwin's theory of evolution by means of natural selection. What key point was Darwin unable to explain? How do we explain that point now?

10. What is speciation? Identify and describe four component processes of speciation. What is the effect of geographic isolation on speciation? Provide an example of allopatric speciation.

11. Describe the process of dispersal. Provide a few examples of plants and animals suited to long-distance dispersal.

12. Imagine yourself as a biogeographer discovering a new group of islands. Select a global location for your island group, including climate and proximity to nearby continents or land masses. What types of organisms would you expect to find within your island group and why?

SELF-TEST

1. Within an ecosystem, energy transformations occur through a series of levels commonly referred to as the food web, within which marsh grass, shown here, represent the ______________.

a. secondary producers
b. primary consumers
c. primary producers
d. decomposers

2. During the nitrogen cycle, the process in which certain soil bacteria convert nitrogen from usable forms (NO_x) back to N_2 is called ______________.

a. nitrification
b. nitrogen fixation
c. denitrification
d. nitrogen consumption

3. ______________ is a concept that describes how a species obtains its energy and influences other species in its own environment.

a. Habitat
b. Ecological niche
c. Community
d. Ecosystem

4. The annual rhythm of leaf shedding by tropophytes is determined by:

a. light
b. heat
c. wind
d. moisture

5. What features of this plant are adapted to its desert climate? What term is used to describe plants that are adapted to drought conditions?

6. Which of the following is an edaphic factor important in differentiating habitat?

a. soil texture
b. time
c. light
d. all of the above

7. The phenomenon in which chemical toxins produced by one species serves to inhibit the growth of others is:

a. predation
b. allelopathy
c. parasitism
d. herbivory

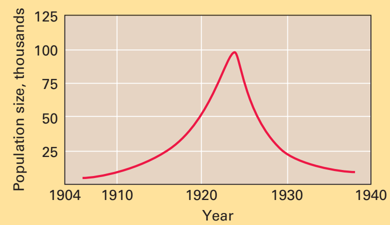
8. The photograph shows an orchid living on the branches of another plant. What advantage, if any, does this relationship have for each plant? This is an example of:

a. commensalism
b. protocooperation
c. mutualism
d. parasitism

9. Positive interactions between species includes:

a. herbivory
b. allelopathy
c. protocooperation
d. all of the above

10. The graph shows the changes in the population size of the Kaibab deer herd in Arizona between about 1904 and 1940. Explain this pattern.



11. Succession that occurs on a site that has been burnt in a forest fire is:

a. primary succession
b. secondary succession
c. tertiary succession
d. old-field succession

12. Pioneer species are:

a. well adapted to dry soil conditions
b. able to withstand temperature extremes
c. larger than other species that replace them
d. all of the above
e. a and b

13. The finch species on the Galápagos Islands are an example of:

a. allopatric speciation
b. sympatric speciation
c. polyploidy speciation
d. genetic drift

14. Species whose distribution is limited to one location or region is:

a. allopatric
b. cosmopolitan
c. endemic
d. disjunct

15. The greatest biodiversity on Earth is found in:

a. tropical and equatorial regions
b. midlatitude regions
c. alpine regions
d. subarctic and arctic regions

Global Biogeography

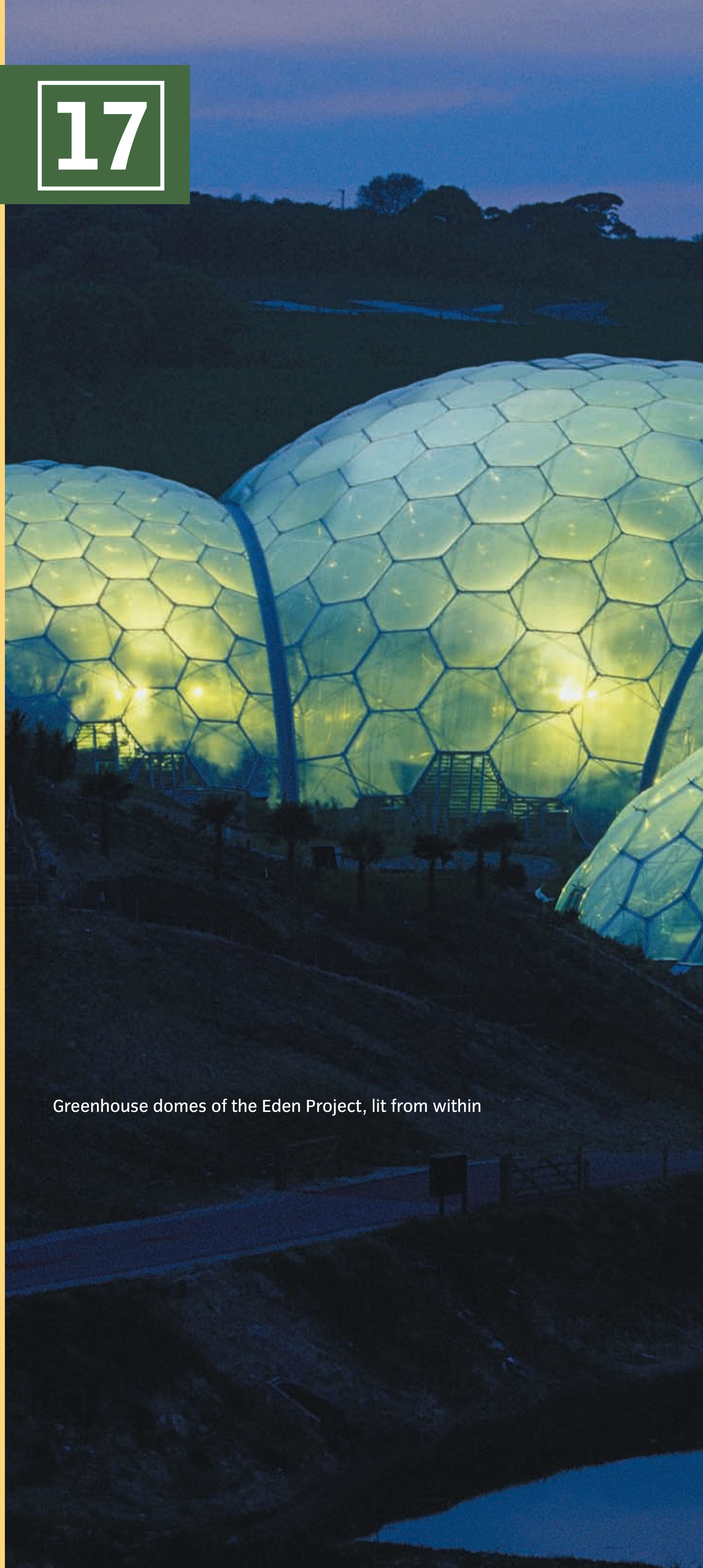
17

Recreating the Garden of Eden is an ambitious task. But a giant conservatory located on an abandoned clay pit in Cornwall, England, is trying to do just that.

Taking two and a half years to construct, the Eden Project, as it is known, opened in March 2001. It houses two huge transparent domes containing more than 4500 plant species from around the world. The first dome emulates an equatorial environment and includes plants from the Oceanic Islands, Malaysia, West Africa, and tropical South America. The second dome mimics a Mediterranean climate, with plants from the Mediterranean, South Africa, and California. This ongoing project is designed to show how different environments develop over time.

The Eden Project isn't our first attempt to create a closed ecological system. Other examples include Biosphere 2, in Oracle, Arizona, constructed between 1987 and 1989. It tested if people could live and work within a closed biosphere, and it explored the possibility that such systems could be used for space colonization. The project conducted two sealed missions in the 1990s. During the first mission, oxygen levels began falling at a steady pace of 0.5 percent per month. Today, Biosphere 2 is no longer airtight—highlighting the immense difficulty in maintaining artificial biospheres.

But what happened to "Biosphere 1," on which Biosphere 2 was modeled? It's still running and is home to an astounding array of plants, animals, and climates. That enormous, natural biosphere is, of course, the Earth. Its ultimate fate has yet to be decided.

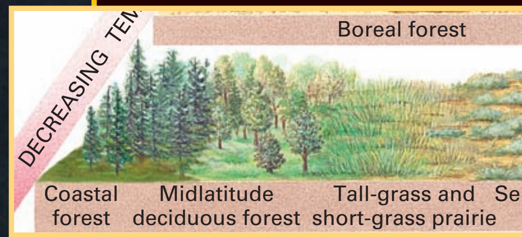


Greenhouse domes of the Edren Project, lit from within

NATIONAL GEOGRAPHIC

CHAPTER OUTLINE

Natural Vegetation p. 518



Terrestrial Ecosystems—The Biomes p. 524

Forest Biome p. 528

Savanna and Grassland Biomes p. 537

Desert and Tundra Biomes p. 543

Natural Vegetation

LEARNING OBJECTIVES

Define natural vegetation.

Describe the structure of different plant life-forms.

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 (FIGURE 17.1). 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 rapidly cleared. Much of the arctic tundra and the boreal forest of the subarctic zones is in a natural state.

Natural vegetation Stable, mature plant cover, largely free from the influences of human activities.

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, such as national parks and national forests, appear to be untouched but are actually dominated by human activity in a subtle manner. For example, most national parks and national forests have been protected from fire for many decades. "What a Geographer Sees: The great Yellowstone fire," looks at the advantages of letting such fires burn. Today, many park managers, including those at Yellowstone National Park, have stopped suppressing most wildfires.

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. Our Visualizing feature explores the human impact on global productivity.

Plants have limited tolerance to the different conditions of soil water, temperature, and soil nutrients. Their structure and outward appearance tends to conform within their native habitats, and each vegetation type is associated with a characteristic geographical region—forest, grassland, or desert.

Natural vegetation FIGURE 17.1

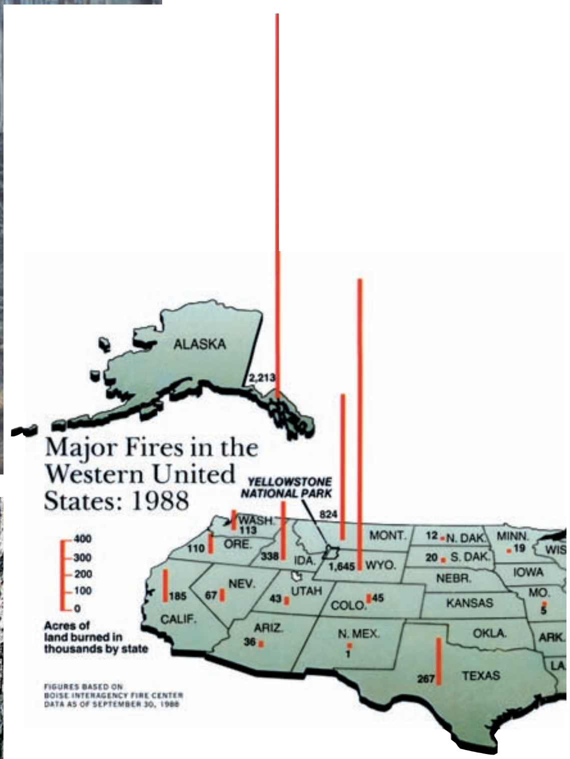
Tropical and equatorial rainforests provide vast areas of vegetation virtually untouched by modern humans. However, human influence is expanding, not just by clearing the rainforest for agriculture, but also in subtle ways. Shown here is a camp for eco-tourists in Belize. Built near an ancient Mayan site, it also helps protect the site from looters.

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.

The upper photograph shows how the fires ravaged the park, leaving scorched, burned, and dying trees in its wake. After 10 years, however, new forests were well on their way to replacing the burned ones (lower photo).

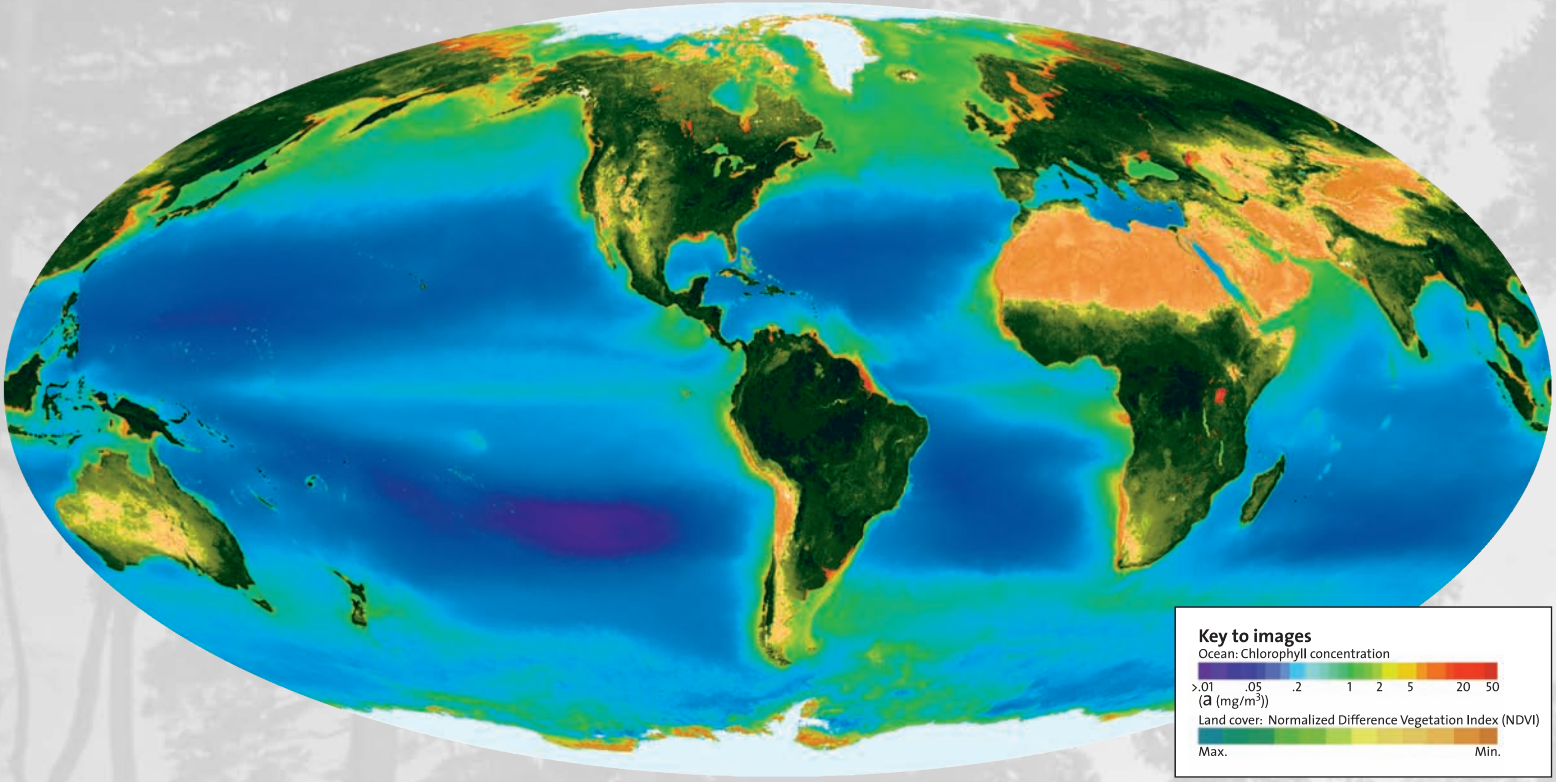
Today, geographers and ecologists realize that periodic burning is part of a forest's natural cycle. When vegetation burns, the ashes containing nutrients remain, enriching the soil and encouraging new tree species to grow.



During the Western fires of 1988, 30,000 fire fighters battled 70,000 blazes totaling 3.7 million acres in the western U.S., plus another two million acres in Alaska. Smoke drifted to the East Coast. Suppression efforts cost 600 million dollars.

PHOTOSYNTHESIS AND BIOMASS

Carbon fixation requires living green biomass, which provides the photosynthetic machinery to turn CO_2 from an atmospheric gas to carbohydrate. Both land plants and oceanic phytoplankton contribute significantly to global carbon cycling.



▲ **EARTH'S GREEN BIOMASS** The Earth's green biomass is the photosynthetic machinery of the planet, producing 50 to 60 billion metric tonnes (55 to 66 billion tons) of carbon each year. On land, equatorial and wet tropical regions are most productive (darkest green). Land is least productive where limited by temperature (polar regions) or moisture (deserts). In the oceans, coastal waters and zones of upwelling are most productive (red).

▶ **OVERGRAZING** Overgrazing strips vegetation from the land, reducing evapotranspiration, increasing temperatures, and leaving the soil without cover. The result is land degradation that may require decades to reverse.

▶ **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.

NATIONAL GEOGRAPHIC

Visualizing

Human Impact on Global Productivity

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.

▲ **CLEAR-CUTTING** Clear-cutting of large tracts of timber, without sustainable replanting, contributes to deforestation, erosion, and loss of habitat.

▼ **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.

