GLOBAL
EDITION

Geosystems

An Introduction to Physical Geography

NINTH EDITION

Robert W. Christopherson • Ginger H. Birkeland

ALWAYS LEARNING

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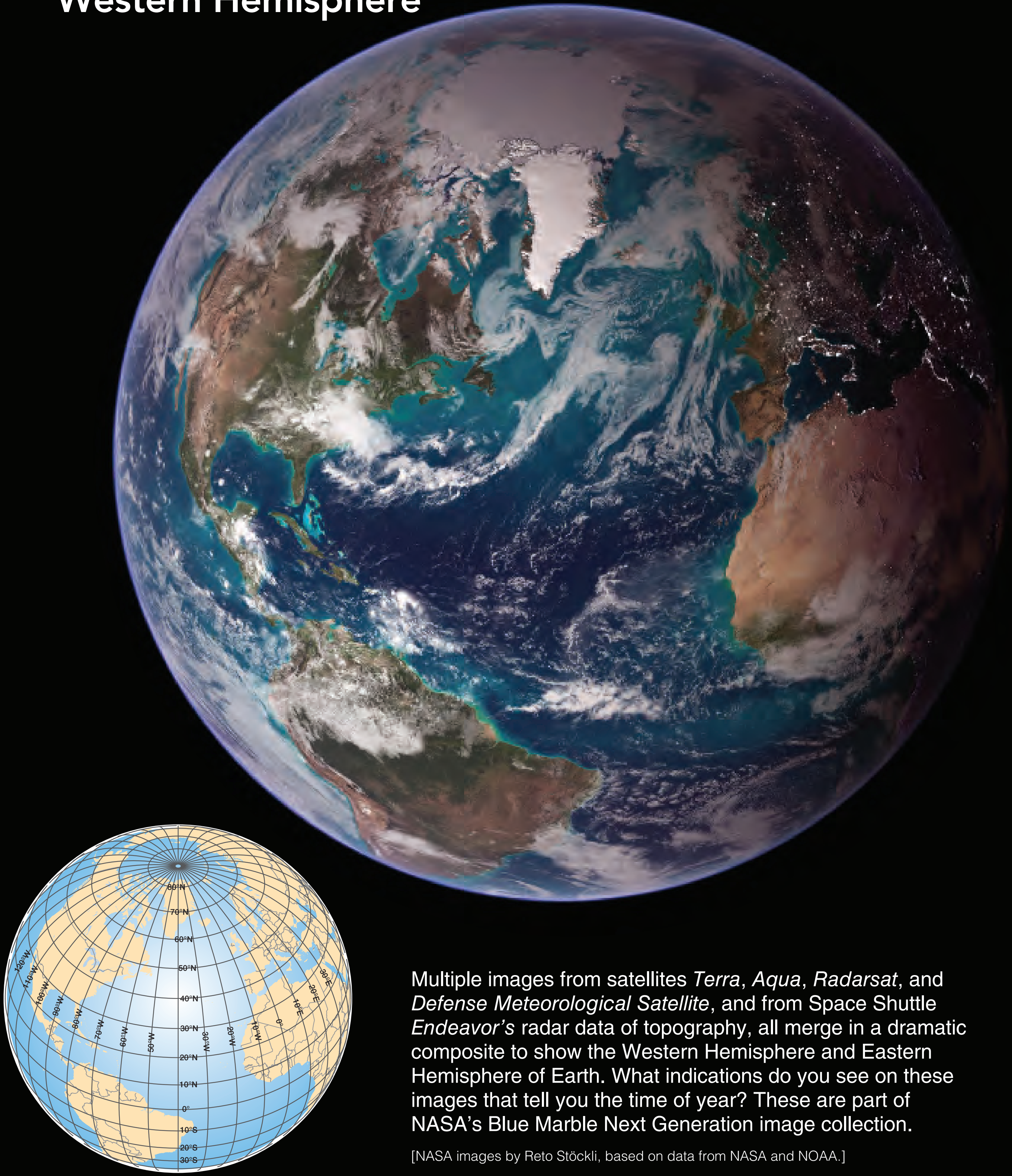
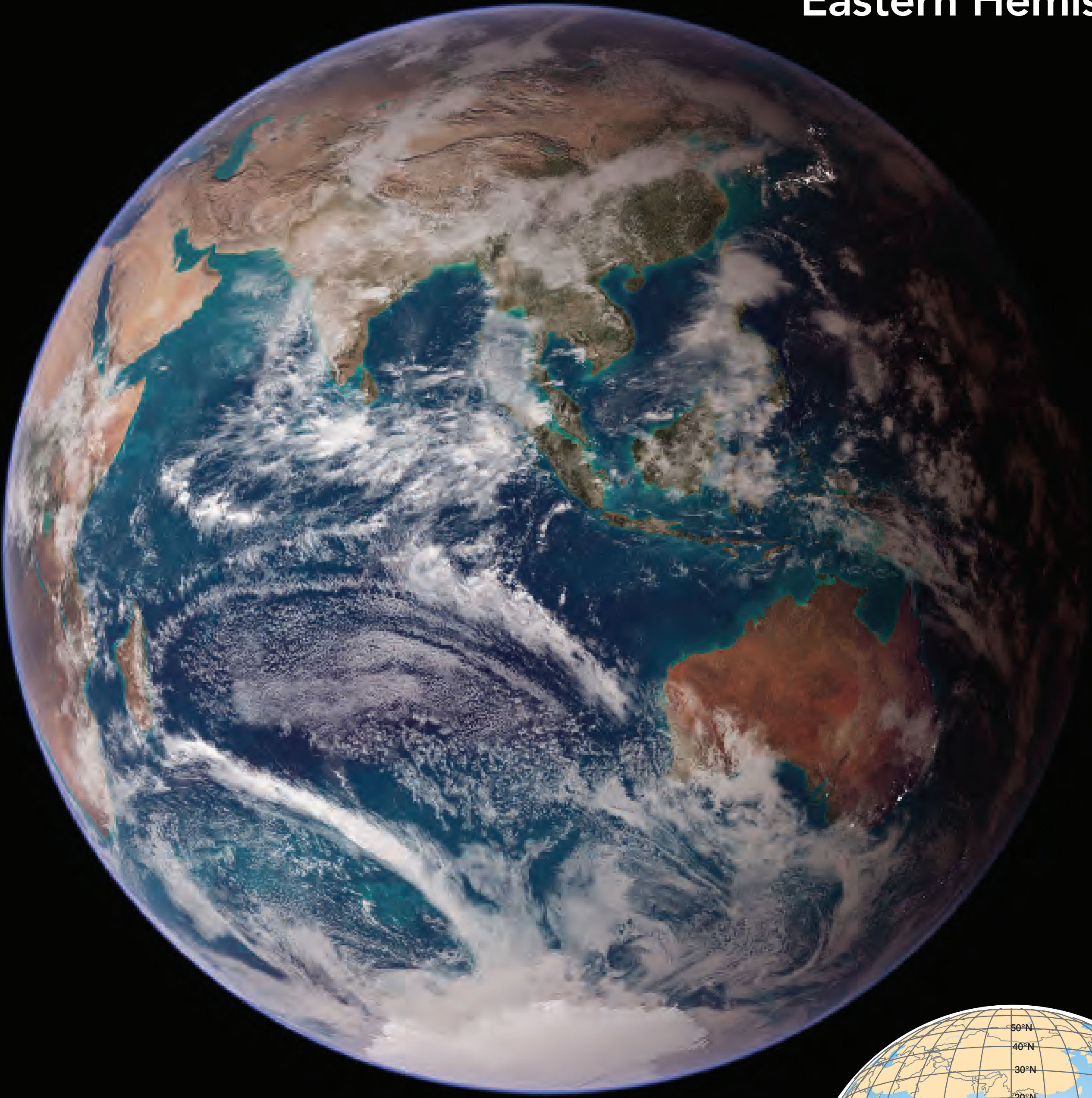
Western Hemisphere

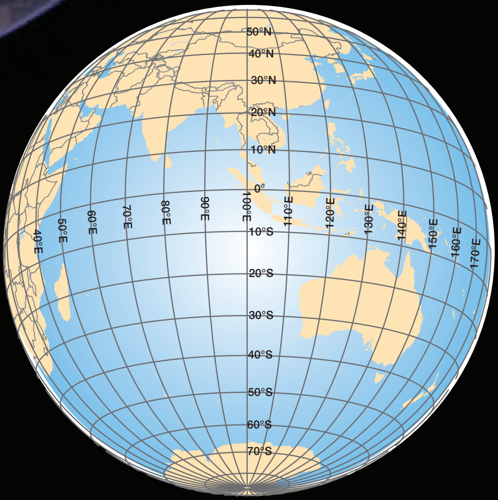


Multiple images from satellites *Terra*, *Aqua*, *Radarsat*, and *Defense Meteorological Satellite*, and from Space Shuttle *Endeavor's* radar data of topography, all merge in a dramatic composite to show the Western Hemisphere and Eastern Hemisphere of Earth. What indications do you see on these images that tell you the time of year? These are part of NASA's Blue Marble Next Generation image collection.