▲ **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.

▼ **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.

STRUCTURE AND LIFE-FORM OF PLANTS

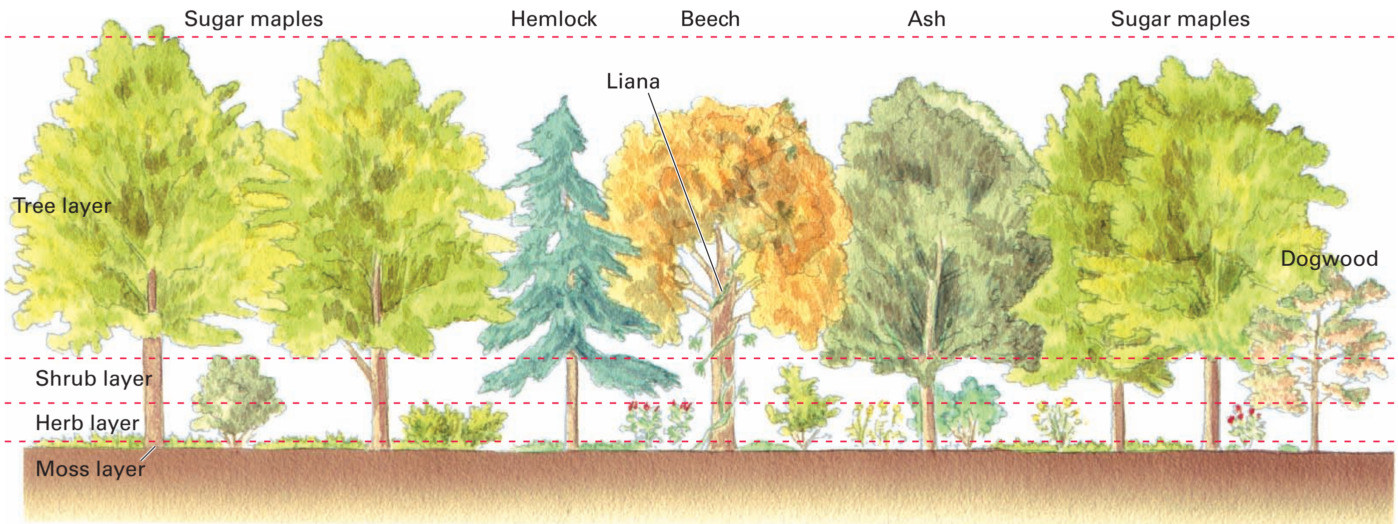
Plants come in many types, shapes, and sizes. Botanists recognize and classify plants by species. However, the plant geographer is less concerned with individual species and more interested in plant cover as a whole. So, when talking about plant cover, plant geographers discuss the **life-form** of the 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.

Life-form Characteristic physical structure, size, and shape of a plant or of an assemblage of plants.

FIGURE 17.2 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.

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, while others are *perennials*, living for multiple seasons. 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



Layers of a beech-maple-hemlock forest FIGURE 17.2

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.

Lichens FIGURE 17.3

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, Saskatechewan.

the ground (FIGURE 17.3). They are plant 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.

Forest
Assemblage of trees growing close together, their crowns forming a layer of foliage that largely shades the ground.

CONCEPT CHECK STOP

What is natural vegetation?

How do humans influence vegetation?

What are the different life-forms that plant geographers refer to when discussing plant cover?

Terrestrial Ecosystems—The Biomes

LEARNING OBJECTIVES

Define terrestrial ecosystem and biome.

Identify and describe the five principal biomes: forest, savanna, grassland, desert, and tundra.

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 (FIGURE 17.4). 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 and interact with the soil, so they are closely woven into the fabric of physical geography.

Terrestrial ecosystem Ecosystem of land plants and animals found on upland surfaces of the continents.

Marine environments FIGURE 17.4

A Saltwater Coral reefs are among the most diverse aquatic ecosystems. Here a school of smallmouth grunts swim over a reef on Dominica Island in the Caribbean.

B Fresh water Marshes, ponds, and swamps are also habitats of striking diversity. Here, an underwater view shows water lilies in a pond fed by volcanic springs in the heart of Mexico's Chihuahuan Desert. This unique habitat includes many endemic species.

Biomes

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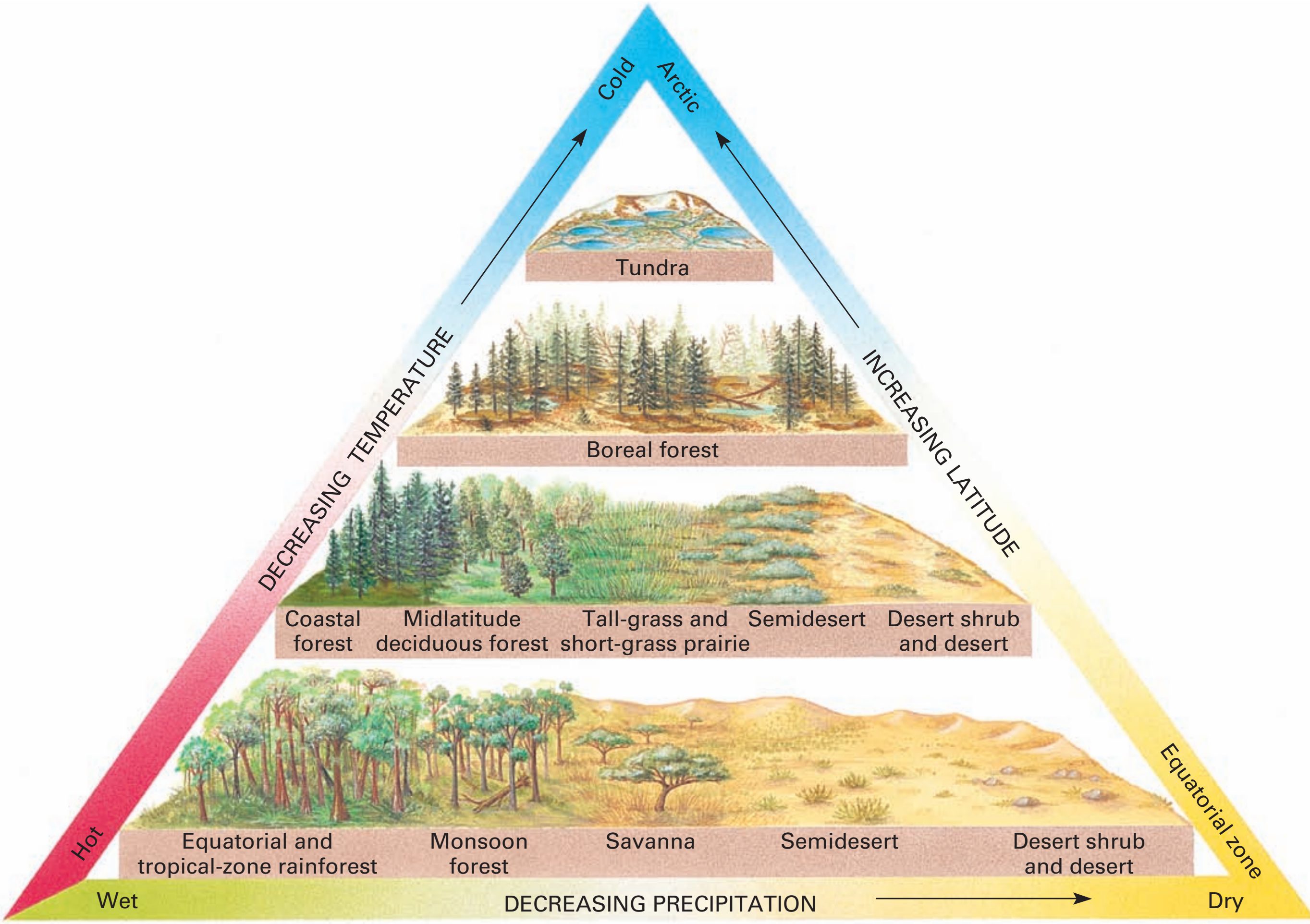
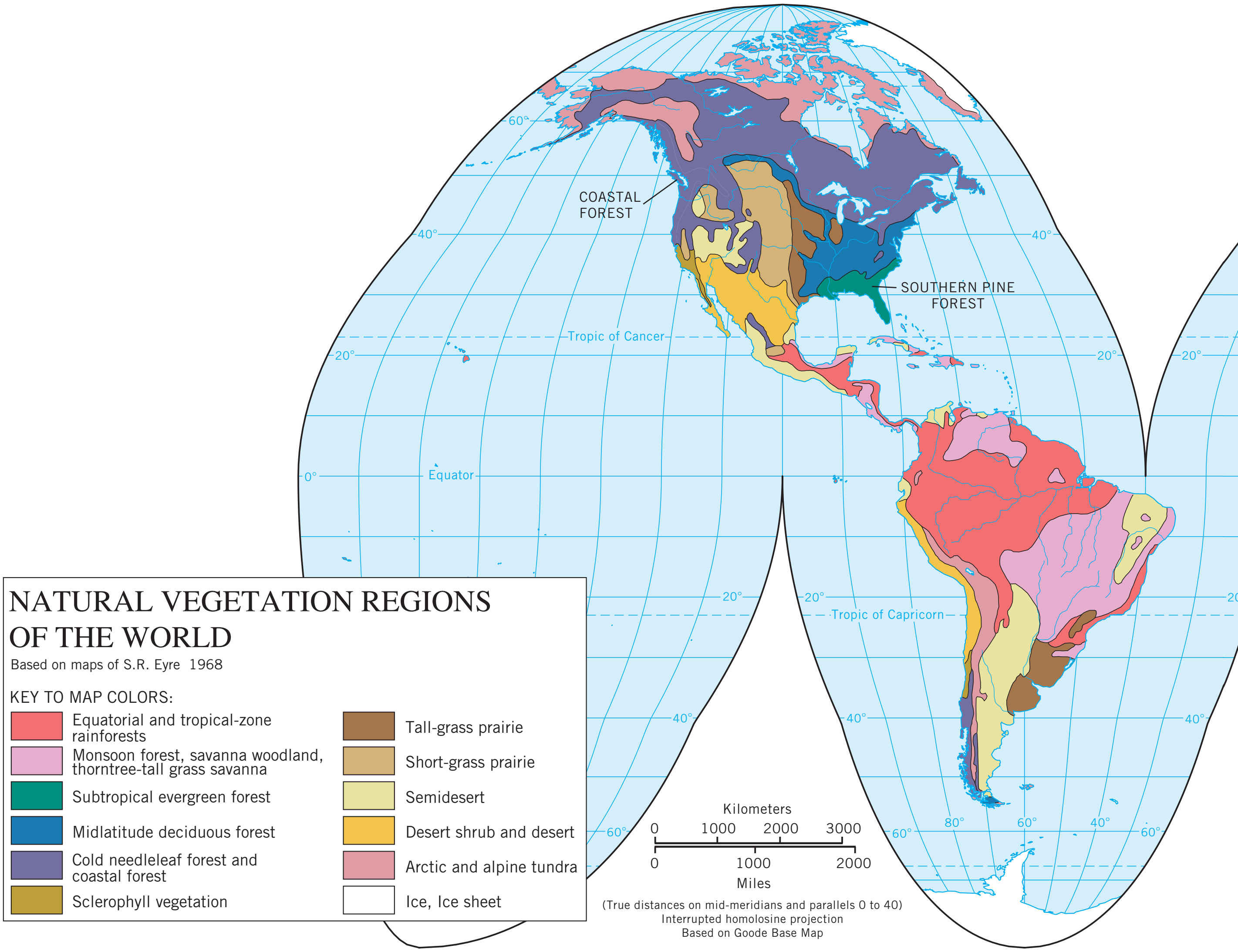
Process Diagram



Temperature and precipitation are the two most important factors in determining the pattern of natural vegetation types. 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 conifer forests.

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.

Biome Largest recognizable subdivision of terrestrial ecosystems.

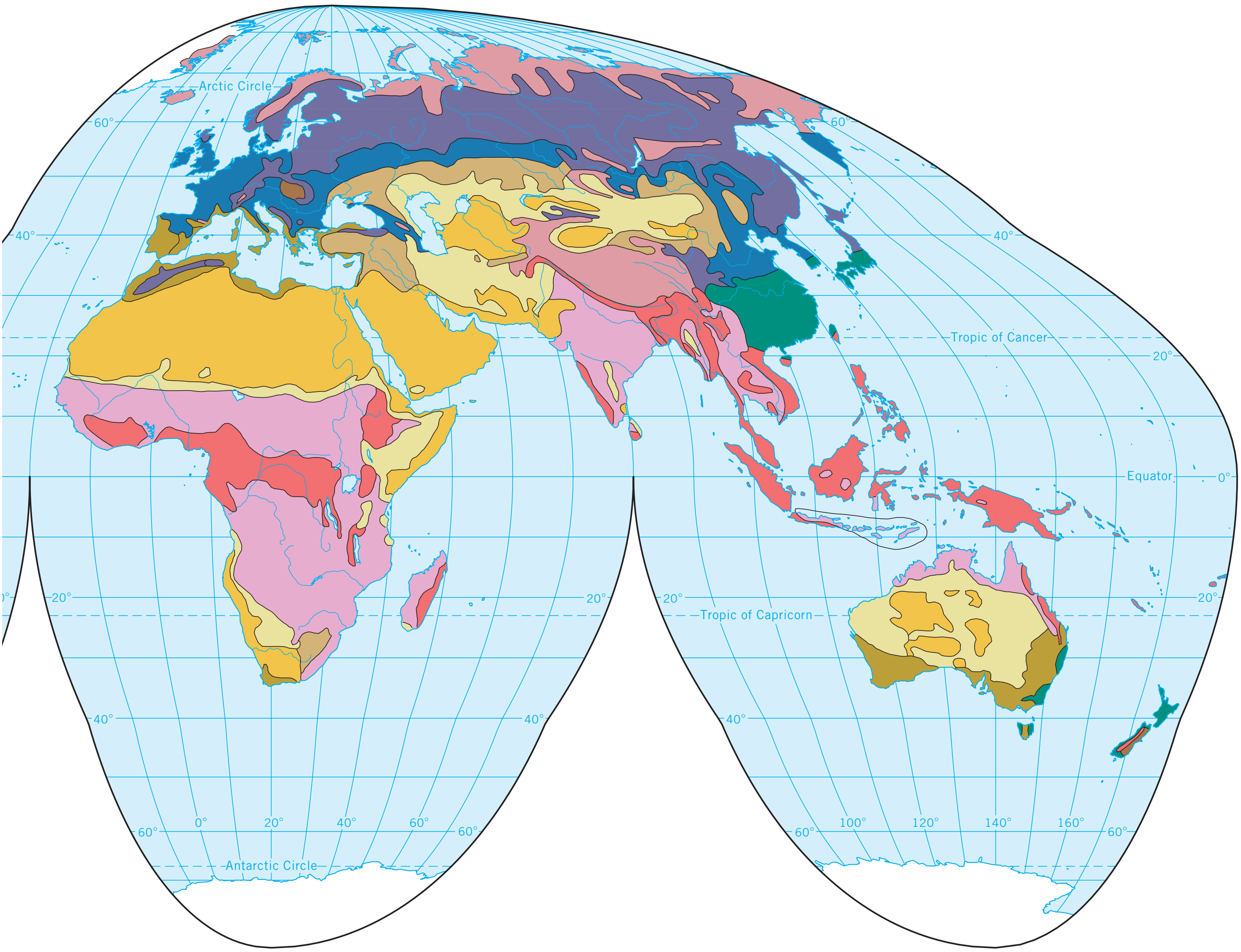


Natural vegetation of the world FIGURE 17.5

There are five principal biomes: forest, savanna, grassland, desert, and tundra, described in the process diagram "Biomes." Biogeographers break the biomes down further 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. FIGURE 17.5 is a generalized world map of the 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.

CLIMATIC GRADIENTS AND VEGETATION TYPES

The major formation classes of vegetation depend heavily on climate. As climate changes with latitude or longitude, vegetation will also change. The Process Diagram shows how vegetation formation classes respond to temperature and precipitation gradients. As pictured in the diagram, the changes between vegetation types don't



occur abruptly. Instead, they grade into each other slowly. But global maps of both vegetation and climate—including the ones in this book—show distinct boundaries between regions. Which is correct? The real situation is gradational rather than abrupt. But maps need to use sharp boundaries to communicate information, even though climate and vegetation know no specific boundaries. So, when studying any map of natural features, keep in mind that boundaries are almost always approximate and gradational.

CONCEPT CHECK **STOP**

What are terrestrial ecosystems? What are biomes?

List the five principal biomes.

What is the problem with the way that maps depict climate and vegetation regions?

Forest Biome

Learning Objectives

Define forest biome.

Describe low-latitude rainforest, monsoon forest, subtropical evergreen forest, midlatitude deciduous forest, needleleaf forest, and sclerophyll forest.

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.