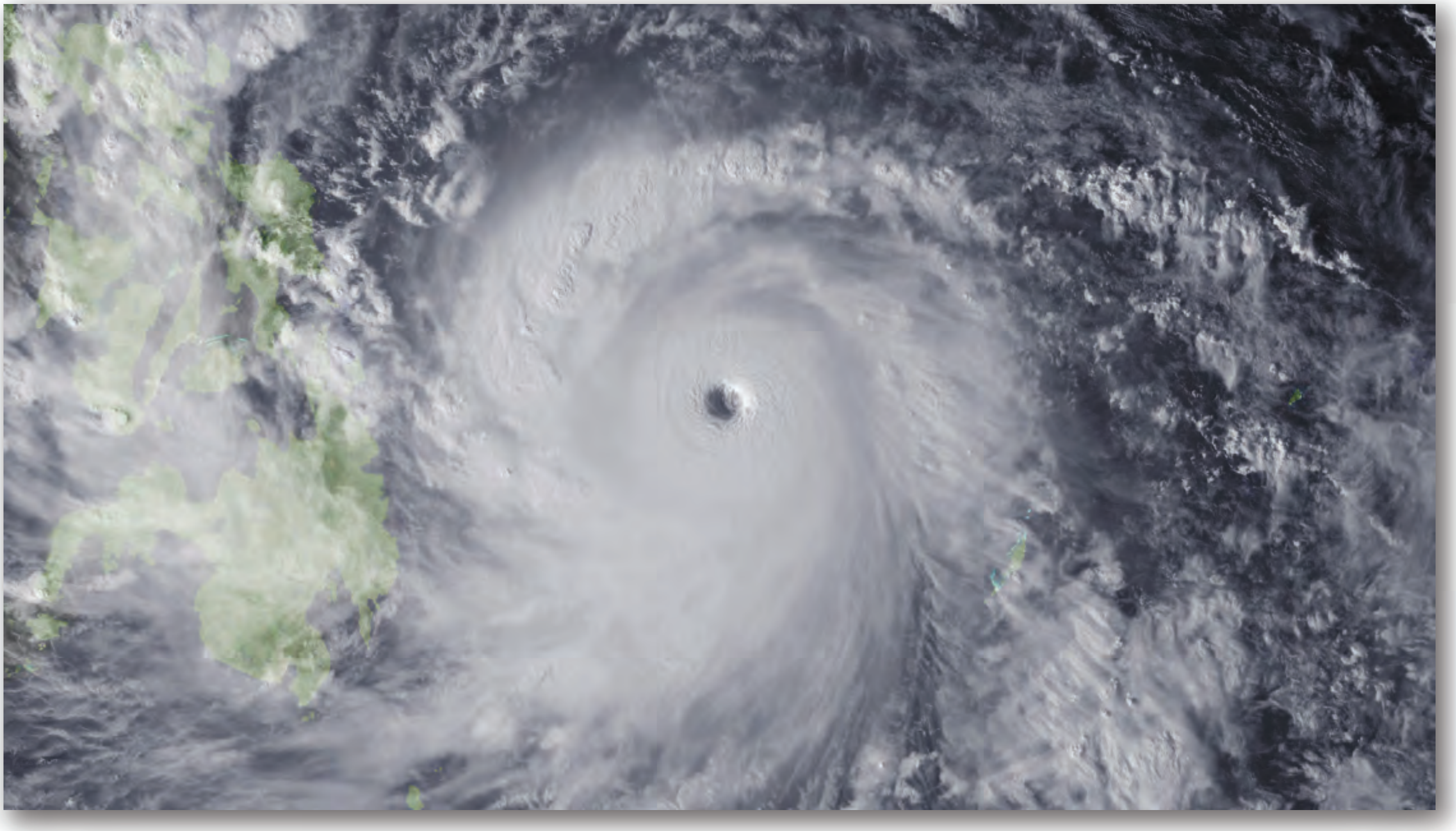
[NASA images by Reto Stöckli, based on data from NASA and NOAA.]

Eastern Hemisphere



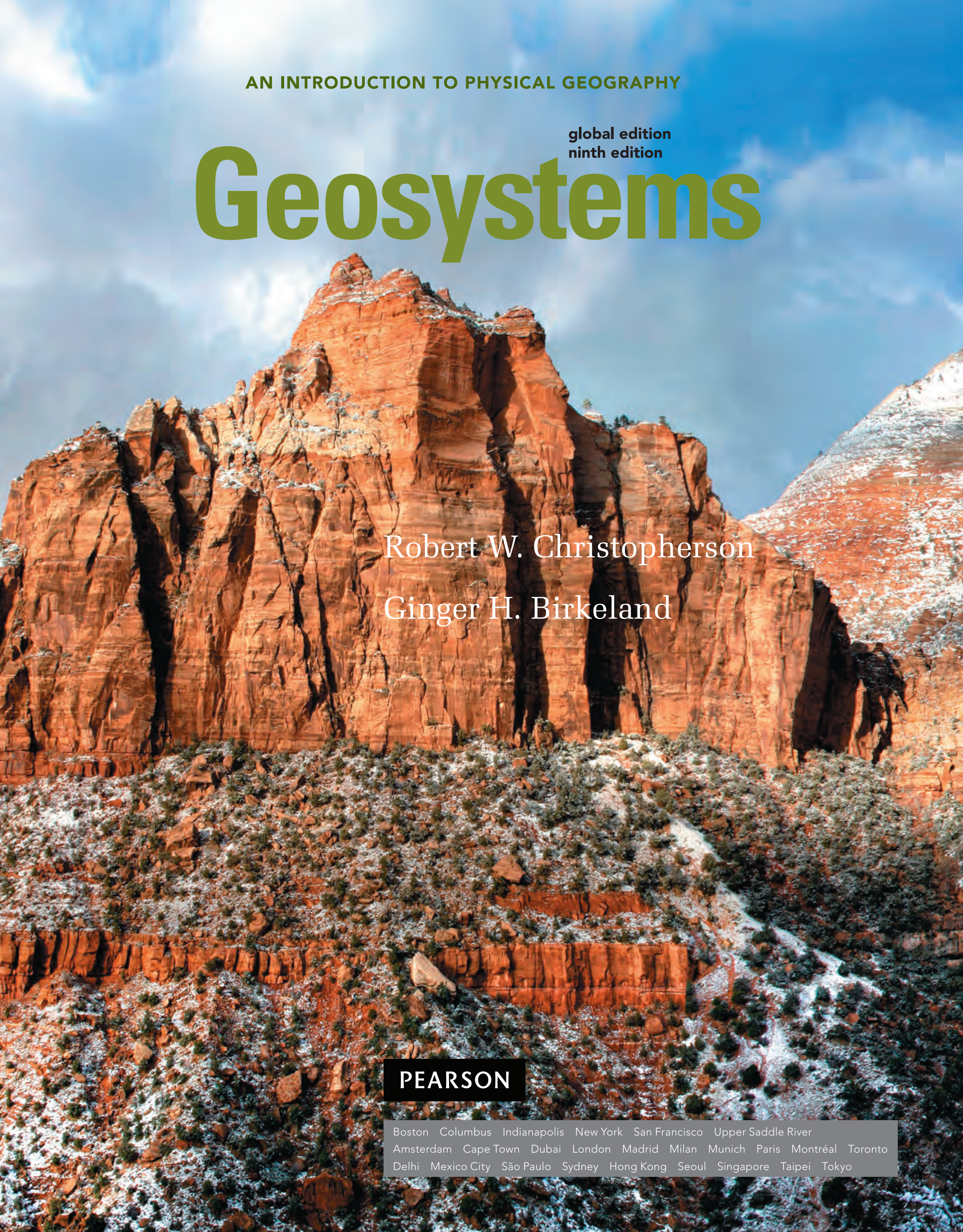


Geosystems



Super Typhoon Haiyan made landfall in the central Philippines on the morning of November 7, 2013, with sustained winds over 306 kmph (190 mph), the strongest ever recorded for a tropical cyclone at landfall using satellite measurements. In *Geosystems*, we discuss tropical cyclones and other severe weather events on Earth, including the effects of Superstorm Sandy on the U.S. East Coast in 2012 (see Focus Study 8.1 in Chapter 8). [NOAA.]

Sandstone cliffs along the Virgin River in Zion National Park, Utah. [GeoStills/Alamy.]



AN INTRODUCTION TO PHYSICAL GEOGRAPHY

global edition
ninth edition

Geosystems

Robert W. Christopherson

Ginger H. Birkeland

PEARSON

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dedication

To the students and teachers of Earth, and to all the children and grandchildren, for it is their future and home planet.

The land still provides our genesis, however we might like to forget that our food comes from dank, muddy Earth, that the oxygen in our lungs was recently inside a leaf, and that every newspaper or book we may pick up is made from the hearts of trees that died for the sake of our imagined lives. What you hold in your hands right now, beneath these words, is consecrated air and time and sunlight.

—Barbara Kingsolver

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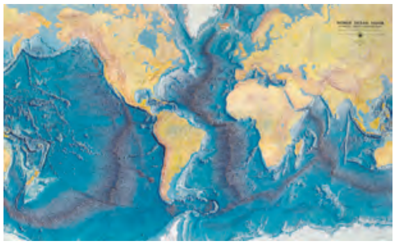

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preface

Welcome to the Ninth Edition of *Geosystems*. This edition marks the addition of Dr. Ginger Birkeland as a coauthor to Robert Christopherson. This Ninth Edition features significant revision, with a new chapter on climate change, new features, updated content, and many new photos and illustrations. We continue to build on the success of the first eight editions, as well as the companion texts, *Elemental Geosystems*, now in its Seventh Edition, and *Geosystems*, *Canadian Edition*, Third Edition. Students and teachers appreciate the systems organization, scientific accuracy, integration of figures and text, clarity of the summary and review sections, and overall relevancy to what is happening to Earth systems in real time. *Geosystems* continues to tell Earth's story in student-friendly language.

The goal of physical geography is to explain the spatial dimension of Earth's dynamic systems—its energy, air, water, weather, climate, tectonics, landforms, rocks, soils, plants, ecosystems, and biomes. Understanding human–Earth relations is part of physical geography as it seeks to understand and link the planet and its inhabitants. Welcome to physical geography!

New to the Ninth Edition

Nearly every page of *Geosystems*, Ninth Edition, presents updated material, new content in text and figures, and new features. A sampling of new features includes:

- A **new chapter on climate change**. Although climate change science affects all systems and is discussed to some extent in every chapter of *Geosystems*, we now present a stand-alone chapter covering this topic—Chapter 11, Climate Change. This chapter covers paleoclimatology and mechanisms for past climatic change (expanding on topics covered in Chapter 17 in previous editions), climate feedbacks and the global carbon budget, the evidence and causes of present climate change, climate models and projections, and actions that we can take to moderate Earth's changing climate. This new Chapter 11 expands on the climate change discussion that was formerly part of Chapter 10, Climate Systems and Climate Change, in previous editions.
- A new ***Geosystems in Action*** feature focusing on key topics, processes, systems, or human–Earth connections. In every chapter, *Geosystems in Action* is a one- to two-page highly visual presentation of a topic central to the chapter, with active learning questions as well as a GeoQuiz to aid student learning. Throughout each part of the *Geosystems in Action* figure, students are asked to analyze, explain, infer, or predict based on the information presented. Topics include Earth–Sun Relations (Chapter 2), Air Pollution (Chapter 3), Earth–Atmosphere Energy Balance (Chapter 4), The Global Carbon Budget (Chapter 11), Glaciers as Dynamic Systems (Chapter 17), and Biological Activity in Soils (Chapter 18).
- A new feature, ***The Human Denominator***, that links chapter topics to human examples and applications. At the end of Chapters 2 through 20, this new feature includes maps, photos, graphs, and other diagrams to provide visual examples of many human–Earth interactions. This feature replaces and expands on the former Chapter 21 in previous *Geosystems* editions, called *Earth and the Human Denominator*.
- New and revised illustrations and maps to improve student learning. More than 250 new photos and images bring real-world scenes into the classroom. Our photo and remote sensing program, updated for this edition, exceeds 500 items, integrated throughout the text.
- New images and photos for the 20 chapter openers, and redesigned schematics and photos for the 4 part openers.