Forest biome Biome that includes all regions of forest over the lands of the Earth.

LOW-LATITUDE RAINFOREST

Low-latitude rainforest, found in the equatorial and tropical latitude zones, consists of tall, closely spaced trees (FIGURE 17.6). 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.

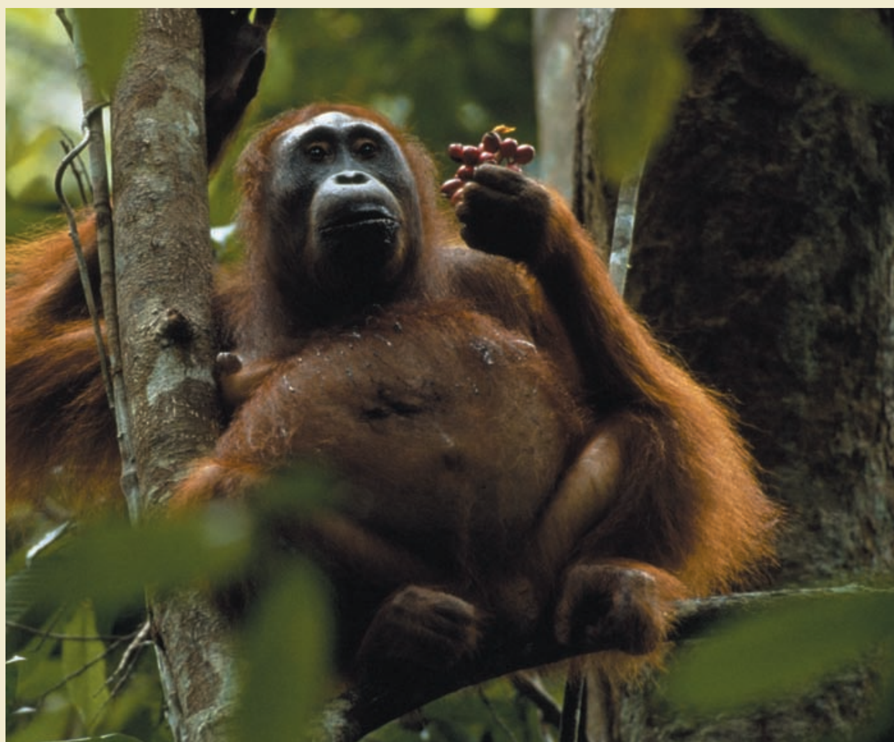
FIGURE 17.7 shows the world distribution of low-latitude rainforests. These rainforests develop in a climate that is continuously warm, frost-free, and has abundant precipitation in all months of the year (or, at most, has only one or two dry months). These conditions occur in the wet equatorial climate ① and the monsoon and trade-wind coastal climate ②. Plants grow continuously throughout the year.

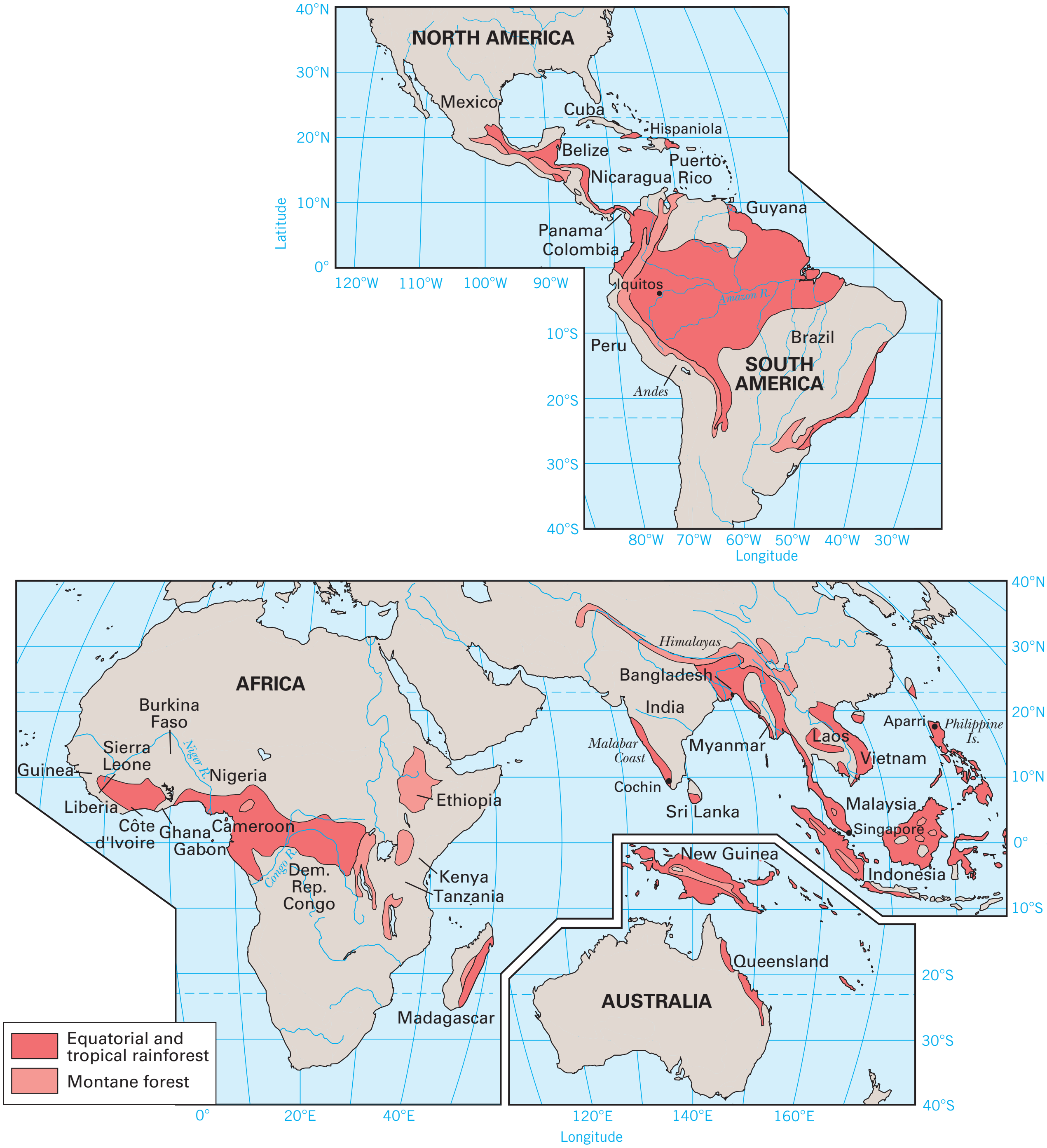
A particularly important characteristic of the low-latitude rainforest is the large number of species of plants and animals that coexist. Equatorial rainforests contain as many as 3000 tree species within a few square

Rainforest FIGURE 17.6

A Rainforest 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.

B Rainforest dweller Many animal species of the rainforest are adapted to arborescent life. Here an orangutan in Gunung Palung National Park, Borneo, Indonesia, snacks on *Polyalthia* fruit high above the forest floor. Toucans, parrots, and fruit-eating bats also exploit the resources of the rainforest canopy.





Low-latitude rainforest FIGURE 17.7

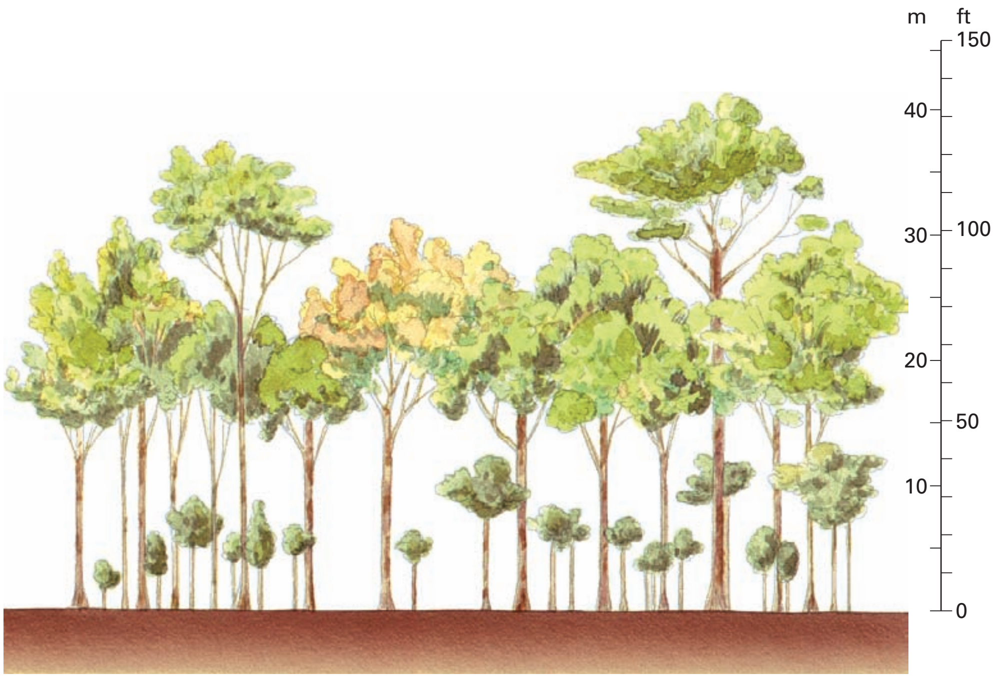
World map of low-latitude rainforest, showing equatorial and tropical rainforest types. A large area of rainforest lies astride the equator and extends poleward through the tropical zone (lat. 10° to 25° N and S) along monsoon and trade-wind coasts. Within the low-latitude rainforest are many highland 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.

kilometers. The trees define a number of distinct rainforest layers (FIGURE 17.8).

Biologists haven't yet identified many of the plants and animals that live in the low-latitude rainforests. These areas, and the species within them, are now under threat. Slowly but surely, the rainforest is being conquered by logging, clearcutting, and conversion to grazing and farming.

MONSOON FOREST

Monsoon forest is typically open. It grades into woodland, with open areas occupied by shrubs and grasses (FIGURE 17.9). 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.



Rainforest layers FIGURE 17.8

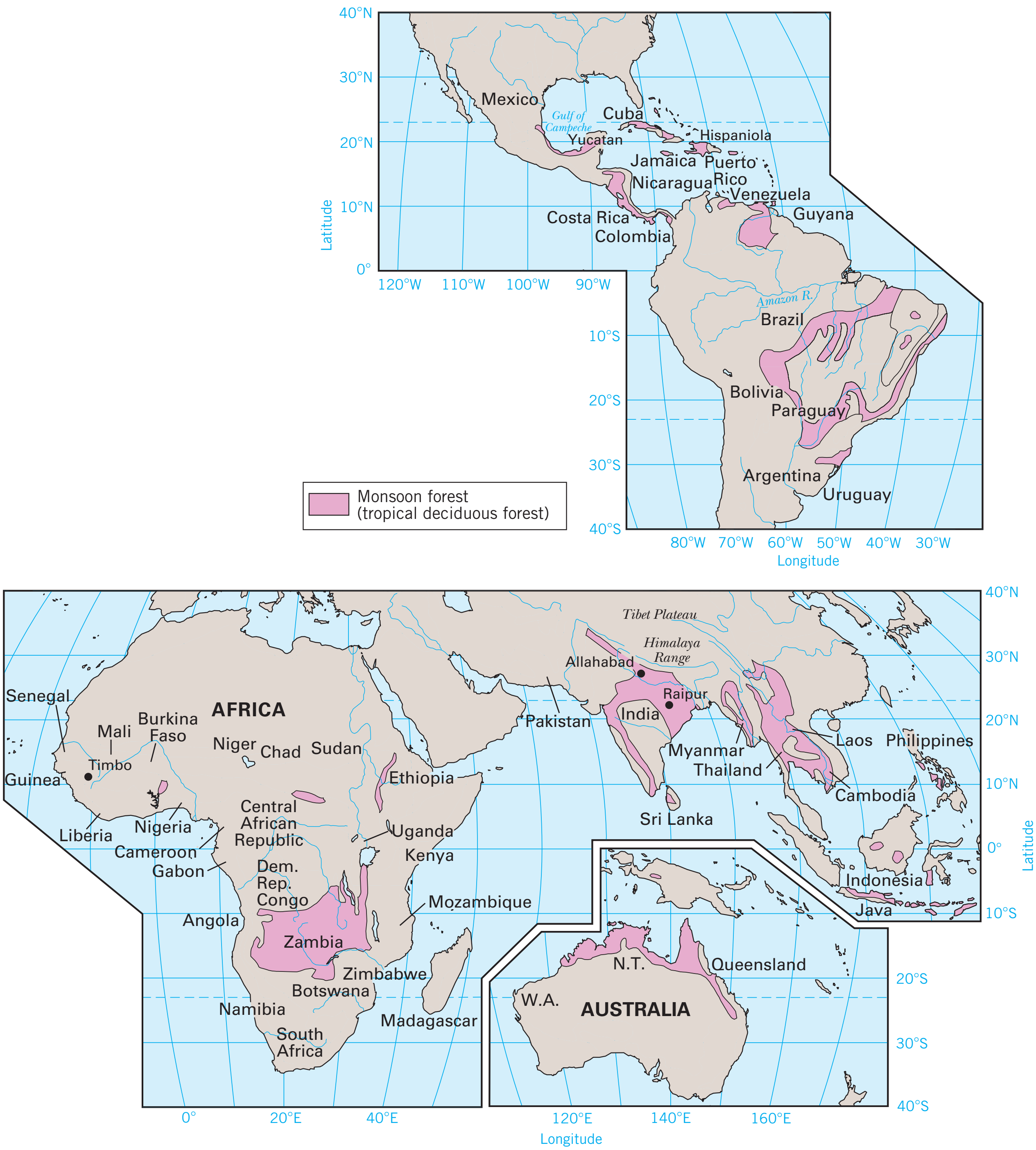
This diagram shows the typical structure of equatorial rainforest. Crowns of the trees of the low-latitude rainforest tend to form two or three layers. The highest layer consists of scattered "emergent" crowns that protrude from the closed canopy below, often rising to 40 m (130 ft). Some emergent species 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.

Monsoon woodland FIGURE 17.9

Because of its open nature, light easily reaches the lower layers of the monsoon forest, so these lower layers are better developed than in the rainforest. Tree heights are also lower. Tree trunks are massive, often with thick, rough bark. Branching starts at a comparatively low level and produces large, round crowns. Here a group of Asiatic wild dogs, called dholes, explores a road in Bandipur National Park, Karnataka, India.

FIGURE 17.10 is a world map of the monsoon forest. This forest develops in the wet-dry tropical climate ③ in which a long rainy season alternates with a dry, rather cool season. The typical regions of monsoon forest are in Myanmar, Thailand, and Cambodia. Large areas of monsoon forest also occur in south-central Africa and in Central and South America, bordering the equatorial and tropical rainforests.

World map of monsoon forest FIGURE 17.10



SUBTROPICAL EVERGREEN FOREST

Subtropical evergreen forest is generally found in regions of moist subtropical climate ⑥, where winters are mild and there is ample rainfall throughout the year (FIGURE 17.11). This forest occurs in two forms: broadleaf and needleleaf. The *subtropical broadleaf evergreen forest* doesn't have as many tree species as the low-latitude rainforests, which are also broadleaf evergreen types. Trees are also not as tall as in the low-latitude

Subtropical evergreen forest FIGURE 17.11

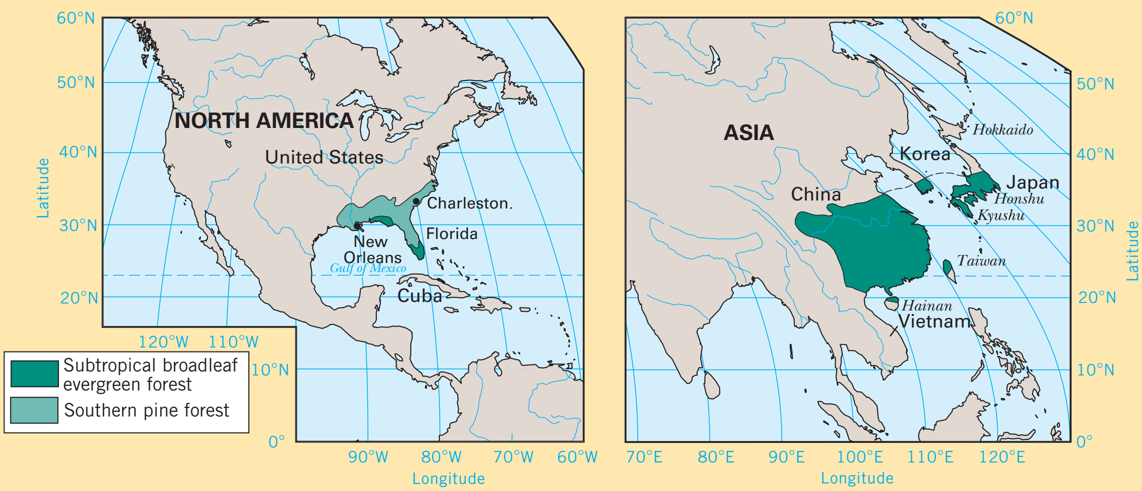
This forest of mild and moist climates includes both broadleaf and needleleaf types.