Continuing in the Ninth Edition

- Twenty ***Focus Studies***, with either updated or new content, explore relevant applied topics in greater depth and are a popular feature of the *Geosystems* texts. In the Ninth Edition, these features are grouped by topic into five categories: Pollution, Climate Change, Natural Hazards, Sustainable Resources, and Environmental Restoration.

  Nine new Focus Study topics include:

  Heat Waves (Chapter 5)
  Hurricanes Katrina and Sandy: Storm Development and Links to Climate Change (Chapter 8)
  Thawing Methane Hydrates—Another Arctic Methane Concern (Chapter 11)
  Earthquakes in Haiti, Chile, and Japan: A Comparative Analysis (Chapter 13)
  Stream Restoration: Merging Science and Practice (Chapter 15)
  The 2011 Japan Tsunami (Chapter 16)
  Snow Avalanches (Chapter 17)
  Wildfire and Fire Ecology (Chapter 19)
  Global Conservation Strategies (Chapter 20)

- The chapter-opening *Geosystems Now* case study feature presents current issues in geography and Earth systems science. These original, unique essays, updated for the Ninth Edition, immediately engage readers into the chapter with relevant, real-world examples of physical geography. New *Geosystems Now* topics in the Ninth Edition include shale gas as an energy resource in the United States (Chapter 1), coastal redwood trees and declining summer moisture in California (Chapter 7), the effects of proposed dams on rivers in China (Chapter 15), and coastal erosion caused by Hurricane Sandy (Chapter 16). Many of these features emphasize linkages across chapters and Earth systems, exemplifying the Geosystems approach.

- *Geo Reports* continue to describe timely and relevant events or facts related to the discussion in the chapter, provide student action items, and offer new sources of information. The 75 *Geo Reports* in the Ninth Edition, placed along the bottom of pages, are updated, with many new to this edition. Example topics include:

  Did light refraction sink the *Titanic*? (Chapter 4)
  The hottest temperature on Earth (Chapter 5)
  Storm causes Hawai'i hailstorm and tornado (Chapter 8)
  Satellite GRACE enables groundwater measurements (Chapter 9)
  Tropical climate zones advance to higher latitudes (Chapter 10)
  Surprise waves flood a cruise ship (Chapter 16)
  Greenland ice sheet melting (Chapter 17)
  Overgrazing effects on Argentina's grasslands (Chapter 18)

- *Critical Thinking* exercises are integrated throughout the chapters. These carefully crafted action items bridge students to the next level of learning, placing students in charge of further inquiry. Example topics include:

  Applying Energy-Balance Principles to a Solar Cooker
  What Causes the North Australian Monsoon?
  Identify Two Kinds of Fog
  Analyzing a Weather Map
  Allocating Responsibility and Cost for Coastal Hazards
  Tropical Forests: A Global or Local Resource?

- The *Geosystems Connection* feature at the end of each chapter provides a preview "bridge" between chapters, reinforcing connections between chapter topics.
- *Key Learning Concepts* appear at the outset of each chapter, many rewritten for clarity. Each chapter concludes with *Key Learning Concepts Review*, which summarizes the chapter using the opening objectives.
- *Geosystems* continues to embed Internet URLs within the text. More than 200 appear in this edition. These allow students to pursue topics of interest to greater depth, or to obtain the latest information about weather and climate, tectonic events, floods, and the myriad other subjects covered in the book.

Author Acknowledgments

After all these years, the strength of a publishing team remains ever essential. Continuing thanks to President Paul Corey for his leadership since 1990 and to Frank Ruggirello, Senior Vice-president and Editorial Director for Geosciences, for his vision. Thanks to Senior Geography Editor Christian Botting for his guidance and for the attention devoted to the Geosystems texts; and to Program Manager Anton Yakovlev and Assistant Editors Bethany Sexton and Kristen Sanchez for their careful attention. Maya Melenchuk, Image Management, is a great addition to the team and a help to us. Thanks to Managing Editor Gina Cheselka, Program Manager Janice Stangel, and Director of Development Jennifer Hart, for their skills and continuing support.

Our appreciation to designers Mark Ong and Jeanne Calabrese, for such skill in a complex book design. Thanks to the late Randall Goodall for his design work over the years on the previous several editions of *Geosystems* and *Elemental Geosystems*. Thanks also to Maureen McLaughlin, Senior Marketing Manager, Nicola Houston, Senior Marketing Assistant, and the many publisher representatives who spend months in the field communicating the *Geosystems* approach. Our gratitude is extended to the entire "*Geosystems* Team" for allowing us to participate in the publishing process.

Our sincere appreciation for production coordination goes to Editorial Director for Higher Education Cindy Miller of Cenveo LLC for our friendship and sustaining care through eight books, and to Senior Project Manager Suganya Karuppasamy for her ability to respond to our feedback as she oversees manuscript, copy editing, complex compositing, and page proofs. With so many changes in this edition, her skills make it work. To photo researcher Erica Gordon, copy editor Kathy Pruno, proofreader Jeff Georgeson, and indexer Robert Swanson we give thanks for quality work. We offer special thanks to development editor Moira Lerner Nelson for advice and suggestions that improved many aspects of this edition. Our appreciation also goes to Jay McElroy and Jonathan Cheney for their creative talent in helping develop the new *Geosystems in Action* features, and to Jay for his detailed work improving the art program.

Thanks to all the colleagues who served as reviewers on one or more editions of each book, or who offered helpful suggestions in conversations at our national and regional geography meetings. Thanks to the accuracy reviewers of all ninth edition chapters: Todd Fagin, *Oklahoma University*; Giraldo Mario, *California State University, Northridge*; Stephen Cunha, *Humboldt State University*; Charlie Thomsen, *American River College*. And thanks for special reviews for the new Chapter 11 in this edition from Jason Allard, *Valdosta State University*; Marshall Shepherd, *University of Georgia*; Scott Mandia, *Suffolk County Community College, Long Island*; David Kitchen, *University of Richmond*.

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As you read this book, you will learn from more than 300 content-specific, beautiful photographs made by my wife, photographer, and expedition partner, Bobbé Christopherson. Her contribution to the success of *Geosystems* is obvious and begins with the spectacular cover photo and continues through the text. Bobbé is my expedition partner, colleague, wife, and best friend.

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From us both: Physical geography teaches us a holistic view of the intricate supporting web that is Earth's environment and our place in it. Dramatic global change is underway in human–Earth relations as we alter physical, chemical, and biological systems. Our attention to climate change science and applied topics is in response to the impacts we are experiencing and the future we are shaping. All things considered, this is a critical time for you to be enrolled in a physical geography course! The best to you in your studies—and ***carpe diem!***

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digital and print resources

For Students and Teachers

Television for the Environment Earth Report Geography Videos on DVD (0321662989). This three-DVD set helps students visualize how human decisions and behavior have affected the environment and how individuals are taking steps toward recovery. With topics ranging from the poor land management promoting the devastation of river systems in Central America to the struggles for electricity in China and Africa, these 13 videos from Television for the Environment's global *Earth Report* series recognize the efforts of individuals around the world to unite and protect the planet.

Geoscience Animation Library 5th edition DVD-ROM (0321716841). Created through a unique collaboration among Pearson's leading geoscience authors, this resource offers over 100 animations covering the most difficult-to-visualize topics in physical geology, physical geography, oceanography, meteorology, and earth science. The animations are provided as Flash files and preloaded into PowerPoint(R) slides for both Windows and Mac.

Practicing Geography: Careers for Enhancing Society and the Environment by Association of American Geographers (0321811151). This book examines career opportunities for geographers and geospatial professionals in the business, government, nonprofit, and education sectors. A diverse group of academic and industry professionals shares insights on career planning, networking, transitioning between employment sectors, and balancing work and home life. The book illustrates the value of geographic expertise and technologies through engaging profiles and case studies of geographers at work.

Teaching College Geography: A Practical Guide for Graduate Students and Early Career Faculty by Association of American Geographers (0136054471). This two-part resource provides a starting point for becoming an effective geography teacher from the very first day of class. Part One addresses "nuts-and-bolts" teaching issues. Part Two explores being an effective teacher in the field, supporting critical thinking with GIS and mapping technologies, engaging learners in large geography classes, and promoting awareness of international perspectives and geographic issues.

Aspiring Academics: A Resource Book for Graduate Students and Early Career Faculty by Association of American Geographers (0136048919). Drawing on several years of research, this set of essays is designed to help graduate students and early career faculty start their careers in geography and related social and environmental sciences. *Aspiring Academics* stresses the interdependence of teaching, research, and service—and the importance of achieving a healthy balance of professional and personal life—while doing faculty work. Each chapter provides accessible, forward-looking advice on topics that often cause the most stress in the first years of a college or university appointment.

For Students

***Applied Physical Geography—Geosystems in the Laboratory,* Ninth Edition** (0321987284) by Charlie Thomsen and Robert Christopherson. A variety of exercises provides flexibility in lab assignments. Each exercise includes key terms and learning concepts linked to *Geosystems*. The ninth edition includes new exercises on climate change, a fully updated exercise on basic GIS using ArcGIS online, and more integrated media, including Google Earth and Quick Response (QR) codes. Supported by a website with media resources needed for exercises, as well as a downloadable Solutions Manual for teachers.

Companion website for *Applied Physical Geography: Geosystems in the Laboratory*. The website for lab manual provides online worksheets as well as KMZ files for all of the Google Earth" exercises found in the lab manual. www.mygeoscienceplace.com

***Goode's World Atlas*, 22nd Edition** (0321652002). *Goode's World Atlas* has been the world's premiere educational atlas since 1923—and for good reason. It features over 250 pages of maps, from definitive physical and political maps to important thematic maps that illustrate the spatial aspects of many important topics. The 22nd Edition includes 160 pages of digitally produced reference maps, as well as thematic maps on global climate change, sea-level rise, CO_2 emissions, polar ice fluctuations, deforestation, extreme weather events, infectious diseases, water resources, and energy production.