A Broadleaf Here broadleaved species dominate over a lower layer of smaller plants. This example is from New South Wales, Australia, and includes many species of Eucalyptus.

B 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.

Subtropical evergreen forest FIGURE 17.12

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.



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.

FIGURE 17.12 is a map of 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.

MIDLATITUDE DECIDUOUS FOREST

Midlatitude deciduous forest is the native forest type of eastern North America and Western Europe (FIGURE 17.13). 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 lowermost 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.

Deciduous forest FIGURE 17.13

A Trees of the forest 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. Shown here is a forest of maple, oak, and hickory in fall colors. Monongahela National Forest, West Virginia.

B 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.

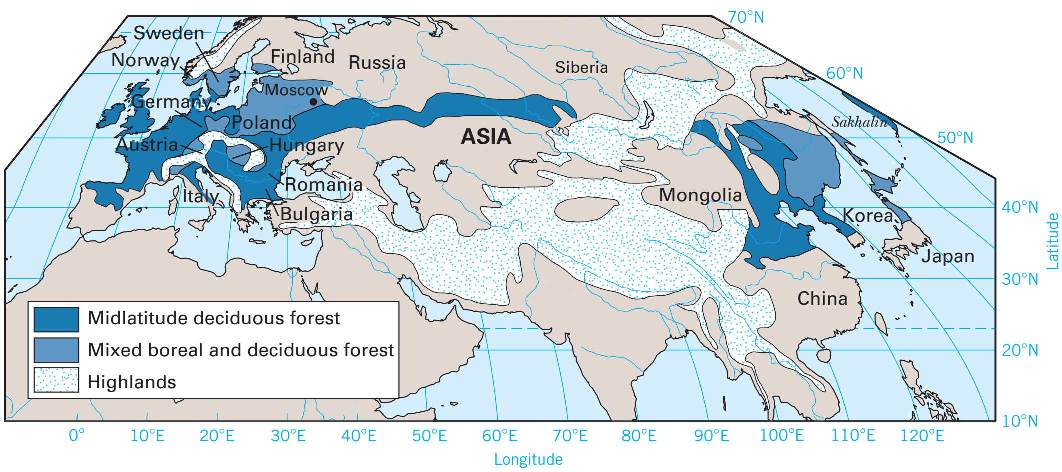
C Woodchuck Many small mammals burrow in forest soils for shelter or food, including the woodchuck, or groundhog, shown here. They are joined by ground squirrels, mice, and shrews.

D 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.

FIGURE 17.14 is a map of midlatitude deciduous forests, which are found almost entirely in the northern hemisphere. Throughout much of its range, this forest type is associated with the moist continental climate ⑩. This climate receives adequate 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.

Midlatitude deciduous forest FIGURE 17.14

Northern hemisphere map of midlatitude deciduous forests. 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.



NEEDLELEAF FOREST

Needleleaf forest is composed largely of straight-trunked, cone-shaped trees with relatively short branches and small, narrow, needle-like leaves (FIGURE 17.15). These trees are conifers. Most are evergreen, retaining their needles for several years before shedding them. 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. Species are few—in fact, large tracts of needleleaf forest consist almost entirely of only one or two species.

Boreal forest is the cold-climate needleleaf forest of high latitudes. It occurs in two great continental belts, one in North America and one in Eurasia (FIGURE 17.16). These belts 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.

Mammals of the boreal needleleaf forest in North America include deer, moose, elk, black bear, marten, mink, wolf, wolverine, and fisher. Common birds include jays, ravens, chickadees, nuthatches, and a number of warblers. The caribou, lemming, and snowshoe rabbit inhabit both needleleaf forest and the adjacent tundra biome. The boreal forest often experiences large fluctuations in animal species populations, a result of its highly variable environment.

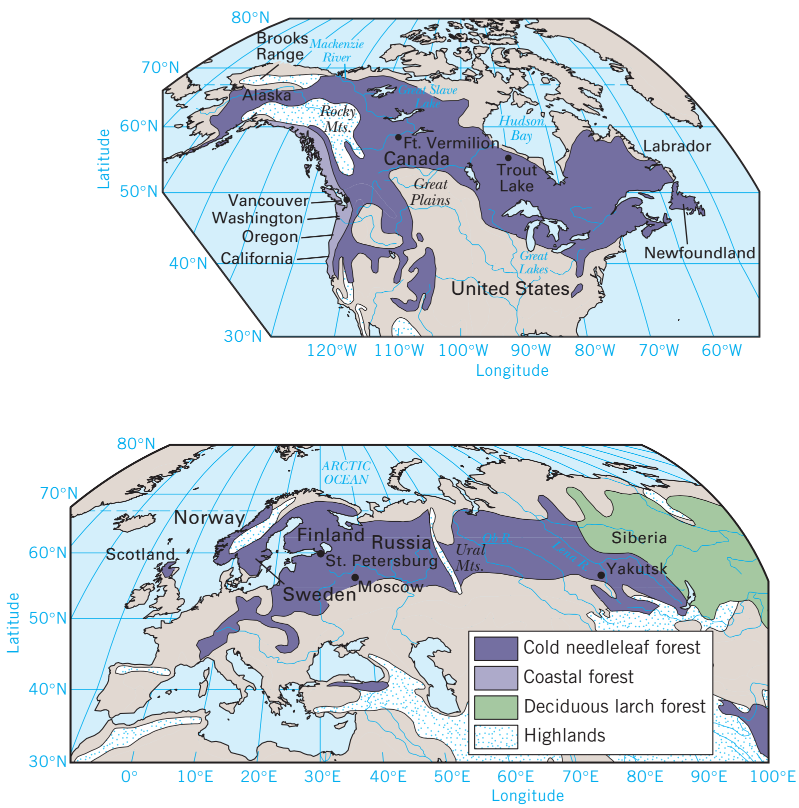
Coastal forest is a distinctive needleleaf evergreen forest of the Pacific Northwest coastal belt, ranging in latitude from northern California to southern Alaska (FIGURE 17.17).

Boreal forest FIGURE 17.15

A view of the boreal forest at the shore of Caribou Lake in the Mackenzie River Valley, Northwest Territories, Canada. Reds and yellows mark maples and deciduous birches in their fall colors. The needleleaf trees are red and black spruce.

Needleleaf forest FIGURE 17.16

Northern hemisphere map of cold-climate needleleaf forests, including coastal forest.



Coastal forest FIGURE 17.17

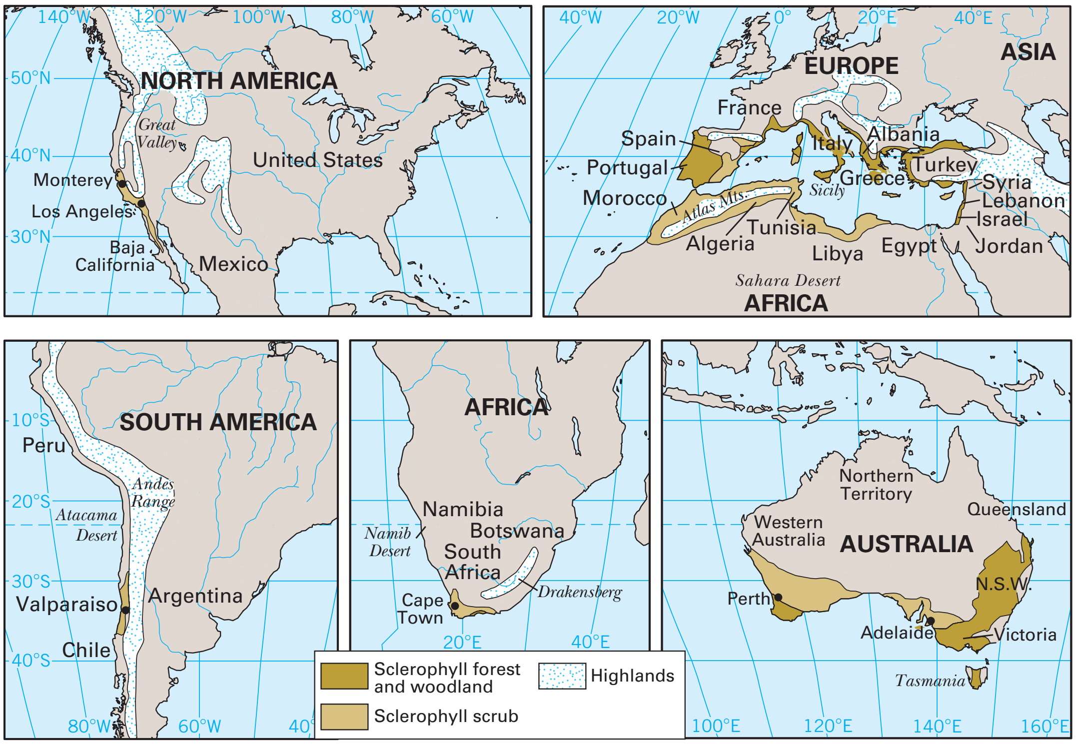
Along the western coast of North America from central California to Alaska, in a band of heavy orographic precipitation, mild temperatures, and high humidity, is a forest dominated by many unique species of needleleaf trees. Shown here is the coast redwood, *Sequoia sempervirens*, which is found at the 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.

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 17.18**, includes forest, woodland, and scrub types. Over the centuries, human activity has reduced the sclerophyll forest to woodland or destroyed it entirely. To-



Sclerophyll forest Figure 17.18

Sclerophyll forest is closely associated with the Mediterranean climate ⑦ and is narrowly limited to west coasts between 30° and 40°–45° N and S latitude. 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. The other northern hemisphere region of sclerophyll vegetation is the California coast ranges. 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.

Chaparral FIGURE 17.19

Chaparral varies in composition with elevation and exposure. It may contain wild lilac, as shown here in bloom, manzanita, mountain mahogany, poison oak, and live oak.

day, large areas of this former forest consist of dense scrub. In the California coastal range, the sclerophyll forest or woodland is typically dominated by live oak and white oak. Grassland occupies the open ground between the scattered oaks. Much of the remaining vegetation is sclerophyll scrub or "dwarf forest," known as *chaparral* (FIGURE 17.19).

CONCEPT CHECK STOP

What is the forest biome?

List the six formations of forest biome.

Savanna and Grassland Biomes

LEARNING OBJECTIVES

Define savanna biome and grassland biome.

Describe the climate, plants, and animals of the 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's too little soil moisture during the dry season to support a full tree cover (FIGURE 17.20). 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.

Savanna biome Biome that consists of a combination of trees and grassland in various proportions.

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 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 17.21. In Africa, the savanna woodland grades into a belt of *thorntree-tall-grass savanna*, a formation class transitional to the desert biome. 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 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.

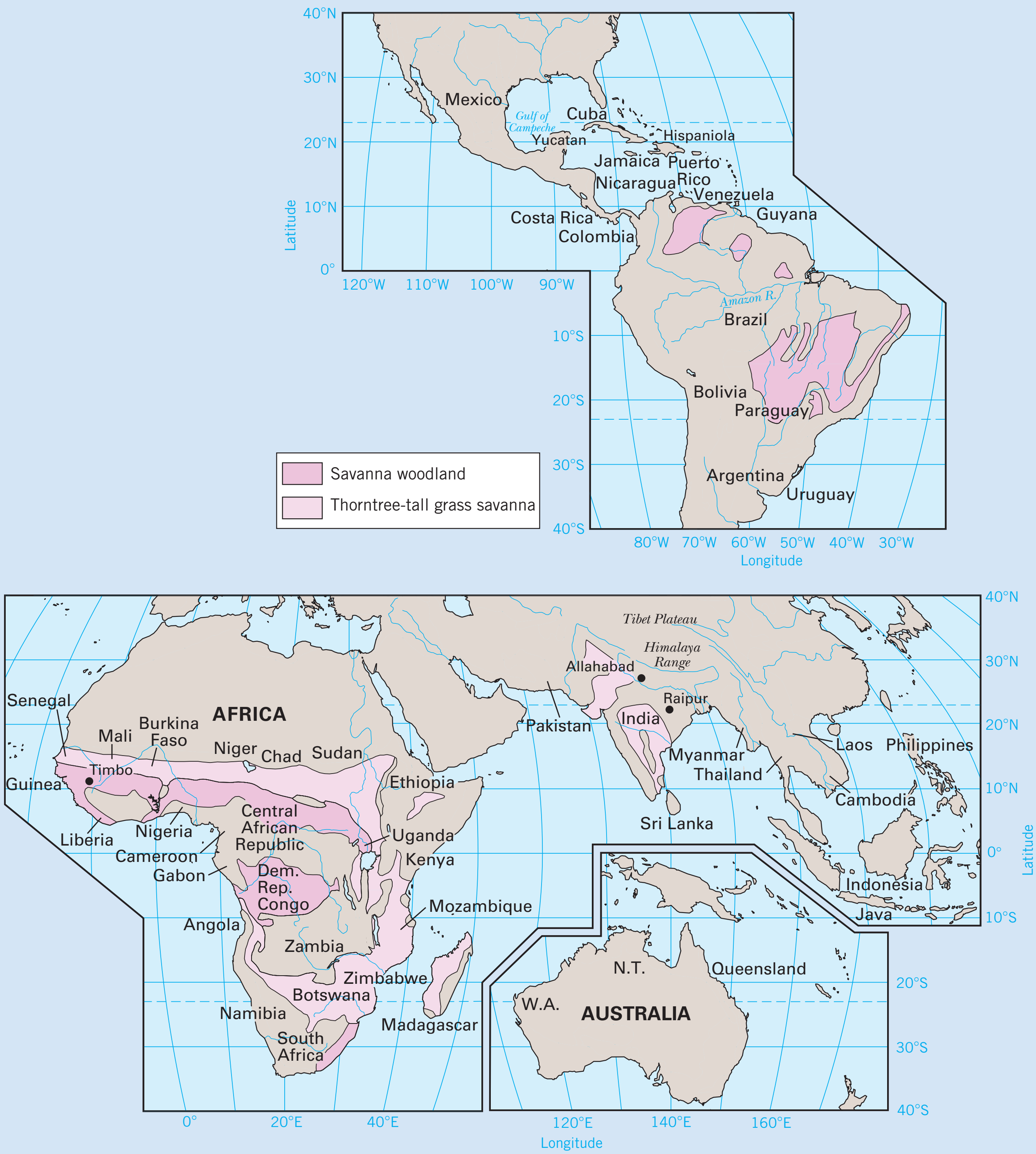
Savanna biome vegetation is described as raingreen. That's because the thorntree-tall-grass savanna is closely identified with the semiarid subtype of the dry tropical and subtropical climates (④*s*, ⑤*s*). In the semiarid climate, soil-water storage is only enough for plants during the brief rainy season. After rains begin, the trees and grasses quickly green. Vegetation of the monsoon forest is also rain-green.

Savanna FIGURE 17.20

A 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.

B Thorntree-tall-grass savanna The long dry season of the wet-dry climate 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.

World map of savanna woodland and thorntree-tall-grass savanna FIGURE 17.21



The African savanna is widely known for the diversity of its large grazing mammals (FIGURE 17.22). 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.

Animals of the African savanna

FIGURE 17.22

A **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.

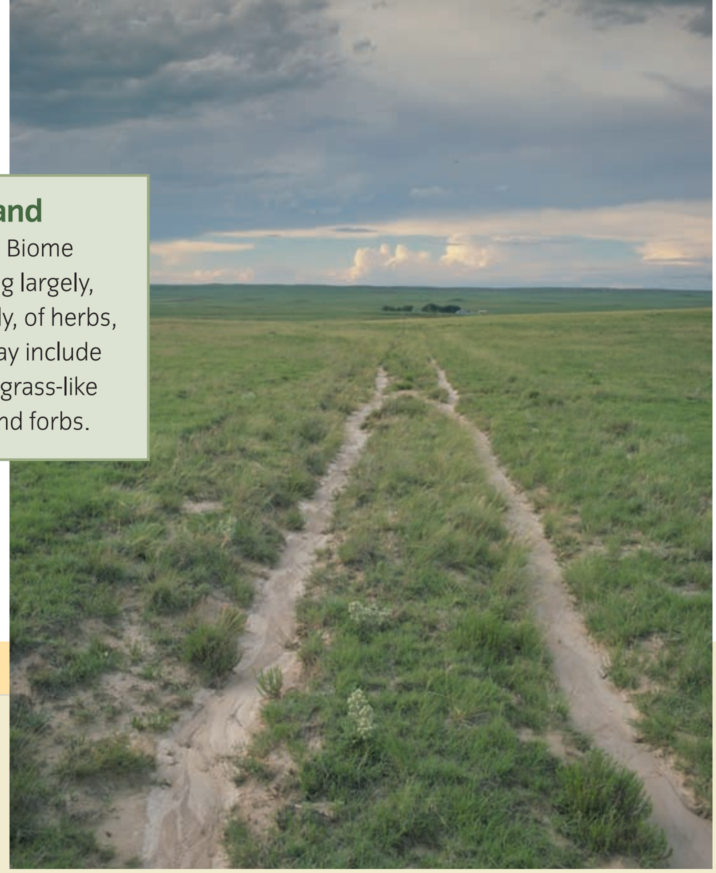
B **Lions** The abundance of large grazing herbivores brings predators, including the lion. Shown here is a pride of lions on a walk through the tall grass of Masai Mara National Reserve, Kenya.