Pearson's Encounter Series provides rich, interactive explorations of geoscience concepts through Google Earth" activities, covering a range of topics in regional, human, and physical geography. All chapter explorations are available in print workbooks, as well as in online quizzes at www.mygeoscienceplace.com, accommodating different classroom needs. Each exploration consists of a worksheet, online quizzes whose results can be emailed to teachers, and a corresponding Google Earth" KMZ file.

- *Encounter Physical Geography* by Jess C. Porter and Stephen O'Connell (0321672526)
- *Encounter Geosystems* by Charlie Thomsen (0321636996)
- *Encounter World Regional Geography* by Jess C. Porter (0321681754)
- *Encounter Human Geography* by Jess C. Porter (0321682203)
- *Encounter Earth* by Steve Kluge (0321581296)

Dire Predictions: Understanding Global Warming by Michael Mann, Lee R. Kump (0136044352) Appropriate for any science or social science course in need of a basic understanding of the reports from the Intergovernmental Panel on Climate Change (IPCC). These periodic reports evaluate the risk of climate change brought on by humans. But the sheer volume of scientific data remains inscrutable to the general public, particularly to those who still question the validity of climate change. In just over 200 pages, this practical text presents and expands upon the essential findings in a visually stunning and undeniably powerful way to the lay reader. Scientific findings that provide validity to the implications of climate change are presented in clear-cut graphic elements, striking images, and understandable analogies.

For Teachers

Instructor Resource Manual **(Download)** by Charlie Thomsen includes lecture outlines and key terms, additional source materials, teaching tips, and a complete annotation of chapter review questions. Available from http://www.pearsonglobaleditions.com/Christopherson.

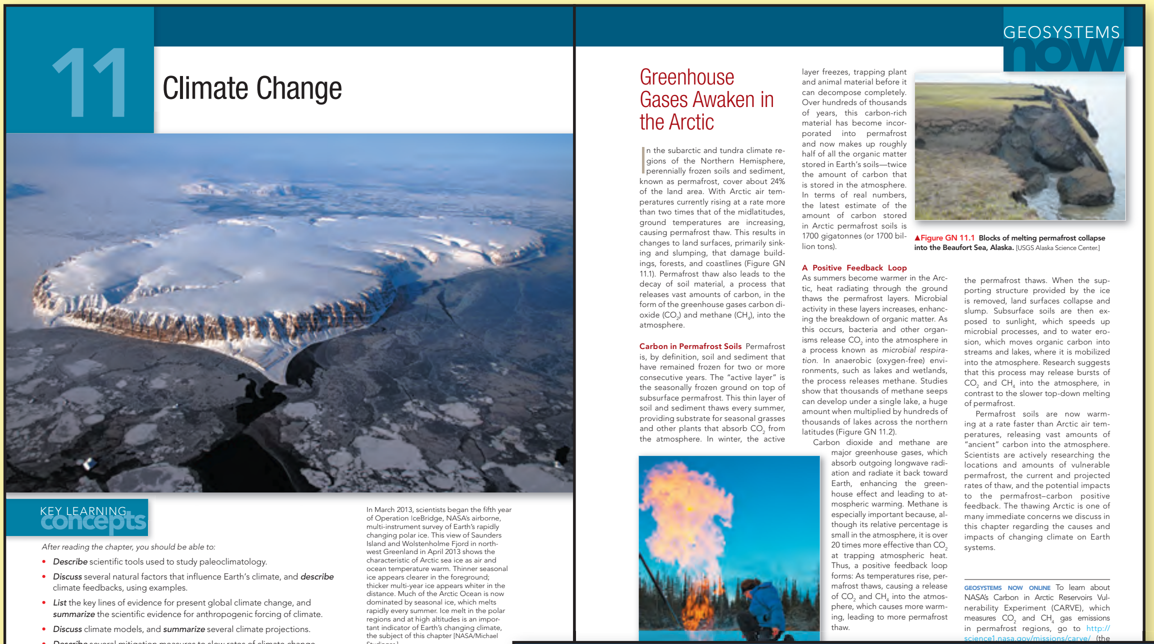
TestGen® Test Bank **(Download)** by Tod Fagin. TestGen® is a computerized test generator that lets you view and edit *Test Bank* questions, transfer questions to tests, and print tests in a variety of customized formats. This *Test Bank* includes around 3,000 multiple-choice, true/false, and short answer/essay questions. All questions are correlated against the National Geography Standards, textbook key concepts, and Bloom's Taxonomy. The *Test Bank* is also available in Microsoft Word® and importable into Blackboard and WebCT. Available from http://www.pearsonglobaleditions.com/Christopherson.

This *Instructor Resource* content is also available online via http://www.pearsonglobaleditions.com/Christopherson.

Exploring Earth's Dynamic Systems

Geosystems is organized around the natural flow of energy, materials, and information, presenting subjects in the same sequence in which they occur in nature—an organic, holistic Earth systems approach that is unique in this discipline. Offering current examples and modern science, Geosystems combines a structured learning path, student-friendly writing, current applications, outstanding visuals, and a strong multimedia program for a truly unique physical geography experience.

▼ NEW! **Chapter 11: Climate Change.** Incorporating the latest climate change science and data, this new chapter covers paleoclimatology and mechanisms for past climatic change, climate feedbacks and the global carbon budget, the evidence and causes of present climate change, climate forecasts and models, and actions that we can take to moderate Earth's changing climate.



Climate Change

KEY LEARNING concepts

After reading the chapter, you should be able to:

- ***Describe*** scientific tools used to study paleoclimatology.
- ***Discuss*** several natural factors that influence Earth's climate, and ***describe*** climate feedbacks, using examples.
- ***List*** the key lines of evidence for present global climate change, and ***summarize*** the scientific evidence for anthropogenic forcing of climate.
- ***Discuss*** climate models, and ***summarize*** several climate projections.
- ***Describe*** several mitigation measures to slow rates of climate change.

In March 2013, scientists began the fifth year of Operation IceBridge, NASA's airborne, multi-instrument survey of Earth's rapidly changing polar ice. This view of Saunders Island and Wolstenholme Fjord in northwest Greenland in April 2013 shows the characteristic of Arctic sea ice as air and ocean temperature warm. Thinner seasonal ice appears clearer in the foreground; thicker multi-year ice appears whiter in the distance. Much of the Arctic Ocean is now dominated by seasonal ice, which melts rapidly every summer. Ice melt in the polar regions and at high altitudes is an important indicator of Earth's changing climate, the subject of this chapter [NASA/Michael Studinger.]

Greenhouse Gases Awaken in the Arctic

In the subarctic and tundra climate regions of the Northern Hemisphere, perennially frozen soils and sediment, known as permafrost, cover about 24% of the land area. With Arctic air temperatures currently rising at a rate more than two times that of the midlatitudes, ground temperatures are increasing, causing permafrost thaw. This results in changes to land surfaces, primarily sinking and slumping, that damage buildings, forests, and coastlines (Figure GN 11.1). Permafrost thaw also leads to the decay of soil material, a process that releases vast amounts of carbon, in the form of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4), into the atmosphere.

Carbon in Permafrost Soils Permafrost is, by definition, soil and sediment that have remained frozen for two or more consecutive years. The "active layer" is the seasonally frozen ground on top of subsurface permafrost. This thin layer of soil and sediment thaws every summer, providing substrate for seasonal grasses and other plants that absorb CO_2 from the atmosphere. In winter, the active layer freezes, trapping plant and animal material before it can decompose completely. Over hundreds of thousands of years, this carbon-rich material has become incorporated into permafrost and now makes up roughly half of all the organic matter stored in Earth's soils—twice the amount of carbon that is stored in the atmosphere. In terms of real numbers, the latest estimate of the amount of carbon stored in Arctic permafrost soils is 1700 gigatonnes (or 1700 billion tons).

▲Figure GN 11.1 **Blocks of melting permafrost collapse into the Beaufort Sea, Alaska.** [USGS Alaska Science Center.]

A Positive Feedback Loop As summers become warmer in the Arctic, heat radiating through the ground thaws the permafrost layers. Microbial activity in these layers increases, enhancing the breakdown of organic matter. As this occurs, bacteria and other organisms release CO_2 into the atmosphere in a process known as *microbial respiration*. In anaerobic (oxygen-free) environments, such as lakes and wetlands, the process releases methane. Studies show that thousands of methane seeps can develop under a single lake, a huge amount when multiplied by hundreds of thousands of lakes across the northern latitudes (Figure GN 11.2).

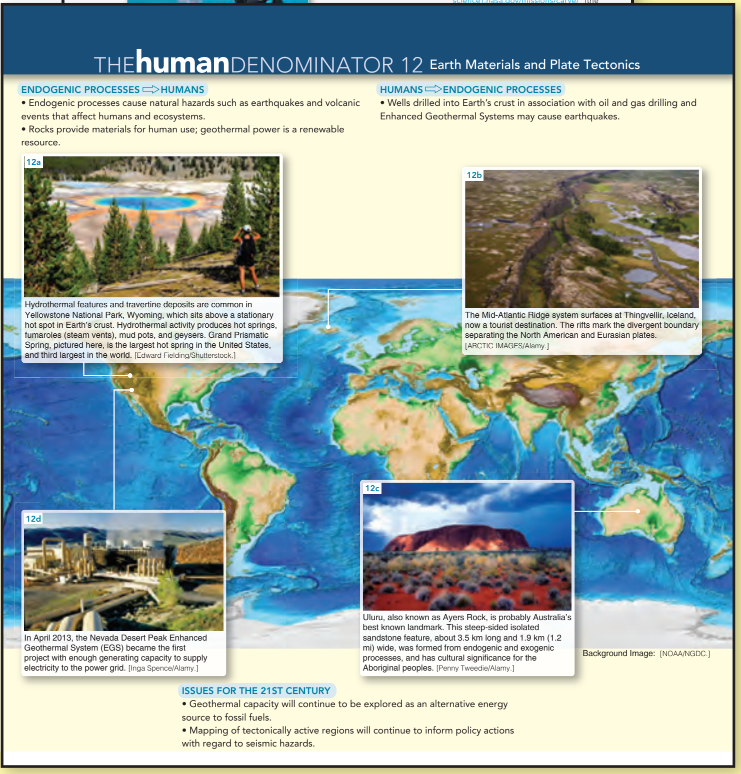
Carbon dioxide and methane are major greenhouse gases, which absorb outgoing longwave radiation and radiate it back toward Earth, enhancing the greenhouse effect and leading to atmospheric warming. Methane is especially important because, although its relative percentage is small in the atmosphere, it is over 20 times more effective than CO_2 at trapping atmospheric heat. Thus, a positive feedback loop forms: As temperatures rise, permafrost thaws, causing a release of CO_2 and CH_4 into the atmosphere, which causes more warming, leading to more permafrost thaw.

the permafrost thaws. When the supporting structure provided by the ice is removed, land surfaces collapse and slump. Subsurface soils are then exposed to sunlight, which speeds up microbial processes, and to water erosion, which moves organic carbon into streams and lakes, where it is mobilized into the atmosphere. Research suggests that this process may release bursts of CO_2 and CH_4 into the atmosphere, in contrast to the slower top-down melting of permafrost.

Permafrost soils are now warming at a rate faster than Arctic air temperatures, releasing vast amounts of "ancient" carbon into the atmosphere. Scientists are actively researching the locations and amounts of vulnerable permafrost, the current and projected rates of thaw, and the potential impacts to the permafrost–carbon positive feedback. The thawing Arctic is one of many immediate concerns we discuss in this chapter regarding the causes and impacts of changing climate on Earth systems.

GEOSYSTEMS NOW ONLINE To learn about NASA's Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), which measures CO_2 and CH_4 gas emissions in permafrost regions, go to http://science1.nasa.gov/missions/carve/ (the

▶ NEW! *The Human Denominator* summarizes Human-Earth relationships, interactions, challenges for the 21st century through dynamic visuals, including maps, photos, graphs, and diagrams.



THE human DENOMINATOR 12 Earth Materials and Plate Tectonics

ENDOGENIC PROCESSES ⇨ HUMANS

- Endogenic processes cause natural hazards such as earthquakes and volcanic events that affect humans and ecosystems.
- Rocks provide materials for human use; geothermal power is a renewable resource.

HUMANS ⇨ ENDOGENIC PROCESSES

- Wells drilled into Earth's crust in association with oil and gas drilling and Enhanced Geothermal Systems may cause earthquakes.

Hydrothermal features and travertine deposits are common in Yellowstone National Park, Wyoming, which sits above a stationary hot spot in Earth's crust. Hydrothermal activity produces hot springs, fumaroles (steam vents), mud pots, and geysers. Grand Prismatic Spring, pictured here, is the largest hot spring in the United States, and third largest in the world. [Edward Fielding/Shutterstock.]

The Mid-Atlantic Ridge system surfaces at Thingvellir, Iceland, now a tourist destination. The rifts mark the divergent boundary separating the North American and Eurasian plates. [ARCTIC IMAGES/Alamy.]

In April 2013, the Nevada Desert Peak Enhanced Geothermal System (EGS) became the first project with enough generating capacity to supply electricity to the power grid. [Inga Spence/Alamy.]

Uluru, also known as Ayers Rock, is probably Australia's best known landmark. This steep-sided isolated sandstone feature, about 3.5 km long and 1.9 km (1.2 mi) wide, was formed from endogenic and exogenic processes, and has cultural significance for the Aboriginal peoples. [Penny Tweedie/Alamy.]

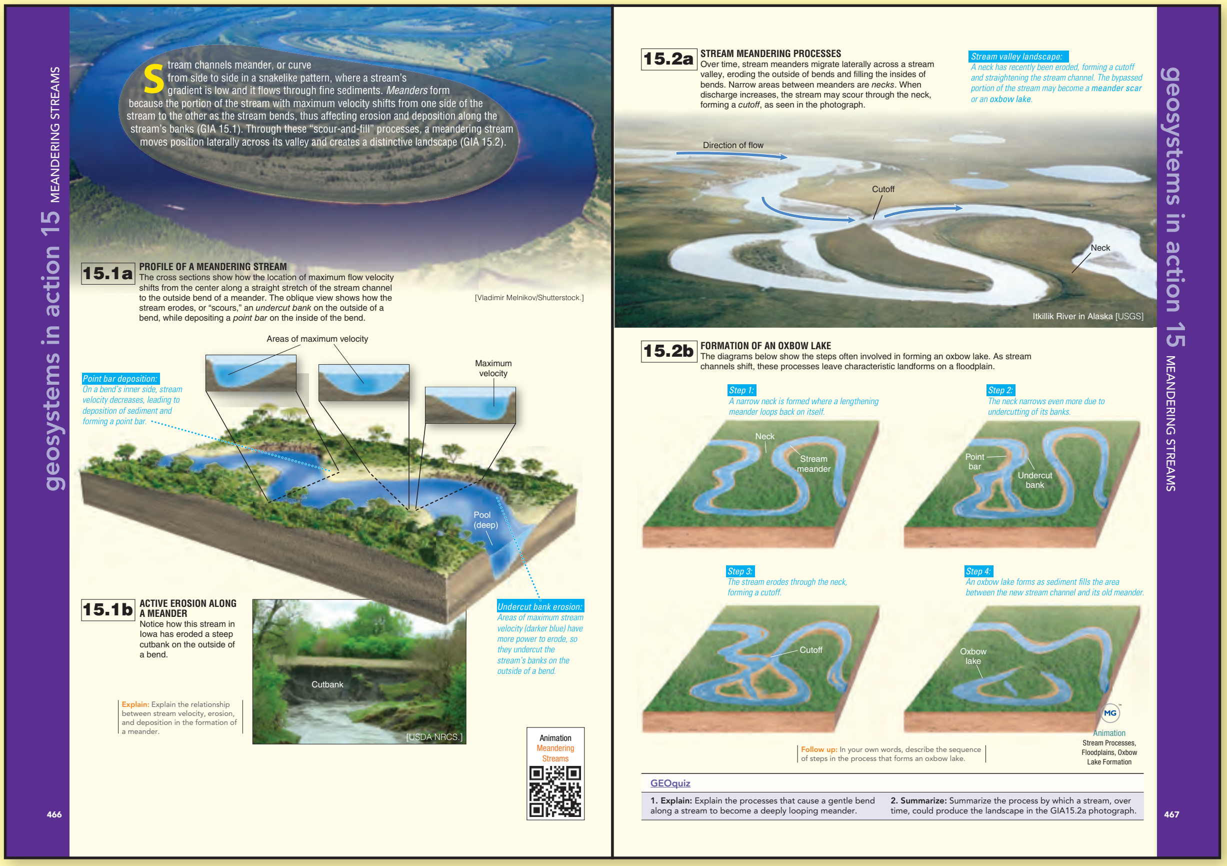
Background Image: [NOAA/NGDC.]

ISSUES FOR THE 21ST CENTURY

- Geothermal capacity will continue to be explored as an alternative energy source to fossil fuels.
- Mapping of tectonically active regions will continue to inform policy actions with regard to seismic hazards.

Visualizing Processes and Landscapes

▼ NEW! *Geosystems in Action* present highly-visual presentations of core physical processes and critical chapter concepts. These features include links to mobile-ready media as well as GeoQuizzes and integrated active learning tasks that ask students to analyze, explain, infer, or predict based on the information presented.



geosystems in action 15 MEANDERING STREAMS

Stream channels meander, or curve from side to side in a snakelike pattern, where a stream's gradient is low and it flows through fine sediments. *Meanders* form because the portion of the stream with maximum velocity shifts from one side of the stream to the other as the stream bends, thus affecting erosion and deposition along the stream's banks (GIA 15.1). Through these "scour-and-fill" processes, a meandering stream moves position laterally across its valley and creates a distinctive landscape (GIA 15.2).

15.1a PROFILE OF A MEANDERING STREAM
The cross sections show how the location of maximum flow velocity shifts from the center along a straight stretch of the stream channel to the outside bend of a meander. The oblique view shows how the stream erodes, or "scours," an *undercut bank* on the outside of a bend, while depositing a *point bar* on the inside of the bend.

[Vladimir Melnikov/Shutterstock.]

Point bar deposition: *On a bend's inner side, stream velocity decreases, leading to deposition of sediment and forming a point bar.*

Undercut bank erosion: *Areas of maximum stream velocity (darker blue) have more power to erode, so they undercut the stream's banks on the outside of a bend.*

15.1b ACTIVE EROSION ALONG A MEANDER
Notice how this stream in Iowa has eroded a steep cutbank on the outside of a bend.

[USDA NRCS.]

Explain: Explain the relationship between stream velocity, erosion, and deposition in the formation of a meander.

Animation
Meandering Streams

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15.2a STREAM MEANDERING PROCESSES
Over time, stream meanders migrate laterally across a stream valley, eroding the outside of bends and filling the insides of bends. Narrow areas between meanders are *necks*. When discharge increases, the stream may scour through the neck, forming a *cutoff*, as seen in the photograph.

Stream valley landscape: *A neck has recently been eroded, forming a cutoff and straightening the stream channel. The bypassed portion of the stream may become a* ***meander scar*** *or an* ***oxbow lake****.*

Itkillik River in Alaska [USGS]

15.2b FORMATION OF AN OXBOW LAKE
The diagrams below show the steps often involved in forming an oxbow lake. As stream channels shift, these processes leave characteristic landforms on a floodplain.

Step 1: *A narrow neck is formed where a lengthening meander loops back on itself.*

Step 2: *The neck narrows even more due to undercutting of its banks.*

Step 3: *The stream erodes through the neck, forming a cutoff.*

Step 4: *An oxbow lake forms as sediment fills the area between the new stream channel and its old meander.*

Follow up: In your own words, describe the sequence of steps in the process that forms an oxbow lake.