C **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 dead gazelle in its vise-grip jaws. Masai Mara National Reserve, Kenya.

GRASSLAND BIOME

The **grassland biome** includes two major formation classes that we will discuss here—tall-grass prairie and steppe (FIGURE 17.23). *Tall-grass prairie* is made of largely tall grasses. There are also some broad-leaved herbs, named *forbs*. We don't see trees or shrubs in the prairie, but they do occur in narrow patches of forest in stream valleys. FIGURE 17.24 shows the distribution of grassland around the world.

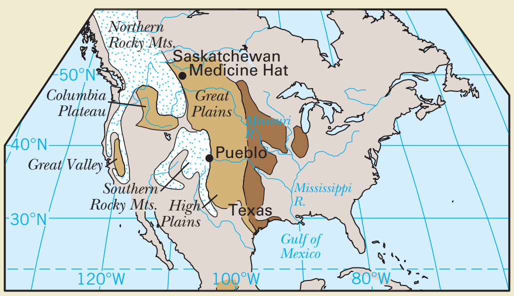
Grassland biome Biome consisting largely, or entirely, of herbs, which may include grasses, grass-like plants, and forbs.

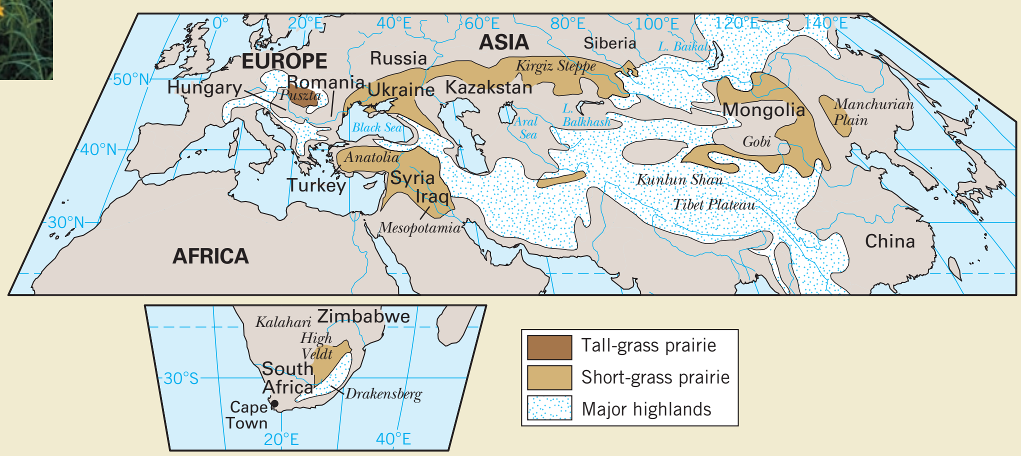


Grasslands FIGURE 17.23

A 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.

B 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.





World map of grassland FIGURE 17.24

World map of the grassland biome in subtropical and midlatitude zones. Prairie grasslands are associated with the drier areas of moist continental climate ⑩. The 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. Steppe grasslands correspond well with the semiarid subtype of the dry continental climate ⑨.

Grassland animals FIGURE 17.25

▲ **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.

▲ **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.

▲ **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.

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 17.25). 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 with the burrows of rodents, where extremes of moisture and temperature are substantially moderated.

CONCEPT CHECK STOP

What is the savanna biome?

Why can't many rainforest tree species establish themselves in the savanna biome?

What is the grassland biome?

What formation classes do we find in the grassland biome?

Desert and Tundra Biomes

LEARNING OBJECTIVES

Define desert biome and tundra biome.

Describe the climate, plants, and animals of the 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. Here we recognize two basic formation classes: semidesert and dry desert.

Desert biome Biome of the dry climates consisting of thinly dispersed plants that may be shrubs, grasses, or perennial herbs, but lacking in trees.

Semidesert is found in a wide latitude range—from the tropical zone to the midlatitude zone (FIGURE 17.26). The arid subtypes of all three dry climates can be thought of as semidesert. 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** 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.

▼ **Sagebrush semidesert** Sparse grasses and shrubs, largely sagebrush, provide the vegetation cover near Monument Valley, Arizona. You can also see mesas and buttes.

Desert vegetation FIGURE 17.26

▲ **Kangaroo rat** This small, noctural 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.

▲ **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.

Desert animals FIGURE 17.27

Thorntree semidesert of the tropical zone is made up of xerophytic trees and shrubs (FIGURE 17.26B). These plants are adapted to a climate 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 you can also see cactus plants.

Dry desert is a formation class of plants that are widely dispersed over only a very small proportion of the ground. It's made up 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 designated to desert vegetation on maps have no plant cover at all because the surface consists of shifting dune sands or sterile salt flats.

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. There, you can find the tree-like saguaro cactus, the prickly pear cactus, the ocotillo, creosote bush, and smoke tree. Desert animals, like the plants, are typically adapted to the dry conditions of the desert (FIGURE 17.27). FIGURE 17.28 is a world map of the desert biome.

Desert biome FIGURE 17.28

World map of the desert biome, including desert and semidesert formation classes.

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. We don't usually find large plants in the tundra. This is because frost action in the soil fractures and breaks large roots, keeping tundra plants small (FIGURE 17.29). In winter, wind-driven snow and extreme cold also injure plant parts that project above the snow.

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.

Arctic tundra in Lapland FIGURE 17.29

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.

▲ **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.

▲ **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.

◀ **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.

Animals of the tundra FIGURE 17.30

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.

There aren't many diverse species in the tundra, but there are a large number of individual animals (FIGURE 17.30). 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.

CONCEPT CHECK STOP

Define desert biome.

What are xerophytic plants?

Define tundra biome.

Name two formation classes of the tundra biome. Where would you find them?

What is happening in this picture ?

Natural vegetation near Phoenix, Arizona In this scene we can see the tall, columnar saguaro cactus and the delicate wand-like ocotillo plant.

- Small clumps of prickly pear cactus lie between groups of hard-leaved shrubs.
- What biome is this?
- Why are these plants well-suited to this biome?
- Look at the gravel-covered ground. Why would you expect to see coarse rock fragments such as these covering the ground, rather than finer particles?

VISUAL SUMMARY

1 Natural Vegetation

1. Natural vegetation is a plant cover that develops with little or no human interference.
2. The life-form of a plant refers to its physical structure, size, and shape. Life-forms include trees, shrubs, lianas, herbs, and lichens.
3. Climate changes gradually with latitude, and so biome changes are typically gradual.

2 Terrestrial Ecosystems—The Biomes

1. The largest unit of terrestrial ecosystems is the biome.
2. The five principal biomes are: forest, grassland, savanna, desert, and tundra.

3 Forest Biome

1. The low-latitude rainforest exhibits a dense canopy and open floor with a very large number of species.
2. Subtropical evergreen forest occurs in broadleaf and needleleaf forms in the moist subtropical climate ⑥.
3. Monsoon forest is largely deciduous, with most species shedding their leaves after the wet season.
4. Midlatitude deciduous forest is associated with the moist continental climate ⑩.
5. Needleleaf forest consists largely of evergreen conifers.
6. Sclerophyll forest, comprised of trees with small, hard, leathery leaves, is found in the Mediterranean climate ⑦ region.

4 Savanna and Grassland Biomes

1. The savanna biome consists of widely spaced trees with an understory, often of grasses. Dry-season fire is frequent, limiting the number of trees and encouraging the growth of grasses.
2. The grassland biome of midlatitude regions includes tall-grass prairie in moister environments and short-grass prairie, or steppe, in semiarid areas.

5 Desert and Tundra Biomes

1. Vegetation of the desert biome ranges from thorny shrubs and small trees to dry desert vegetation.
2. Tundra biome vegetation is limited largely to low herbs that are adapted to the severe drying cold.

KEY TERMS

- **natural vegetation** p. 518
- **life-form** p. 522
- **forest** p. 523
- **terrestrial ecosystem** p. 524
- **biome** p. 525
- **forest biome** p. 528
- **savanna biome** p. 537
- **grassland biome** p. 541
- **desert biome** p. 543
- **tundra biome** p. 546

CRITICAL AND CREATIVE THINKING QUESTIONS

1. Plant geographers describe vegetation by its overall structure and by the life-forms of individual plants. Define and differentiate the following terms: forest, woodland, tree, shrub, herb, liana, perennial, deciduous, evergreen, broadleaf, and needleleaf. Sketch a cross-section of a forest, including typical life-forms, and identify them with labels.

2. 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.

3. Monsoon forest and midlatitude deciduous forest are both deciduous but for different reasons. Compare the characteristics of these two formation classes and their climates.

4. 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?

5. 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?

6. 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?

7. Compare the two formation classes of the grassland biome. How do their climates differ?

8. Describe the vegetation types of the desert biome.

9. What are the features of arctic and alpine tundra? How does the cold tundra climate influence the vegetation cover?

SELF-TEST

1. Natural vegetation _______________.
   a. is a plant cover that develops with little or no human interference
   b. is a plant cover that develops with no human interference
   c. no longer exists as humans have affected every part of the globe's surface
   d. is an ideal state from which human modifications can be judged

2. Name the plant form in the photo, in which algae and fungi live together as a single plant structure.

3. The _______________ biome develops in regions with moderate shortages of soil water.
   a. forest
   b. savanna
   c. desert
   d. grassland

4. Which biome is represented by a sparse and open cover of trees with grasses and herbs underneath?
   a. forest
   b. desert
   c. grassland
   d. savanna

5. _______________ are plants that are well adapted to drought conditions.
   a. Forbs
   b. Xerophytes
   c. Deciduous trees
   d. Evergreens

6. Of the following climates, which has a strong wet-dry alternation and many xerophytic plants?
   a. Mediterranean
   b. tundra
   c. wet equatorial
   d. moist subtropical

7. ______________ include marine environments and the fresh-water environments of the lands.
   a. Marine ecosystems
   b. Aquatic ecosystems
   c. Terrestrial ecosystems
   d. Biomes

8. Biogeographers split the five principal biomes down further into smaller vegetation units, called ______________, using the life-form of plants.
   a. formation classes
   b. climate classes
   c. climax classes
   d. life-form classes

9. The diagram shows the layer structure of one type of forest. Identify the forest and the broad latitude zones in which it can be found.

10. A forest formation class with broadleaf and needleleaf forms is ______________.
   a. low-latitude forest
   b. monsoon forest
   c. midlatitude deciduous forest
   d. subtropical evergreen forest

11. Needleleaf forests are noted for ______________.
   a. generally having few tree species
   b. the low level of shade they provide
   c. evergreens that hold on to their needles for about a year
   d. poor quality pulp wood

12. The ______________ is dominated by low trees with thick, leathery leaves that are well-adapted to the long summer drought of the Mediterranean climate.
   a. deciduous forest
   b. coastal forest
   c. low-latitude rainforest
   d. sclerophyll forest

13. Many plants of the ______________ grow, bloom and set seed during a short summer thaw following harsh cold winters.
   a. desert biome
   b. tundra biome
   c. grassland biome
   d. savanna biome

14. Which major formation class found in the grassland biome is shown in this photo? In what type of climate would you expect to find it?

15. A problem with maps in the display of natural features is that ______________.
   a. they create a large amount of distortion
   b. it is impossible to display a natural feature on a map
   c. many boundaries are approximate and gradational
   d. maps are two-dimensional

APPENDIX ANSWERS TO SELF-TESTS

Chapter 1: **1c.** oblate ellipsoid; **2c.** rotates, revolves; **3.** Lat. 50° N, long. 60° W.; **4b.** distortion; **5c.** polar, straight; **6c.** Mercator; **7b.** Goode; **8d.** Standard, 15; **9.** It will be 9 A.M. in Chicago. Mumbai lies along the 82.5° E meridian.; **10c.** correspond more closely with the modern pace of society and is accomplished by moving the clock ahead one hour; **11c.** elliptical, 365 $\frac{1}{4}$; **12d.** 23 1/2 degrees from a perpendicular to the plane of the ecliptic; **13c.** circle of illumination; **14a.** North and South Poles; **15.** Winter solstice. The subsolar point lies on the Tropic of Capricorn at this time. See Figure 1.24.

Chapter 2: **1.** See Figure 2.3; **2a.** hotter; cooler; **3d.** ultraviolet radiation; **4c.** longwave radiation; **5a.** angle at which the insolation is received by the Earth's surface; **6b.** equatorial; **7a.** polar; **8.** See Figure 2.10; **9c.** O3; **10c.** chlorofluorocarbons (CFCs); **11d.** by conduction and/or convection; **12a.** diffuse radiation; **13c.** albedo; **14b.** upwards, in all directions; **15c.** Counterradiation, greenhouse effect; **16b.** Poleward heat transfer

Chapter 3: **1a.** a measure of the level of sensible heat of matter; **2c.** convection; **3c.** downtown areas are always warmer; **4b.** drier surfaces have less water to evaporate than do moist soils; **5a.** more transpiration is occurring in the city than in the surrounding country side; **6.** See Figure 3.8. Temperature inversions can cause killing frosts. To combat these, growers use fans to mix warmer and cooler air, and also use oil-burning heaters; **7b.** shortly after sunrise; **8d.** about one-half hour after sunrise; **9b.** stronger; **10f.** slowly; **11d.** Isotherms; **12c.** environmental temperature lapse rate; **13a.** homosphere; **14.** See Figure 3.19; **15a.** aerosols

Chapter 4: **1a.** atmospheric water; **2c.** hydrologic cycle; **3.** See Figure 4.1; **4d.** is the amount of water vapor in the air compared to the amount it could hold; **5c.** specific humidity; **6.** The air mass cools. Adiabatic temperature change; **7d.** wet adiabatic lapse rate; dry adiabatic lapse rate; **8.** Cirrus. High; **9d.** sleet; **10b.** orographic; **11a.** convective; **12c.** warm, moist air and an environmental lapse rate with an absolute value greater than the wet and dry rates; **13c.** polycarbonates; **14d.** 20; **15c.** nitric oxide

Chapter 5: **1a.** air pressure; **2d.** harder it is to breathe because the air is thinner; **3c.** air pressure is less at higher elevations; **4.** See Figure 5.6; **5a.** at night, when the land cools below the surface temperature of the sea; **6b.** frictional; **7b.** a result of the Earth's rotation from the west to the east and causes objects to curve to the right in the Northern Hemisphere; **8.** See Figure 5.12; **9d.** cyclones; **10c.** subtropical high-pressure cells; **11c.** monsoon; **12a.** geostrophic wind; **13b.** narrow zones at a high altitude in which wind streams sometimes reach speeds of over 150 miles per hour; **14.** See Figure 5.21; **15d.** ocean currents in the southern Pacific Ocean

Chapter 6: **1b.** Continental polar; **2.** See Figure 6.2; **3c.** cold front ; **4d.** cyclones, anticyclones; **5.** Occluded front; **6a.** anticyclone; **7b.** tornado; **8c.** convectional in nature; **9d.** a cold front with squalls; **10c.** eight to fifteen degrees North and South; **11b.** South American; **12a.** storm surge; **13.** Wave cyclones. See Process Diagram: Wave cyclones, block A; **14d.** a net cooling of the planet; **15d.** acts as a greenhouse gas and emits longwave radiation

Chapter 7: **1.** Walvis Bay lies near the coast, whereas In Salah is inland; **2d.** a very strong temperature cycle; **3d.** stationary subtropical cells of high pressure; **4a.** extremely cold, dry air with high relative humidity; **5c.** a precipitation maximum during the low-Sun season; **6c.** cP; **7a.** polar-front zone; **8c.** northern; **9.** Joshua tree, dry subtropical climate ⑤. Plants adapted to dry climates; **10f.** no permanently flowing streams; **11c.** show no seasonal rainfall pattern; **12.** Boreal forest climate; **13d.** center; east sides; **14c.** Mediterranean; **15.** See Figures 7.29 (Pueblo, Colorado), 7.37 (Upernavik, Greenland), and 7.15 (Timbo, Guinea).

Chapter 8: **1.** See Figure 8.1; **2b.** mineral; **3a.** large mineral crystals; **4b.** quartzite; **5a.** Sedimentary rocks; **6c.** plate tectonics; **7d.** asthenosphere; **8d.** Precambrian; **9a.** 18 minutes; **10.** Folding occurs when plates are compressed (converging plates). Rifting occurs when plates are pulled apart (separating oceanic plates).; **11c.** midocean ridge, axial rift; **12a.** passive; active; **13d.** subduction; **14c.** Converging, subduction; **15c.** Pangea

Chapter 9: **1b.** viscosity; **2a.** caldera; **3c.** lahar; **4.** See Process Diagram: Hotspot Volcano Chain; **5a.** compressional and extensional; **6a.** anticlines and synclines; **7.** Reverse; **8.** Graben, horst; **9d.** Reverse; **10d.** focus; **11d.** mesa; **12a.** consequent stream; **13c.** cuestas; **14a.** a circular structure in which strata have been forced upward; **15.** See Figure 9.20c

Chapter 10: **1c.** weathering; **2.** See Figure 10.8; **3b.** Mass wasting; **4d.** Regolith; **5c.** niche; **6a.** carbonic acid, carbonate sedimentary rocks; **7a.** earthflow; **8a.** landslide, earthquake; **9c.** lahars; **10c.** periglacial; **11b.** ground ice; **12c.** active; **13a.** permafrost table; **14a.** ice-wedge polygons; **15b.** pingo; **16a.** thermokarst lakes

Chapter 11: **1.** See Figure 11.3; **2b.** under the highest areas of land surface; **3c.** aquifer; **4b.** karst; **5c.** nonrenewable; **6a.** saltwater intrusion; **7c.** channel; **8.** See Figure 11.17; **9d.** discharge; **10d.** drainage basin; **11a.** the size of the drainage basin feeding the stream; **12d.** flood stage; **13.** small; steep; **14c.** lakes; **15a.** salt buildup

Chapter 12: **1d.** running water; **2b.** erosional; **3a.** rill erosion; **4b.** alluvium; **5c.** abrasion; **6d.** corrosion; **7.** See Figure 12.6. Dissolved load.; **8c.** stream capacity; **9b.** turbulence;

10f. exceeds; **11c.** a reduced ability of the stream to carry bed load; **12c.** graded stream; **13a.** block faulting of large crustal blocks; **14b.** aggradation; **15.** See Figure 12.12

Chapter 13: **1c.** shoreline, coastline; **2a.** estuary; **3d.** wave; **4.** wave-cut niche

5b. progradation; **6c.** beach drift and longshore drift; **7b.** ebb and flood; **8.** ria coast; **9c.** lagoons; **10f.** delta; **11b.** coral-reef; **12d.** Desert pavement, loess; **13a.** barchan; **14d.** erg; **15c.** star

Chapter 14: **1c.** The ice mass must become so thick that the bottom layers become plastic.; **2.** See Figure 14.4; **3.** Surface midline regions. Meltwater may cause the glacier to slip more easily, and surge; **4b.** Glacial abrasion; **5a.** arête ; **6c.** terminal moraine; **7a.** North Pole; **8b.** Icebergs; **9c.** ice age; **10.** See Figure 14.13b; **11c.** pluvial; **12d.** glacial till is often stony and hard to cultivate; **13d.** all of the above; **14c.** both a and b; **15a.** Holocene Epoch

Chapter 15: **1d.** humus; **2c.** parent material; **3.** See Figure 15.5 ; **4a.** cold, humid; **5b.** high clay content; **6d.** percolates down to the ground-water zone; **7.** See Figure 15.9. Soil profile.; **8d.** translocation; **9a.** cold, warm; **10d.** Aridisols; **11c.** Inceptisols; **12.** Ultisol; **13a.** Vertisols; **14b.** Andisols; **15.** Spodosol. In regions covered by ice sheets during the Pleistocene Epoch.

Chapter 16: **1c.** primary producers; **2c.** denitrification; **3b.** Ecological niche; **4a.** light; **5.** Spines help the plant conserve water in drought conditions. Xerophytes; **6a.** soil texture; **7b.** allelopathy; **8.** The orchid needs the eucalyptus for support. a. commensalism ; **9c.** protocooperation; **10.** Between 1907 and 1924 the deer population grew because the government controlled predation. But in the 1930s, the population was too large to sustain, and crashed back down to a stable level that the environment could support; **11b.** secondary succession;12 e. a and b; **13a.** allopatric speciation; **14c.** endemic;15a. tropical and equatorial regions

Chapter 17: **1a.** is a plant cover that develops with little or no human interference; **2.** Lichen; **3d.** grassland; **4d.** savanna; **5b.** Xerophytes; **6a.** Mediterranean; **7b.** Aquatic ecosystems; **8a.** formation classes; **9.** Low-latitude rainforest. Equatorial and tropical latitude zones.; **10d.** subtropical evergreen forest; **11a.** their lack of species; **12d.** sclerophyll forest; **13b.** tundra biome; **14.** Tall-grass prairie. Moist continental climate ⑩; **15c.** many boundaries are approximate and gradational

GLOSSARY

This glossary contains definitions of terms shown in the text in italics or boldface.

A horizon mineral horizon of the soil, overlying the E and B horizons

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 stream bed; abrasion is also an activity of glacial ice, waves, and wind

absorption process in which electromagnetic energy is transferred to heat energy when radiation strikes molecules or particles in a gas, liquid, or solid

acid mine drainage sulfuric acid effluent from coal mines, mine tailings, or spoil ridges made by strip mining

active continental margins continental margins that coincide with tectonically active plate boundaries

active layer shallow surface layer subject to seasonal thawing in permafrost regions

adiabatic principle the physical principle that a gas cools as it expands and warms as it is compressed, provided that no heat flows in 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

aerosols tiny particles present in the atmosphere, so small and light that the slightest air movements keep them aloft

aggradation raising of stream channel altitude by continued deposition of bed load

air mass extensive body of air in which temperature and moisture characteristics are fairly uniform over a large area

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


aerosols


albedo

albedo proportion of solar radiation reflected upward from a surface

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

alleopathy 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

alluvial meanders sinuous bends of a graded stream flowing in the alluvial deposit of a floodplain

alluvial river stream of low gradient flowing upon 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 sediment laid by a stream that is found in a stream channel or 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 avalanches debris flood of steep mountain slopes, often laden with tree trunks, limbs, and large boulders

alpine glacier long, narrow mountain glacier occupying the floor of a trough-like valley

alpine tundra a plant formation class within the tundra biome, found at high altitudes above the limit of tree growth

Andisols a soil order that includes soils formed on volcanic ash; often enriched by organic matter, yielding a dark soil color


anticline

annuals plants that live only a single growing season, passing the unfavorable season as a seed or spore

anticline upfold of layered rock in an arch-like structure

anticyclone center of high atmospheric pressure

aphelion point on the Earth's elliptical orbit at which the Earth is farthest from the Sun

aquiclude rock mass or layer that impedes or prevents the movement of ground water

aquifer layers of rock or sediment that contain a lot of freely flowing ground water

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

arête sharp, knife-like divide or crest formed between two cirques by alpine glaciation

arid (dry climate subtype) subtype of the dry climates that is extremely dry and supports little or no vegetation cover

Aridisols 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

asthenosphere soft layer of the upper mantle, beneath the rigid lithosphere

astronomical hypothesis explanation for glaciations and interglaciations based on cyclic variations in the solar energy received at the Earth's surface

atmosphere envelope of gases surrounding the Earth, held by gravity

atmospheric pressure pressure exerted by the atmosphere because of the force of gravity acting upon the overlying column of air

atoll circular or closed-loop coral reef enclosing an open lagoon with no island inside

autogenic (self-producing) succession form of ecological succession that is self-producing—that is, results from the actions of plants and animals themselves

autumnal (September) equinox equinox occurring on September 22 or 23

axial rift narrow, trench-like depression situated along the center line of the midoceanic ridge and identified with active seafloor spreading


atmosphere

axis an imaginary straight line through the center and the poles of Earth

B horizon horizon mineral soil horizon located beneath the A or E horizon, and usually characterized by a gain of mineral matter (such as clay minerals and oxides of aluminum and iron) and organic matter (humus)

backswamps 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

barchan dune sand dune of crescentic base outline with a sharp crest and a steep lee slip face, with crescent points (horns) pointing downwind

barometer instrument that measures atmospheric pressure

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 reefs 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

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 positively charged plant nutrient ions

batholith large, deep-seated body of intrusive igneous rock, usually with an area of surface exposure greater than 100 km^2 (40 mi^2)

Beach thick, wedge-shaped deposit of sand, gravel, or cobbles in the zone of breaking waves

bedrock solid rock layer under soil and regolith, which is relatively unchanged by weathering

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

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 distribution patterns of organisms over space and time and of the processes that produced these patterns

biomass dry weight of living organic matter in an ecosystem within a designated surface area

biome largest recognizable subdivision of terrestrial ecosystems

biosphere all living organisms of the Earth and the environments with which they interact

block mountains class of mountains produced by block faulting and usually bounded by normal faults

blowout shallow depression produced by continued deflation

bluffs steeply rising ground slopes marking the outer limits of a floodplain

Boralfs suborder of the soil order Alfisols; includes Alfisols of boreal forests or high mountains

boreal forest climate ⑪ cold climate of the subarctic zone in the northern hemisphere with long, extremely severe winters and several consecutive months of frozen ground

Borolls suborder of the soil order Mollisols; includes Mollisols of cold-winter semiarid plains (steppes) or high mountains

butte prominent, steep-sided hill or peak, often representing the final remnant of a resistant layer in a region of flat-lying strata

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

caldera large, steep-sided circular depression resulting from the explosion and subsidence of a stratovolcano

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

carbon cycle biogeochemical cycle in which carbon moves through the biosphere

carbon fixation (See photosynthesis.)

chaparral sclerophyll scrub and dwarf forest plant formation class found throughout the coastal mountain ranges and hills of central and Southern California

chemical weathering chemical change in rock minerals through exposure to the atmosphere and water

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

chlorophyll pigment that absorbs sunlight during photosynthesis; often found in plants, algae, and some bacteria

clast rock or mineral fragment broken from a parent rock source

clastic sediment sediment consisting of particles broken away physically from a parent rock source

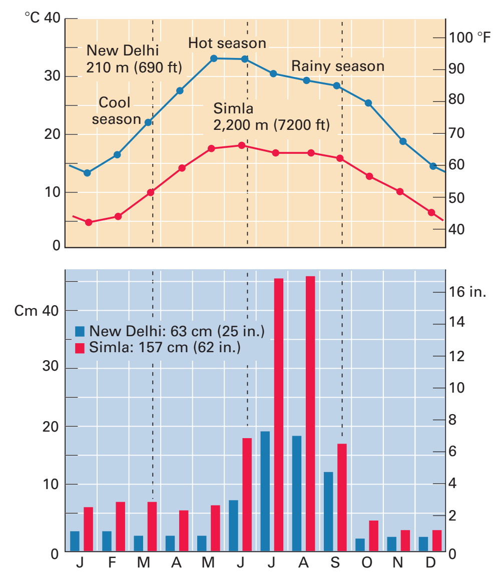
clay minerals class of minerals produced by alteration of silicate minerals, having plastic properties when moist

climate the annual cycle of prevailing weather conditions at a given place, based on statistics taken over a long period

climax stable community of plants and animals reached at the end point of ecological succession

climograph graph on which two or more climate variables are plotted for each month of the year

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



climatograph

coastline (coast) zone in which coastal processes operate or have a strong influence

col natural pass or low notch in an arête between opposed cirques

cold front moving weather front along which a cold air mass moves underneath a warm air mass, lifting the warm air mass

cold-blooded animal animal whose body temperature passively follows the temperature of the environment

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.)


commensalism

commensalism symbiotic relationship in which one organism is benefited and the other is neither benefited nor harmed

competition form of interaction among plant or animal species in which both draw resources from the same pool

compressional tectonic activity squeezing together, as horizontal compression of crustal layers by tectonic processes

condensation nucleus a tiny bit of solid matter (aerosol) in the atmosphere on which water vapor condenses to form a tiny water droplet

cone of depression conical configuration of the lowered water table around a well from which water is being rapidly withdrawn

consequent streams stream that takes its course down the slope of an initial landform, such as a newly emerged coastal plain or a volcano

continental crust crust of the continents, of felsic composition in the upper part; thicker and less dense than oceanic crust

continental shields ancient crustal rock masses of the continents, largely igneous rock and metamorphic rock, and mostly of Precambrian age

continental suture long, narrow zone of crustal deformation produced by a continental collision; examples: Himalayan Range, European Alps

convection loop circuit of moving fluid, such as air or water, created by unequal heating of the fluid

convectional precipitation 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

coral reef rock-like accumulation of carbonates secreted by corals and algae in shallow water along a marine shoreline

core spherical central mass of the Earth composed largely of iron; consists of an outer liquid zone and an inner solid zone

Coriolis effect effect of the Earth's rotation that acts like a force to deflect a moving object on the Earth's surface to the right in the northern hemisphere and to the left in the southern hemisphere

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 atmospheric radiation moving downward toward the Earth's surface

crescent dune (see barchan dune)

cross-bedding inclined sedimentary structures in a horizontal unit of sediment or rock; often found on the slip faces of moving dunes

crust outermost solid layer of the Earth, composed largely of silicate materials

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

cumuliform cloud clouds of globular shape, often with extended vertical development

cumulus cloud type consisting of low-lying, white cloud masses of globular shape well separated from one another

cyclone center of low atmospheric pressure

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

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 upon steep mountain watersheds

December solstice (see winter solstice)

deciduous tree or shrub that sheds its leaves seasonally

declination of Sun latitude at which the Sun is directly overhead; varies from –23 1/2° (23 1/2° S lat.) to +23 1/2° N lat.

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)

delta sediment deposit built by a stream entering a body of standing water

dentrification chemical reduction of nitrates to nitrites, ammonia, and free nitrogen in the soil under anaerobic conditions

depositional landforms landforms made by the 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


desert pavement

dew-point temperature temperature at which air with a given humidity will reach saturation when cooled without changing its pressure

diffusion the slow extension of the range of a species by normal processes of dispersal

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 cubic meters (feet) per second

disjunction geographic distribution pattern of species in which one or more closely related species are found in widely separated regions

dispersal the capacity of a species to move from a location of birth or origin to new sites

distributary branching stream channel that crosses a delta to discharge into open water

doldrums belt of calms and variable winds occurring at times along the equatorial trough

drainage basin total land surface occupied by a drainage system, bounded by a drainage divide or watershed

drainage divide imaginary line following a crest of high land such that overland flow on opposite sides of the line enters different streams

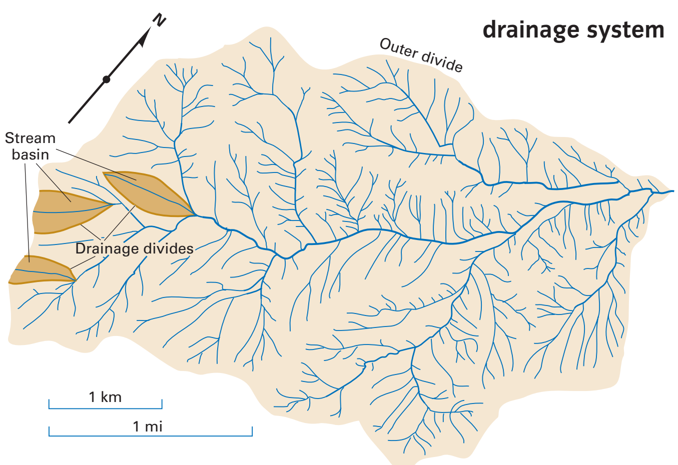
drainage system a branched network of stream channels and adjacent land slopes converging to a single channel at the outlet

drawdown difference in height between base of cone of depression and original water table surface

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 midlatitude climate ⑩ dry climate of the midlatitude zone with a strong annual temperature cycle and cold winters

dry subtropical climate ⑤ dry climate of the subtropical zone, transitional between the dry tropical climate and the dry midlatitude climate

dry tropical climate ④ climate of the tropical zone with high temperatures and low rainfall

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

earthflow moderately rapid downhill flow of water-saturated soil, regolith, or weak shale

earthquake a trembling or shaking of the ground produced by passing seismic waves

easterly wave weak, slowly moving trough of low pressure within the belt of tropical easterlies; causes a weather disturbance with rain showers

ecological biogeography field of biogeography examining how relationships between organisms and environment determines when and where organisms are found

ecological niche functional role of an organism within its community; its "profession"—how and where it obtains energy, how it influences other species and the environment around it

ecological 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, clear cutting, or other agents

ecosystem group of organisms and the environment with which they 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 wave-like form of energy radiated by any substance possessing heat; it travels through space at the speed of light

eluviation downward transport of fine particles, carrying them out of the upper soil horizons

emergence exposure of submarine landforms by a lowering of sea level or a rise of the crust, or both

endemic species a species found only in one region or location.

endogenic processes internal Earth processes that create landforms, such as tectonics and volcanism