Animation
Stream Processes, Floodplains, Oxbow Lake Formation

GEOquiz

1. Explain: Explain the processes that cause a gentle bend along a stream to become a deeply looping meander.

2. Summarize: Summarize the process by which a stream, over time, could produce the landscape in the GIA15.2a photograph.

geosystems in action 15 MEANDERING STREAMS

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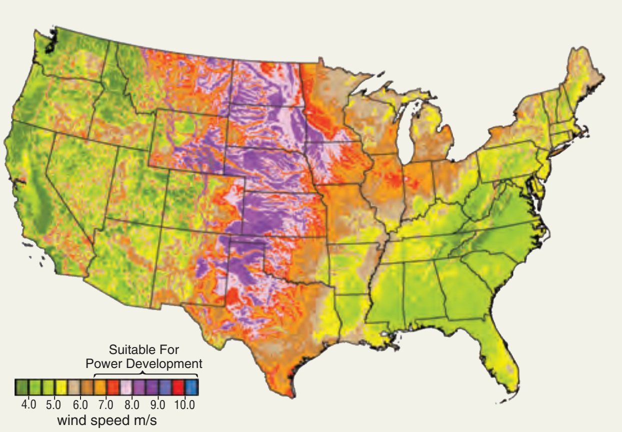
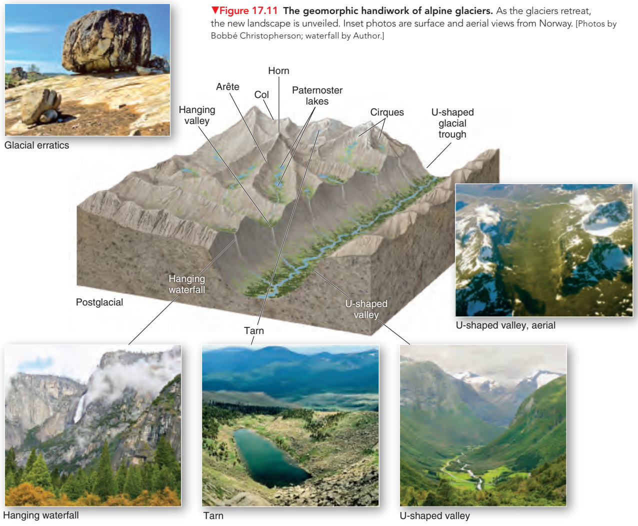
An unparalleled visual program includes a variety of illustrations, maps, photographs, and composites, providing authoritative examples and applications of physical geography and Earth systems science.



▲Figure 6.1.1 **Wind-speed map of the contiguous United States.** Map shows predicted average wind speeds at a height of 80 m (164 ft) above the ground. Areas with wind speeds greater than 6.5 m/s (21 ft/s) are considered suitable for power development. Map has a spatial resolution of 2.5 km (1.6 mi). [NREL and AWS Truepower.]

▼Figure 17.11 **The geomorphic handiwork of alpine glaciers.** As the glaciers retreat, the new landscape is unveiled. Inset photos are surface and aerial views from Norway. [Photos by Bobbé Christopherson; waterfall by Author.]



Physical Geography in the Real World

Geosystems **integrates current real events and phenomena and presents the most thorough and integrated treatment of systems trends and climate change science, giving students compelling reasons for learning physical geography.**

▼ ***Geosystems*** **Now** open each chapter with interesting, current applications of physical geography and Earth systems science. New **Geosystems Now Online** features direct students online to related resources.

GEOSYSTEMS now

Sand Dunes Prevent Coastline Erosion during Hurricane Sandy

During the winter of 2013, in the ongoing aftermath of Hurricane Sandy, many residents along New Jersey's coastline added their discarded Christmas trees to carefully stacked lines of trees intended to act as "seeds" for new sand dune formation along several area beaches. The hope is that the trees will catch windblown sand to begin the dune formation process, in one of many such restoration efforts along the Atlantic coast. In the face of Sandy's winds, houses and neighborhoods with protective dunes in place experienced less damage than those that were more exposed to and closer to the ocean.

Dune Protection versus Ocean Views The effectiveness of dune systems as protection from wave erosion and storm surge during Hurricane Sandy, far from being a subtle statistical phenomenon, was easily observed by local residents. However, the fostering of large and sometimes obtrusive sand dunes near the shoreline is controversial in coastal communities with million-dollar homes. For such dunes to function as barriers to erosion, they must sit between oceanfront property and the sea, thus blocking ocean views and decreasing property values (Figure GN 16.1). For many landowners, establishing dunes for storm protection means financial loss. in the short term, even if long-term protection is the result.

Coastal Dune Geomorphology Coastal sand dunes originate from sediment supplied by the work of ocean waves and by fluvial processes that move sediment onto deltas and estuaries. Once sand is deposited on shore, it is reworked by wind processes into the shape of dunes. Dunes along seacoasts are either *foredunes*, where sand is pushed up the seaward-facing slope, or *backdunes*, which form further away from the beach and are protected from onshore winds; backdunes are more stable and may be hundreds of years old. Most areas of coastal dunes are relatively small in size (especially when compared with desert dune fields that may cover large portions of continents).

Along the Atlantic coast, foredunes are moving inland as sea level rises and storm energy increases with climate change. In developed areas, the foredunes cannot retreat inland without impinging on human development. When storms occur, dune movement is intensified, and either dune erosion or sand deposition, or both, occurs within the developed area of the coast (Figure GN 16.2).

Dune Restoration Efforts The establishment of new foredunes replenishes the sand supply and protects structures and infrastructure, making this a potentially worthwhile investment of money and effort for communities along the New Jersey shoreline. Many experts point out that dunes are *not* a guarantee of storm protection and that Sandy's winds and storm surge were strong enough to erode some large natural dune systems along the Atlantic Seaboard. However, in Bradley Beach, New Jersey, where the storm eroded several miles of restored dunes about 4.6 m (15 ft) in height, the community still escaped excessive damage since the dunes absorbed much of the storm's impact.

Thus, local communities are supporting dune restoration, as evidenced by the Christmas tree initiative. Because vegetation is important for dune stabilization, the planting of grasses is another protective strategy being embraced by New Jersey residents. In this chapter, we discuss coastal systems, wind processes, and dune formation processes.

▲Figure GN 16.1 **Constructed dunes.** Restored sand dunes shield homes in Mantoloking, New Jersey, from an incoming nor'easter a few weeks after Hurricane Sandy. [Sharon Karr/FEMA.]

May 21, 2009

November 5, 2012

▲Figure GN 16.2 **Coastal damage from Sandy in Mantoloking, New Jersey.** View looking west before and after Hurricane Sandy. The yellow arrow points to the same feature in each image. [USGS.]

GEOSYSTEMS NOW ONLINE For information and links to research on dunes in New Jersey and along the Atlantic coast, see http://marine.rutgers.edu/geomorph/geomorph/_pages/dunes.html. MG

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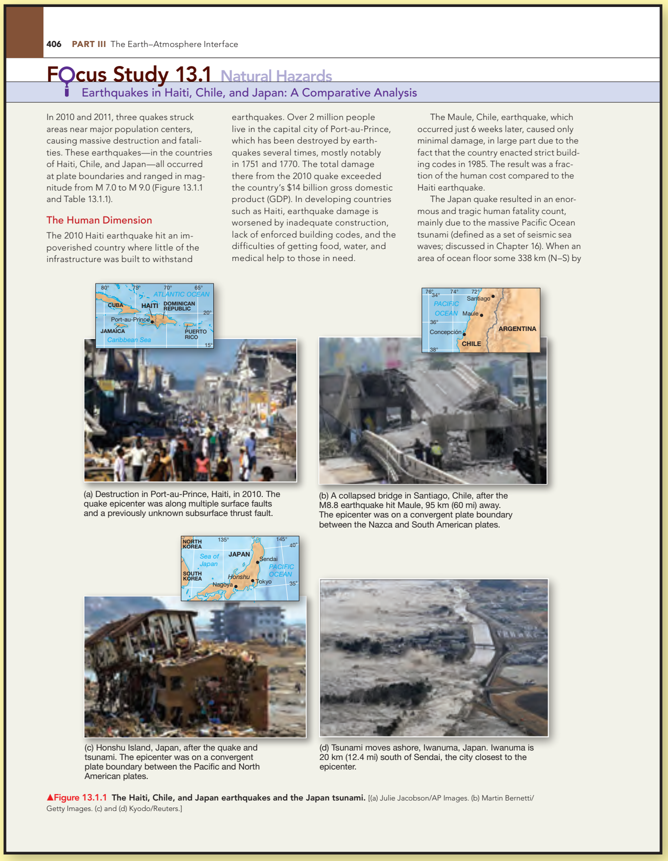
▼ ***Focus Studies*** present detailed discussions of critical physical geography topics, emphasizing the applied relevance of physical geography today.



406 PART III The Earth–Atmosphere Interface

Focus Study 13.1 Natural Hazards

Earthquakes in Haiti, Chile, and Japan: A Comparative Analysis

In 2010 and 2011, three quakes struck areas near major population centers, causing massive destruction and fatalities. These earthquakes—in the countries of Haiti, Chile, and Japan—all occurred at plate boundaries and ranged in magnitude from M 7.0 to M 9.0 (Figure 13.1.1 and Table 13.1.1).

The Human Dimension

The 2010 Haiti earthquake hit an impoverished country where little of the infrastructure was built to withstand earthquakes. Over 2 million people live in the capital city of Port-au-Prince, which has been destroyed by earthquakes several times, mostly notably in 1751 and 1770. The total damage there from the 2010 quake exceeded the country's $14 billion gross domestic product (GDP). In developing countries such as Haiti, earthquake damage is worsened by inadequate construction, lack of enforced building codes, and the difficulties of getting food, water, and medical help to those in need.

The Maule, Chile, earthquake, which occurred just 6 weeks later, caused only minimal damage, in large part due to the fact that the country enacted strict building codes in 1985. The result was a fraction of the human cost compared to the Haiti earthquake.

The Japan quake resulted in an enormous and tragic human fatality count, mainly due to the massive Pacific Ocean tsunami (defined as a set of seismic sea waves; discussed in Chapter 16). When an area of ocean floor some 338 km (N–S) by

(a) Destruction in Port-au-Prince, Haiti, in 2010. The quake epicenter was along multiple surface faults and a previously unknown subsurface thrust fault.

(b) A collapsed bridge in Santiago, Chile, after the M8.8 earthquake hit Maule, 95 km (60 mi) away. The epicenter was on a convergent plate boundary between the Nazca and South American plates.

(c) Honshu Island, Japan, after the quake and tsunami. The epicenter was on a convergent plate boundary between the Pacific and North American plates.

(d) Tsunami moves ashore, Iwanuma, Japan. Iwanuma is 20 km (12.4 mi) south of Sendai, the city closest to the epicenter.

▲Figure 13.1.1 **The Haiti, Chile, and Japan earthquakes and the Japan tsunami.** [(a) Julie Jacobson/AP Images. (b) Martin Bernetti/Getty Images. (c) and (d) Kyodo/Reuters.]

► **GeoReports** offer a wide variety of brief interesting facts, examples, and applications to complement and enrich the chapter reading.

GEOreport 8.2 Mountains cause record rains

Mount Waialeale, on the island of Kaua'i, Hawai'i, rises 1569 m (5147 ft) above sea level. On its windward slope, rainfall averaged 1234 cm (486 in., or 40.5 ft) a year for the years 1941–1992. In contrast, the rain-shadow side of Kaua'i receives only 50 cm (20 in.) of rain annually. If no islands existed at this location, this portion of the Pacific Ocean would receive only an average 63.5 cm (25 in.) of precipitation a year. (These statistics are from established weather stations with a consistent record of weather data; several stations claim higher rainfall values but do not have dependable measurement records.)

Cherrapunji, India, is 1313 m (4309 ft) above sea level at 25° N latitude, in the Assam Hills south of the Himalayas. Summer monsoons pour in from the Indian Ocean and the Bay of Bengal, producing 930 cm (366 in., or 30.5 ft) of rainfall in 1 month. Not surprisingly, Cherrapunji is the all-time precipitation record holder for a single year, 2647 cm (1042 in., or 86.8 ft), and for every other time interval from 15 days to 2 years. Th

GEOreport 13.3 Large earthquakes affect Earth's axial tilt

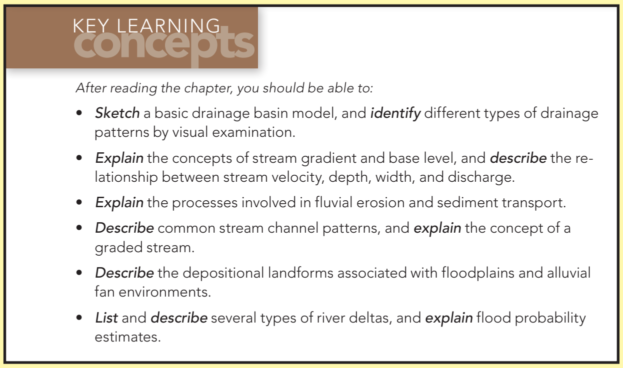
Scientific evidence is mounting that Earth's largest earthquake events have a global influence. Both the 2004 Sumatran–Andaman quake and the 2011 Tohoku quake in Japan caused Earth's axial tilt to shift several centimeters. NASA scientists estimate that the redistribution of mass in each quake shortened daylength by 6.8 millionths of a second for the 2004 event and 1.8 millionths of a second for the 2011 event.

GEOreport 19.2 Sea turtles navigate using Earth's magnetic field

The fact that birds and bees can detect Earth's magnetic field and use it for finding direction is well established. Small amounts of magnetically sensitive particles in the skull of the bird and the abdomen of the bee provide compass directions. Recently, scientists found that sea turtles detect magnetic fields of different strengths and inclinations (angles). This means that the turtles have a built-in navigation system that helps them find certain locations on Earth. Loggerhead turtles hatch in Florida, crawl into the water, and spend the next 70 years traveling thousands of miles between North America and Africa around the subtropical high-pressure gyre in the Atlantic Ocean. The females return to where they were hatched to lay their eggs. In turn, the hatchlings are imprinted with magnetic data unique to the location of their birth and then develop a more global sense of position as they live a life swimming across the ocean.

Tools for Structured Learning

Geosystems provides a structured learning path that helps students achieve a deeper understanding of physical geography through active learning.



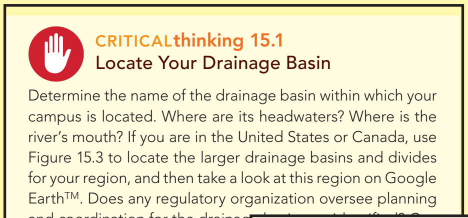
KEY LEARNING **concepts**

After reading the chapter, you should be able to:

- *Sketch* a basic drainage basin model, and ***identify*** different types of drainage patterns by visual examination.
- *Explain* the concepts of stream gradient and base level, and ***describe*** the relationship between stream velocity, depth, width, and discharge.
- *Explain* the processes involved in fluvial erosion and sediment transport.
- *Describe* common stream channel patterns, and ***explain*** the concept of a graded stream.
- *Describe* the depositional landforms associated with floodplains and alluvial fan environments.
- *List* and ***describe*** several types of river deltas, and ***explain*** flood probability estimates.

◄ ***Key Learning Concepts*** at the beginning of every chapter help students identify the key knowledge and skills they will acquire through study of the chapter.

▼ ***Critical Thinking Activities*** integrated throughout chapter sections give students an opportunity to stop, check, and apply their understanding.

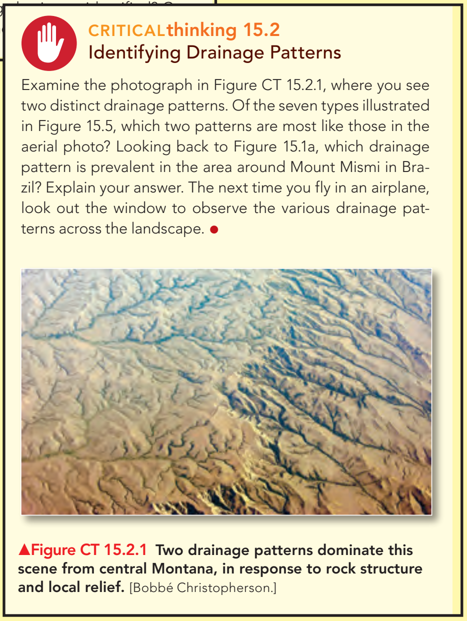


CRITICAL**thinking 15.1**

Locate Your Drainage Basin

Determine the name of the drainage basin within which your campus is located. Where are its headwaters? Where is the river's mouth? If you are in the United States or Canada, use Figure 15.3 to locate the larger drainage basins and divides for your region, and then take a look at this region on Google Earth™. Does any regulatory organization oversee planning and coordination for the drainag

you find topographic maps onlin



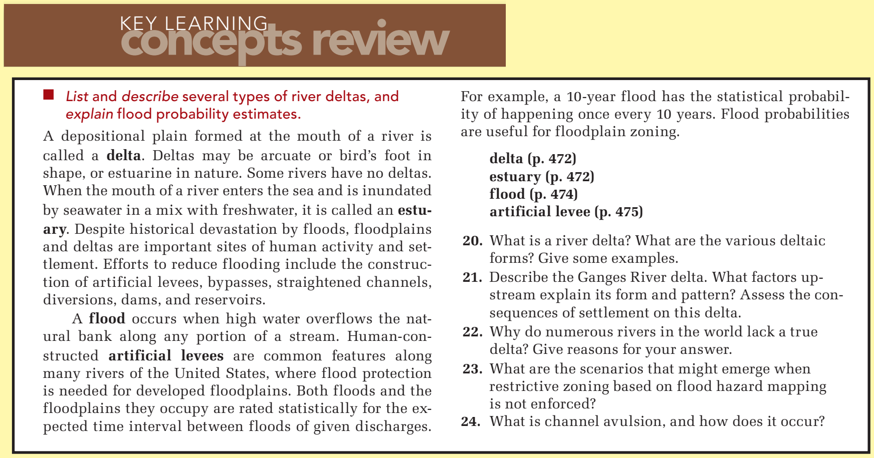
CRITICAL**thinking 15.2**

Identifying Drainage Patterns

Examine the photograph in Figure CT 15.2.1, where you see two distinct drainage patterns. Of the seven types illustrated in Figure 15.5, which two patterns are most like those in the aerial photo? Looking back to Figure 15.1a, which drainage pattern is prevalent in the area around Mount Mismi in Brazil? Explain your answer. The next time you fly in an airplane, look out the window to observe the various drainage patterns across the landscape. ●

▲Figure CT 15.2.1 **Two drainage patterns dominate this scene from central Montana, in response to rock structure and local relief.** [Bobbé Christopherson.]

▼ ***Key Learning Concepts Review*** at the end of each chapter concludes the learning path and features summaries, narrative definitions, a list of key terms with page numbers, and review questions.



KEY LEARNING **concepts review**

■ *List* and *describe* several types of river deltas, and *explain* flood probability estimates.

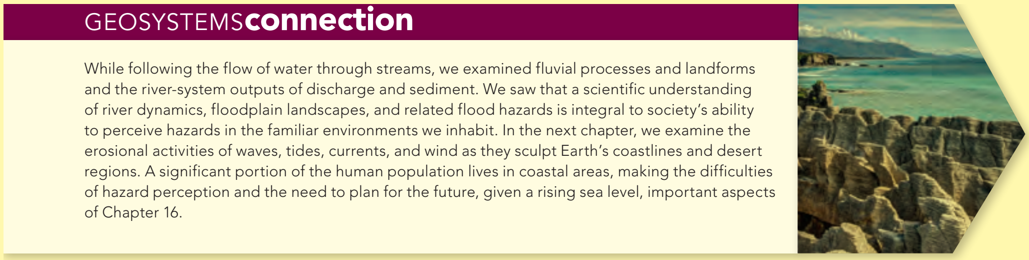
A depositional plain formed at the mouth of a river is called a **delta**. Deltas may be arcuate or bird's foot in shape, or estuarine in nature. Some rivers have no deltas. When the mouth of a river enters the sea and is inundated by seawater in a mix with freshwater, it is called an **estuary**. Despite historical devastation by floods, floodplains and deltas are important sites of human activity and settlement. Efforts to reduce flooding include the construction of artificial levees, bypasses, straightened channels, diversions, dams, and reservoirs.

A **flood** occurs when high water overflows the natural bank along any portion of a stream. Human-constructed **artificial levees** are common features along many rivers of the United States, where flood protection is needed for developed floodplains. Both floods and the floodplains they occupy are rated statistically for the expected time interval between floods of given discharges. For example, a 10-year flood has the statistical probability of happening once every 10 years. Flood probabilities are useful for floodplain zoning.

delta (p. 472)
estuary (p. 472)
flood (p. 474)
artificial levee (p. 475)

20. What is a river delta? What are the various deltaic forms? Give some examples.
21. Describe the Ganges River delta. What factors upstream explain its form and pattern? Assess the consequences of settlement on this delta.
22. Why do numerous rivers in the world lack a true delta? Give reasons for your answer.
23. What are the scenarios that might emerge when restrictive zoning based on flood hazard mapping is not enforced?
24. What is channel avulsion, and how does it occur?