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

eolian landforms landforms formed or deposited by the action of wind

equator parallel of latitude lying midway between the Earth's poles; it is designated latitude 0°

equatorial trough atmospheric low-pressure trough centered more or less over the equator and situated between the two belts of trade winds

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

erg large expanse of active sand dunes in the Sahara Desert of North Africa

erosional landforms landforms shaped by the removal of regolith or bedrock by erosion

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

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

evapotranspiration the combined water loss to the atmosphere by evaporation from soil and transpiration from plants

evergreen tree or shrub that holds most of its green leaves throughout the year

evolution the creation of diversity of life forms through the process of natural selection

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

extensional tectonic activity 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

extrusion release of molten rock magma at the surface, as in a flow of lava or shower of volcanic ash

fault sharp break in rock with a slippage of the crustal block on one side with respect to the block on the other

fault coast coast formed when a shoreline comes to rest against a fault scarp

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 upon an inactive fault line

felsic minerals quartz and feldspars treated as a mineral group of light color and relatively low density. (See also mafic minerals.)

felsic rock igneous rock dominantly composed of felsic minerals

fiord narrow, deep ocean inlet partially filling a glacial trough

fiord coast deeply embayed, rugged coast formed by partial submergence of glacial troughs

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

floodplain a broad belt of low, flat ground bordering a river channel that floods regularly

fluvial landforms landforms shaped by running water

folds corrugations of strata caused by crustal compression

food web (food chain) organization of an ecosystem into levels through which energy flows as the organisms at each level consume energy from the bodies of organisms in the level below

forb broad-leaved herb, as distinguished from the grasses

foredunes ridge of irregular sand dunes typically found adjacent to beaches on low-lying coasts and bearing a partial cover of plants

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 produced from remains of organic matter enclosed in rock; examples are coal, petroleum (crude oil), and natural gas

fringing reef coral reef directly attached to land with no intervening lagoon of open water

front surface of contact between two unlike air masses

frost action rock breakup by forces accompanying the freezing of water

gene flow speciation process in which evolving populations exchange alleles as individuals move among populations

genetic drift speciation process in which chance mutations change the genetic composition of a breeding population until it diverges from other populations

geographic cycle theory suggesting that landscapes go through stages of development and that the rejuvenation of landscapes arises from tectonic uplift of the land

geographic grid network of parallels and meridians, used to fix location on Earth

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

geomorphology science of Earth surface processes and landforms, including their history and processes of origin

geostrophic wind wind at high levels above the Earth's surface blowing parallel with a system of straight, parallel isobars

geothermal energy energy derived from the heat in the Earth's interior

glacial abrasion abrasion by a moving glacier of the bedrock floor beneath it

glacial drift general term for all varieties and forms of rock debris deposited by ice sheets

glacial trough deep, steep-sided rock trench formed by alpine glacier erosion

glaciation 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.)

Goode projection equal-area map projection often used to display information, such as climate or soil type.

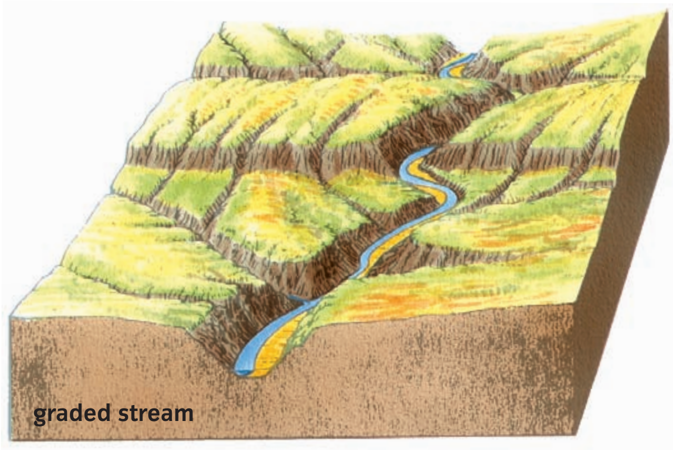
graben trench-like depression representing the surface of a crustal block dropped down between two opposed, infacing normal faults.

graded stream stream with a gradient adjusted so that average bed load transport balances average bed load input

granular disintegration grain-by-grain breakup of the outer surface of coarse-grained rock, yielding sand and gravel and leaving behind rounded boulders

geographic cycle

glaciation



graded stream

grassland biome biome consisting largely, or entirely, of herbs, which may include grasses, grass-like plants, and forbs

greenhouse effect accumulation of heat in the lower atmosphere through the absorption of longwave radiation from the Earth's surface

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 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 in the saturated zone that moves under the force of gravity

guyot sunken remnant of a volcanic island

habitat subdivision of the environment according to the needs and preferences of organisms or groups of organisms

Hadley cell low-latitude atmospheric circulation cell with rising air over the equatorial trough and sinking air over the subtropical high-pressure belts

hanging valley stream valley that has been truncated by marine erosion so as to appear in cross section in a marine cliff, or truncated by glacial erosion so as to appear in cross section in the upper wall of a glacial trough

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-latitude climates group of climates in the subarctic zone, arctic zone, and polar zone, dominated by arctic air masses and polar air masses

historical biogeography field of biogeography concerned with evolution, speciation, dispersal, and extinction of species as they affect the distribution of species and organisms

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 and including the present

homosphere the lower portion of the atmosphere, below about 100 km altitude, in which atmospheric gases are uniformly mixed

horn steep-sided peak formed by glacial erosion from three sides

horst crustal block uplifted between two normal faults

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

humidity the amount of water vapor in the air

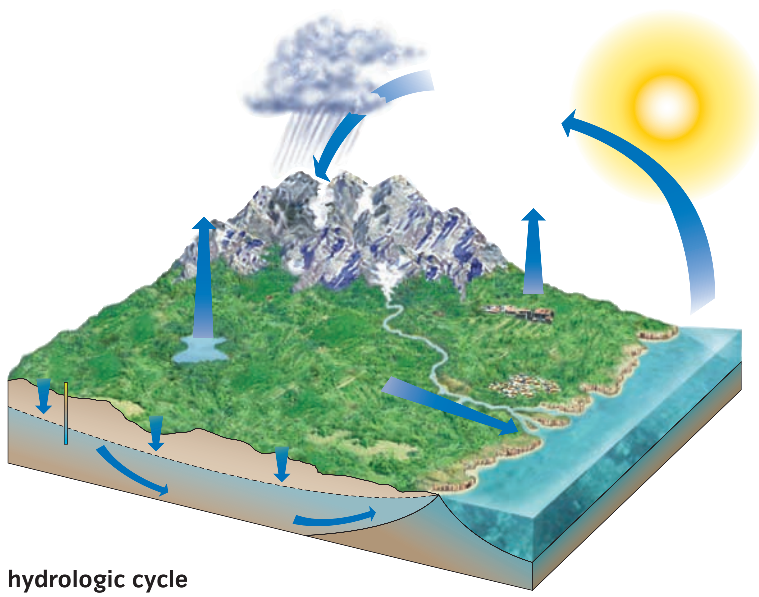
humus dark brown to black organic matter on or in the soil, consisting of fragmented plant tissues partly digested by organisms

hurricane tropical cyclone of the western North Atlantic and Caribbean Sea

hydraulic action stream erosion by impact force of the flowing water upon 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



hydrologic cycle

hydrosphere total water realm of the Earth's surface, including the oceans, surface waters of the lands, ground water, and water held in the atmosphere

ice floe cohesive sheet of ice floating in water

ice sheet large thick plate of glacial ice moving outwards in all directions

ice sheet climate ⑬ severely cold climate found on the Greenland and Antarctic ice sheets

ice shelf thick plate of floating glacial ice attached to an ice sheet and fed by the ice sheet and by snow accumulation

ice wedge vertical, wall-like body of ground ice, often tapering downward, occupying a shrinkage crack in silt of permafrost areas

iceberg mass of glacial ice floating in the ocean that has broken off a glacier that extends into tidal water

ice-wedge polygons polygonal networks of ice wedges

igneous rock rock formed from cooling of magma

illuviation accumulation in a lower soil horizon of materials brought down from upper horizons

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

initial landforms landforms produced directly by internal Earth processes of volcanism and tectonic activity. Examples: volcano, fault scarp

insolation the flow of solar energy intercepted by an exposed surface assuming a uniformly spherical Earth with no atmosphere

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)

intertropical convergence zone (ITCZ) zone of convergence of air masses along the equatorial trough

intrusive igneous rock igneous rock body produced by solidification of magma beneath the surface, surrounded by preexisting rock

isobars change of atmospheric pressure measured along a line at right angles to the isobars

isotherm line on a map drawn through all points with the same temperature

isotope form of an element with a unique atomic mass number

Jet streams high-speed air flow in narrow bands within the upper-air westerlies and along certain other global latitude zones at high levels

joints fractures within bedrock, usually occurring in parallel and intersecting sets of planes

June solstice (see summer solstice)

kames steep-sided mound of stratified sand and gravel deposited at, or near, the terminus of a glacier

karst landscape or topography dominated by surface features of limestone solution and underlain by a limestone cavern system

La Niña cooling of the ocean surface off the western coast of South America, occurring periodically every 4 to 12 years.

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

land breeze local wind blowing from land to water during the night

landslide rapid sliding of large masses of bedrock on steep mountain slopes or from high cliffs

lapse rate rate at which air temperature drops with increasing altitude

Late-Cenozoic Ice Age or the Ice Age series of glaciations, deglaciations, and interglaciations experienced during the late Cenozoic Era

latent heat heat absorbed and stored in a gas or liquid during the processes of evaporation, melting, or sublimation

latitude arc of a meridian between the equator and a given point on the globe

leads narrow strips of open ocean water between ice floes

liana woody vine supported on the trunk or branches of a tree

life-form characteristic physical structure, size, and shape of a plant or of an assemblage of plants

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 winds general term for winds generated as direct or immediate effects of the local terrain


loess

Mercator projection

loess surface deposit of wind-transported silt

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

longwave radiation electromagnetic radiation in the range 3 to 50 μm; the Earth emits longwave radiation

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

mafic minerals minerals, largely silicate minerals, rich in magnesium and iron, dark in color, and of relatively great density

mafic rock igneous rock dominantly composed of mafic minerals

magma mobile, high-temperature molten state of rock

mantle rock layer of the Earth beneath the crust and surrounding the core, composed of ultramafic igneous rock of silicate minerals

map projection a system of parallels and meridians representing the Earth's curved surface drawn on a flat surface

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 abundant precipitation and a distinct winter precipitation maximum

mass wasting spontaneous downhill movement of soil, regolith, and bedrock under the influence of gravity

material cycle a closed matter flow system in which matter flows endlessly, powered by energy inputs (see also biogeochemical cycle)

Mediterranean climate ⑦ climate type of the subtropical zone, characterized by the alternation of a very dry summer and a mild, rainy winter

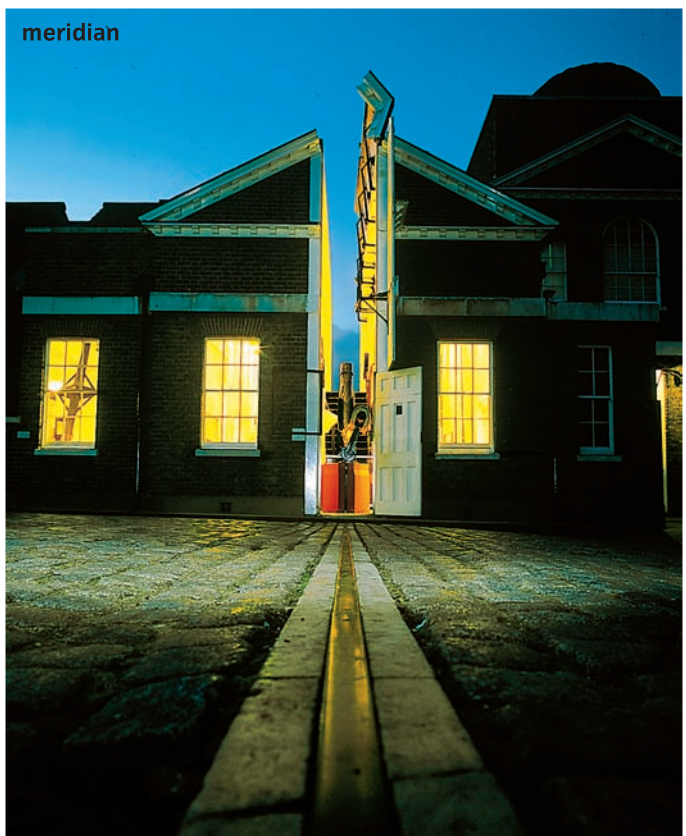
Mercator projection map projection with horizontal parallels and vertical meridians

mercury barometer barometer using the Torricelli principle, in which atmospheric pressure counterbalances a column of mercury in a tube

meridian north-south line on Earth's surface, connecting the poles

mesa table-topped plateau of comparatively small extent bounded by cliffs and occurring in a region of flat-lying strata

metamorphic rock rock altered in physical or chemical composition by heat, pressure, or other processes taking place at a substantial depth below the surface


meridian

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

midoceanic ridge one of three major divisions of the ocean basins, being the central belt of submarine mountain topography with a characteristic axial rift

millibar unit of atmospheric pressure; one-thousandth of a bar. Bar is a force of one million dynes per square centimeter

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 oxides secondary minerals found in soils in which original minerals have been altered by chemical combination with oxygen

moist continental climate ⑩ moist climate of midlatitude zone with strongly defined winter and summer seasons and adequate precipitation throughout the year

moist subtropical climate ⑥ moist climate of the subtropical zone, characterized by a moderate to large annual water surplus and a strong seasonal temperature cycle

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 a mountain that rises out of a surrounding plain and that develops because it consists of more resistant rock than the bedrock of the surrounding region

monsoon and trade-wind coastal climate ② moist climate of low-latitudes showing a strong rainfall peak in the high-Sun season and a short period of reduced rainfall in the low-Sun season

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

moraine accumulation of rock debris carried by an alpine glacier or an ice sheet and deposited by the ice to become a depositional landform

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

mudflow flowing mixture of water and soil or regolith that flows rapidly downhill

mutation change in genetic material of a reproductive cell

mutualism interaction between two different species, in which both species benefit

nappe overturned recumbent fold of strata, usually associated with thrust sheets in a collision orogen

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, largely free from the influences of human activities

needleleaf forest plant formation class within the forest biome, consisting largely of needleleaf trees.

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 the difference in energy flow between all radiant energy coming into a surface and all radiant energy leaving the surface

nitrogen cycle biogeochemical cycle in which nitrogen moves through the biosphere by the processes of nitrogen fixation and denitrification


natural vegetation

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

northeast trade winds surface winds of low latitudes that blow steadily from the northeast.

nutrient cycle (See biogeochemical cycle.)

O_a horizon soil horizon below the O_i horizon containing decaying organic matter that is too decomposed to recognize as specific plant parts, such as leaves or twigs

occluded front weather front along which a moving cold front has overtaken a warm front, forcing the warm air mass aloft

ocean current persistent, dominantly horizontal flow of 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.

O_i horizon surface soil horizon containing decaying organic matter that is recognizable as leaves, twigs, or other organic structures

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 when moist air is forced over a mountain barrier

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

Oxisols soil order consisting of very old, highly weathered soils of low latitudes, with an oxic horizon and low base status

ozone form of oxygen with a molecule consisting of three atoms of oxygen; O_3

pack ice floating sea ice that completely covers the sea surface

Pangea 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

parabolic dunes

parallel east-west circle on the Earth's surface, lying in a plane parallel to the equator

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, material base from which soil is formed

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, 105 Pa = 1 bar

passive continental margins continental margins lacking active plate boundaries at the contact of continental crust with oceanic crust

ped individual natural soil aggregate

percolation slow passage of liquid through a filtering system, such as the movement of water down through soil

perennials plants that live for more than one growing season

periglacial in an environment of intense frost action, located in cold climate regions or near the margins of alpine glaciers or large ice sheets

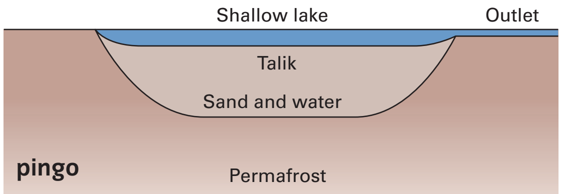
perihelion point on the Earth's elliptical orbit at which the Earth is nearest to the Sun

permafrost soil, regolith, and bedrock at a temperature below 0°C (32°F), found in cold climates

permafrost table in permafrost, the upper surface of perennially frozen ground; lower surface of the active layer

photosynthesis production of carbohydrate from water and carbon dioxide, using light energy

photosynthesis



phreatophytes plants that draw water from the ground water table beneath alluvium of dry stream channels and valley floors in desert regions

physical weathering breakup of massive rock (bedrock) by physical forces at or near the Earth's surface

pingo conspicuous conical mound or circular hill, having a core of ice, found on plains of the arctic tundra where permafrost is present

pioneer stage first stage of an ecological succession

plane of the ecliptic imaginary plane in which the Earth's orbit lies

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

plucking process of glacial erosion, in which ice pulls off pieces of jointed rock

pluvial lakes lake formed during a former period of wet climate

pocket beach beach of crescentic outline located at a bay head

polar front front lying between cold polar air masses and warm tropical air masses

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 or South Pole

poles the two points on the Earth's surface where the axis of rotation emerges.

polyploidy mechanism of speciation in which entire chromosome sets of organisms are doubled, tripled, quadrupled, and so on

precipitation particles of liquid water or ice that fall from the atmosphere and may reach the ground

predation form of negative interaction among animal species in which one species (predator) kills and consumes the other (prey)

pressure gradient lines on a map drawn through all points having the same atmospheric pressure

primary minerals in pedology (soil science), the original, unaltered silicate minerals of igneous rocks and metamorphic rocks

primary succession ecological succession that begins on a newly constructed substrate

progradation shoreward building of a beach, bar, or sandspit by addition of coarse sediment carried by littoral drift or brought from deeper water offshore

protocooperation symbiotic relationship in which both organisms gain from the association, but are able to survive without it

quartz mineral of silicon dioxide composition

radiogenic heat heat from the Earth's interior that is slowly released by the radioactive decay of unstable isotopes

raised shoreline former shoreline lifted above the limit of wave action; also called an elevated shoreline

recombination source of variation in organisms arising from the free interchange of alleles of genes during the reproduction process

reg desert surface armored with a pebble layer, resulting from long-continued deflation; found in the Sahara Desert of North Africa

regolith layer of mineral particles that lies above bedrock

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

respiration the oxidation of organic compounds by organisms that powers bodily functions

retrogradation cutting back (retreat) of a shoreline, beach, marine cliff, or marine scarp by wave action

reverse fault type of fault in which one fault block rides up over the other on a steep fault plane

ria coast deeply embayed coast formed by partial submergence of a land mass previously shaped by fluvial denudation

rill erosion form of accelerated erosion in which numerous, closely spaced miniature channels (rills) are scored into the surface of exposed soil or regolith

rockslide landslide of jumbled bedrock fragments

Rossby waves horizontal undulations in the flow path of the upper-westerlies; also known as upper-air waves

rotation spinning of an object around an axis

runoff flow of water from continents to oceans through stream flow and ground-water flow

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 flats 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


sand dune

salt marsh peat-covered expanse of sediment built up to the level of high tide over a previously formed tidal mud flat

saltation leaping, impacting, and rebounding of sand grains transported over a sand or pebble surface by wind

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

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

saturated zone zone beneath the land surface in which all pores of the bedrock or regolith are filled with ground water

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

scarification general term for artificial excavations and other land disturbances produced for purposes of extracting or processing mineral resources

scattering process in which particles and molecules deflect incoming solar radiation in different directions on collision; atmospheric scattering can redirect solar radiation back to space.

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

sclerophylls hard-leaved evergreen trees and shrubs capable of enduring a long, dry summer

sea breeze local wind blowing from sea to land during the day

sea ice floating ice of the oceans formed by direct freezing of ocean water

secondary minerals minerals derived by chemical alteration of the original silicate minerals found in rock (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

sedimentary domes up-arched strata forming a circular structure with domed summit and flanks with moderate to steep outward dip

sedimentary rock rock formed from the accumulation of sediment

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 dry climate 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 an indication of the intensity of kinetic energy of molecular motion within a substance; it is measured by a thermometer

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


sedimentary rock

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

shortwave radiation electromagnetic energy in the range from 0.2 to 3 μm; most solar radiation is shortwave radiation

shrubs woody perennial plants, usually small or low, with several low-branching stems and a foliage mass close to the ground

silicate minerals minerals containing silicon and oxygen atoms, linked in the crystal space lattice in units of four oxygen atoms to each silicon atom

soil natural terrestrial surface layer containing living matter and supporting, or capable of supporting, plants

soil colloids extremely small mineral or organic particles that can remain suspended in water indefinitely

soil creep extremely slow downhill movement of soil and regolith

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 soil, more or less horizontal, set apart from other layers by differences in physical or chemical composition

soil orders eleven soil classes that form the highest category in soil classification

soil profile display of soil horizons on the face of a freshly cut vertical exposure through the soil

soil structure presence, size, and form of aggregations (lumps or clusters) of soil particles

soil texture descriptive property of the mineral portion of soil based on varying proportions of sand, silt, and clay

soil-water balance water held in the soil and available to plants through their root systems; a form of subsurface water

solifluction a type of earthflow, found in arctic permafrost regions caused by soil that is saturated with water and then deformed into terraces

source region extensive land or ocean surface over which an air mass derives its temperature and moisture characteristics

southeast trades surface winds of low latitudes that blow steadily from the southeast

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

splash erosion soil erosion caused by direct impact of falling raindrops on a wet surface of soil or regolith

spreading 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

standard time time system based on the local time of a standard meridian and applied to belts of longitude extending roughly 7 1/2° on either side of that meridian

star dune large, isolated sand dune with radial ridges culminating in a peaked summit; largely found in the deserts of North Africa and the Arabian Peninsula

stationary front transition zone between two nearly stationary air masses of different properties

steppe semiarid grassland occurring largely in dry continental interiors

storage capacity maximum capacity of soil to hold water against the pull of gravity

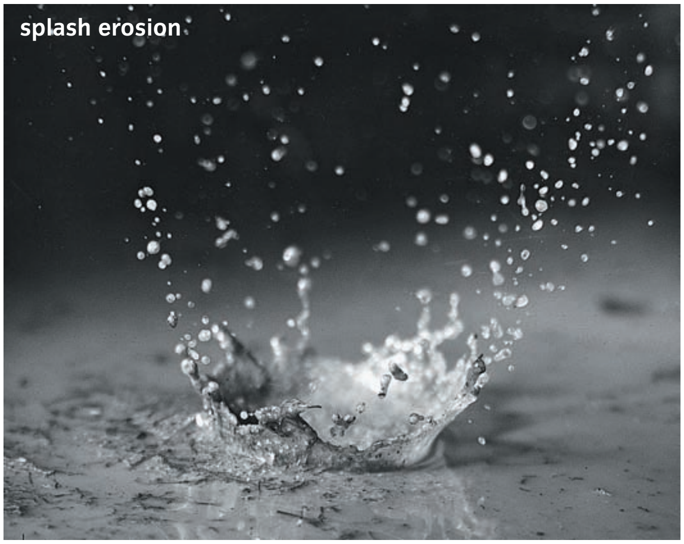
storm surge rapid rise of coastal water level accompanying the onshore arrival of a tropical cyclone

strata layers of sediment or sedimentary rock in which individual beds are separated from one another along bedding planes

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

stratosphere layer of atmosphere directly above troposphere; here temperature slowly increases with height


splash erosion

stratovolcano volcano constructed of multiple layers of lava and tephra (volcanic ash)

stream long, narrow body of flowing water moving along a channel to lower levels under the force of gravity

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 flow water flow in a stream channel; same as channel flow

stream load solid matter carried by a stream in dissolved form (as ions), in suspension, and as bed load

strike-slip faults variety of fault on which the motion is dominantly horizontal along a near-vertical fault plane

subduction descent of the edge of a lithospheric plate under an adjoining plate and into the asthenosphere

submergence inundation or partial drowning of a former land surface by a rise of sea level or a sinking of the crust or both

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

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 belt belts of persistent high atmospheric pressure centered about on lat. 30° N and S

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

succulents plants adapted to resist water losses by means of thickened spongy tissue in which water is stored

summer solstice solstice occurring on June 21 or 22, when the subsolar point is at 23 1/2° N; also termed June solstice

supercooled water water existing in the liquid state at a temperature lower than the normal freezing point

surges episodes of very rapid downvalley movement within an alpine glacier

symbiosis positive interaction between species that is beneficial to at least one of the species and does not harm the other

sympatric speciation type of speciation in which speciation occurs within a larger population

syncline a downfold of rock layers in a trough-like structure

tall-grass prairie a formation class of the grassland biome that consists of tall grasses with broad-leaved herbs

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

temperature gradient rate of temperature change along a selected line or direction

temperature inversion reversal of normal temperature pattern so that air temperature increases with altitude

temperature regime distinctive type of annual temperature cycle

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

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

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

thermosphere atmospheric layer of upwardly increasing temperature, lying above the mesopause

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

thunderstorm intense local storm associated with a tall, dense cumulonimbus cloud in which there are very strong updrafts of air

tidal current current set in motion by the ocean tide

tidal inlets narrow opening in a barrier island or baymouth bar through which tidal currents flow


terrestrial ecosystem

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

time zones zones or belts within which standard time is applied

tornado small, very intense wind vortex with extremely low air pressure in the center, formed between a dense cumulonimbus cloud in proximity to a cold front

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 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

translocation a soil-forming process in which materials are moved within the soil body, usually from one horizon to another

transpiration the process by which plants lose water to the atmosphere by evaporation through leaf pores

transverse dunes field of wave-like sand dunes with crests running at right angles to the direction of the prevailing wind

traveling cyclone center of low pressure and inspiraling winds that travels over the Earth's surface; includes wave cyclones, tropical cyclones, and tornadoes

tree Large, erect woody perennial plant typically having a single main trunk, few branches in the lower part, and a branching crown

tropical cyclone intense traveling cyclone of tropical and subtropical latitudes, accompanied by high winds and heavy rainfall

tropopause boundary between troposphere and stratosphere

tropophytes plant that sheds its leaves and enters a dormant state during a dry or cold season when little soil water is available

troposphere lowest layer of the atmosphere, in which temperature falls steadily with increasing height

tsunami train of sea waves triggered by an earthquake (or other seafloor disturbance) traveling over the ocean surface

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 months of frozen ground

typhoon tropical cyclone of the western North Pacific and coastal waters of Southeast Asia

Udalfs suborder of the soil order Alfisols; includes Alfisols of moist regions, usually in the midlatitude zone, with deciduous forest as the natural vegetation

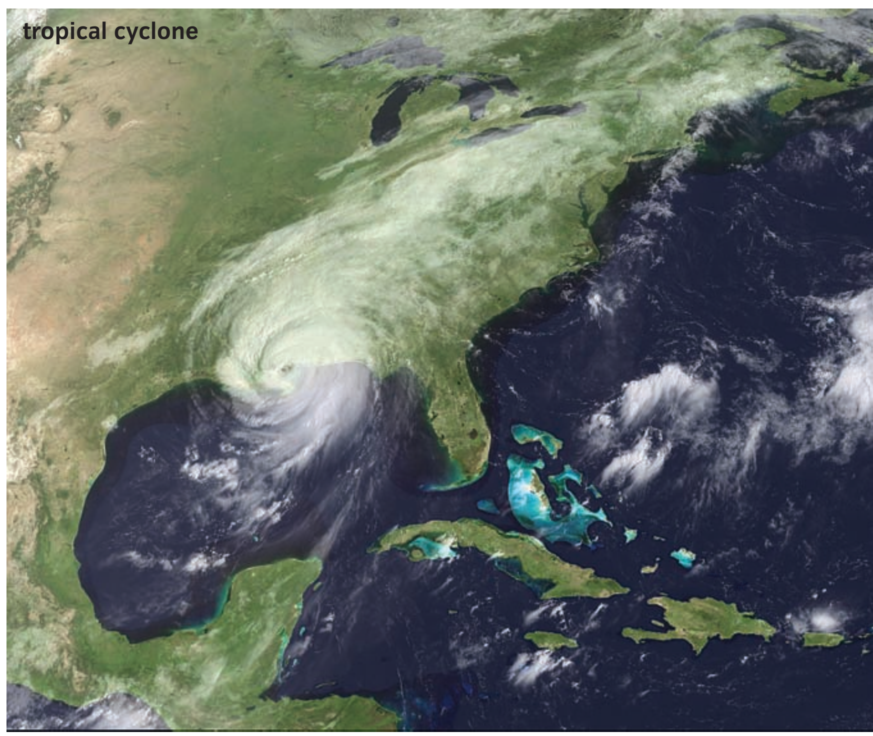
Udolls suborder of the soil order Mollisols; includes Mollisols of the moist soil-water regime in the midlatitude zone and with no horizon of calcium carbonate accumulation

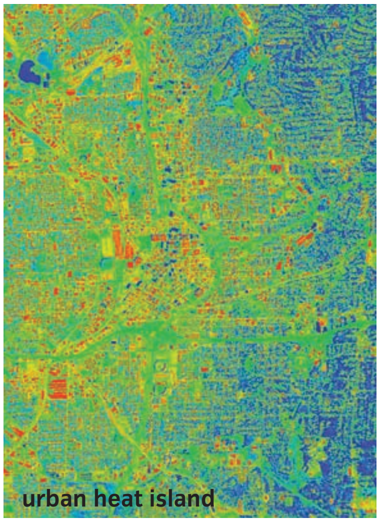
ultramafic igneous rock igneous rock composed almost entirely of mafic minerals, usually olivine or pyroxene group

unloading 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

upper-air westerlies system of westerly winds in the upper atmosphere over middle and high latitudes

urban heat island area at the center of a city that has a higher temperature than surrounding regions




urban heat island

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

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

vernal (March) equinox equinox occurring on March 20 or 21, when the subsolar point is at the equator

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

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 (volcanic ash)

warm front moving weather front along which a warm air mass slides over a cold air mass, leading to the production of stratiform clouds and precipitation

water table upper limit of the body of ground water; marks the boundary between the saturated and unsaturated zones

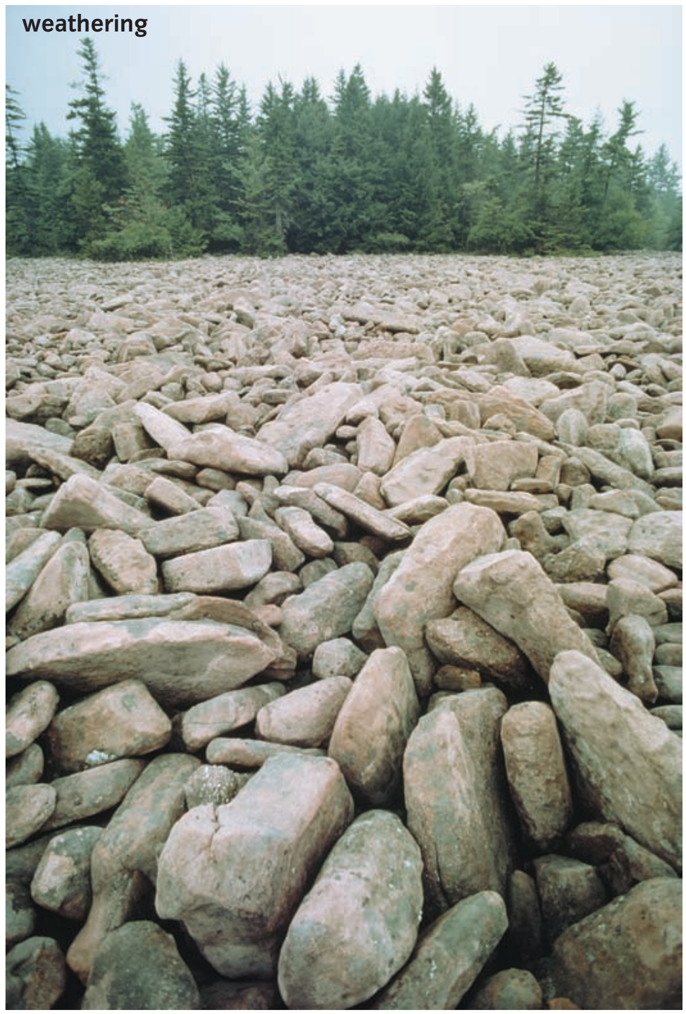
wave cyclone traveling cyclone of the midlatitudes involving interaction of cold and warm air masses along sharply defined fronts

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


volcano

weathering all the processes that physically disrupt or chemically decompose a rock at or near the Earth's surface

wet adiabatic lapse rate rate at which rising air is cooled by expansion when condensation is occurring; ranges from 4 to 9°C per 1000 m (2.2 to 4.9°F per 1000 ft)


weathering

wet equatorial climate ① moist climate of the equatorial zone with a large annual water surplus, and with uniformly warm temperatures through the year

wet-dry tropical climate ③ climate of the tropical zone characterized by a very wet season alternating with a very dry season

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 abrasion mechanical wearing action of wind-driven mineral particles striking exposed rock surfaces

winter solstice solstice occurring on December 21 or 22, when the subsolar point is at 23 1/2° S; also termed December solstice

Wisconsinan Glaciation last glaciation of the late-Cenozoic Ice Age

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


wet equatorial climate

Xerolls suborder of the soil order Mollisols; includes Mollisols of the Mediterranean climate ⑦

xerophytes plants adapted to a dry environment

PHOTO CREDITS

Chapter 1

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