► ***Geosystems Connection*** at the end of chapters help students bridge concepts between chapters, reminding them where they have been and where they are going.



GEOSYSTEMS**connection**

While following the flow of water through streams, we examined fluvial processes and landforms and the river-system outputs of discharge and sediment. We saw that a scientific understanding of river dynamics, floodplain landscapes, and related flood hazards is integral to society's ability to perceive hazards in the familiar environments we inhabit. In the next chapter, we examine the erosional activities of waves, tides, currents, and wind as they sculpt Earth's coastlines and desert regions. A significant portion of the human population lives in coastal areas, making the difficulties of hazard perception and the need to plan for the future, given a rising sea level, important aspects of Chapter 16.

about our sustainability initiatives

Pearson recognizes the environmental challenges facing this planet, as well as acknowledges our responsibility in making a difference. This book has been carefully crafted to minimize environmental impact. The binding, cover, and paper come from facilities that minimize waste, energy consumption, and the use of harmful chemicals. Pearson closes the loop by recycling every out-of-date text returned to our warehouse.

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Essentials of Geography

A snow avalanche roars down Mount Timpanogos, the second highest peak in Utah's Wasatch Mountains. Snow avalanches are a significant hazard in mountainous environments worldwide, killing hundreds of people annually. Avalanches result from the combination of steep, open slopes and unstable snow. The dramatic vertical relief of the Wasatch Range, which rises 2301 m (7,550 ft) above the Great Salt Lake, interacts with moist Pacific air masses, resulting in an average of 160 m (525 in.) of snowfall each winter. Winter storms set the stage for dangerous conditions. New snow and wind that blows snow onto lee slopes are the primary factors contributing to avalanche formation. This January 2005 avalanche stopped short of the houses in the foreground. [Bruce Tremper, Utah Avalanche Center.]

KEY LEARNING concepts

After reading the chapter, you should be able to:

- ***Define*** geography in general and physical geography in particular.
- ***Discuss*** human activities and human population growth as they relate to geographic science, and ***summarize*** the scientific process.
- ***Describe*** systems analysis, open and closed systems, and feedback information, and ***relate*** these concepts to Earth systems.
- ***Explain*** Earth's reference grid: latitude and longitude and latitudinal geographic zones and time.
- ***Define*** cartography and mapping basics: map scale and map projections.
- ***Describe*** modern geoscience techniques—the Global Positioning System (GPS), remote sensing, and geographic information systems (GIS)—and ***explain*** how these tools are used in geographic analysis.

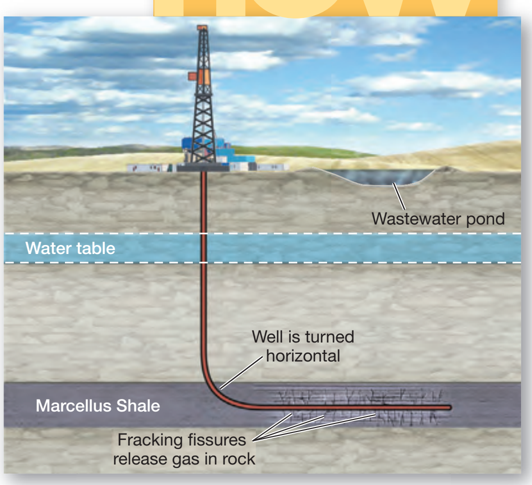
Shale Gas: An Energy Resource for the Future?

In an area stretching 965 km (600 mi) from Ohio to western New York, methane lies deeply buried in a sedimentary rock deposit, the Marcellus Shale. Methane is the primary constituent of natural gas, and scientists suggest that this ancient rock layer, underlying 60% of Pennsylvania, may be one of the most significant reservoirs of natural gas in the world. Pennsylvania alone is dotted with nearly 6000 shale gas wells extracting pressurized methane (Figure GN 1.1).

What Is Methane? Methane is a chemical compound with a formula of CH_4 and is a by-product of several natural processes: digestive activity of animals (cattle, sheep, bison) and termites; melting of arctic permafrost; burning associated with wildfires; and bacterial activity in bogs, swamps, and wetlands. Nearly 60% of the methane in our atmosphere comes from human sources, including natural gas production, beef and dairy production, rice cultivation, coal and oil extraction and burning, landfills, and wastewater treatment. In the United States, the natural gas industry makes up the largest percentage of U.S. methane emissions.

Drilling for Methane To release methane trapped within shale layers, the rock must be broken up so that gas diffuses into the cracks and flows upward. Over the past 20 years, advances in horizontal drilling techniques, combined with the process of hydraulic fracturing, or "fracking," opened access to large amounts of natural gas previously deemed too expensive or difficult to tap. A typical shale gas well descends vertically 2.4 km (1.5 mi), then turns and drills horizontally into the rock strata. Horizontal drilling exposes a greater area of the rock, allowing more of it to be broken up and more gas to be released (Figure GN 1.2).

▲**Figure GN 1.1 Shale deposits and areas of exploration for natural gas extraction, United States and Canada.** [U.S. Energy Information Administration]



▲**Figure GN 1.2 Horizontal drilling for hydraulic fracturing (fracking) and shale gas extraction.**

A pressurized fluid is pumped into the well to break up the rock—90% water, 9% sand or glass beads to prop open the fissures, and 1% chemical additives as lubricants. The specific chemicals used are as yet undisclosed by the industry. This use of an injected fluid to fracture the shale is the process of fracking. Gas then flows up the well to be collected at the surface.

Fracking uses massive quantities of water: approximately 15 million liters (4 million gallons) for each well system, flowing at a rate of 16,000 L (4200 gal) per minute—far more than could be provided by a public water system. In southwestern Pennsylvania, storage ponds hold the water pumped to well sites for fracking operations.

The U.S. Energy Information Administration (EIA) projects a boom in shale gas extraction and production from fracking over the next 20 years, with U.S. production rising from 30% of all natural gas production in 2010 to 49% in 2030.

Environmental Effects As with other resource-extraction techniques, fracking leaves hazardous by-products. It produces large amounts of toxic wastewater, often held in wells or containment ponds. Any leak or failure of pond retaining walls spills pollutants into surface water supplies and groundwater. Methane gas may leak around well casings, which tend to crack during the fracking process. Leaks can cause buildup of methane in groundwater, leading to contaminated drinking water wells, flammable tap water, methane accumulation in barns and homes, and possible explosions.

Methane adds to air pollution as a constituent in smog and is a potent greenhouse gas, absorbing heat from the Sun near Earth's surface and contributing to global climate change. In addition, scientists linked the injection of fluid into wastewater wells to increased ground instability and earthquake activity in Ohio, West Virginia, Texas, Oklahoma, and parts of the Midwest.

This rapidly expanding energy resource has varied impacts on air, water, land, and living Earth systems. However, many of the environmental effects of shale gas extraction remain unknown; further scientific study is critical.

Shale Gas and *Geosystems* Resource location and distribution and human–environment interactions not only are important issues associated with shale gas extraction, but also are at the heart of geographic science. In this chapter, you work with several "Essentials of Geography": the scientific process, Earth systems thinking, spatial concepts, and mapping. Throughout *Geosystems*, we will expand the story of shale gas and its far-reaching effects on global climate, surface water and groundwater resources, and ecosystem functions.

GEOSYSTEMS NOW ONLINE Explore shale gas online at http://ngm.nationalgeographic.com/2012/12/methane/lavelle-text for an interactive diagram called "Breaking Fuel from the Rock" and links to articles. For another perspective, go to http://www.energyfromshale.org/shale-extraction-process, which presents shale gas extraction from the energy industry's point of view. Should the United States and other countries expand shale gas as an energy resource for the future?

Welcome to the Ninth Edition of *Geosystems* and the study of physical geography! In this text, we examine the powerful Earth systems that influence our lives and the many ways humans impact those systems. This is an important time to study physical geography, learning about Earth's environments, including the systems that form the landscapes, seascapes, atmosphere, and ecosystems on which humans depend. In this second decade of the 21st century, a century that will see many changes to our natural world, scientific study of the Earth and environment is more crucial than ever.

Consider the following events, among many similar ones we could mention, and the questions they raise for the study of Earth's systems and physical geography. This text provides tools for answering these questions and addressing the underlying issues.

- In October 2012, Hurricane Sandy made landfall along the U.S. East Coast, hitting New York and New Jersey at high tide with hurricane force winds and record storm surges. The storm cost 110 human lives and over $42 billion in New York State alone, approaching $100 billion in damages overall. What atmospheric processes explain the formation and movement of this storm? Why the unprecedented size and intensity? How is this storm related to record air and ocean temperatures?
- In March 2011, a magnitude 9.0 earthquake and resultant 10- to 20-m (33- to 66-ft) tsunami devastated Honshu Island, Japan—at $309 billion (U.S. dollars), Earth's most expensive natural disaster. Why do earthquakes occur in particular locations across the globe? What produces tsunami, and how far and fast do they travel? This event caused the worst multiple nuclear power plant catastrophe in history, with three core meltdowns, releasing dangerous quantities of radioactivity over land and into the atmosphere and ocean, and eventually reaching the food supply. How will prevailing winds and currents disperse the radiation across the globe?
- By the end of 2012, the removal of two dams on the Elwha River in Washington was almost complete—the largest dam removals in the world to date (Figure 1.1). The project will restore a free-flowing river for fisheries and associated ecosystems. In Brazil, construction of the controversial Belo Monte hydroelectric dam on the Xingu River continues, despite court orders and violent protests. The dam will displace nearly 20,000 people and, when completed, will be the world's third largest hydroelectric project, one of 60 planned to generate power for Brazil's rapidly expanding economy. How do dams change river environments?
- In 2011, the world released 2.4 million pounds of carbon dioxide (CO_2) into the atmosphere every second, mainly from the burning of fossil fuels; China's 1.3 billion people produce 10 billion tons of CO_2 annually. This "greenhouse gas" contributes to climate change by trapping heat near Earth's surface. Each year atmospheric CO_2 levels rise to a new record, altering Earth's climate. What are the effects and what do climate forecasts tell us?

▲**Figure 1.1 Dam removal for river restoration.** Removal of Glines Canyon Dam on the Elwha River, Washington, began in November 2012 to restore river ecosystems. [Brian Cluer/NOAA.]

Physical geography uses a *spatial* perspective to examine processes and events happening at specific locations and follow their effects across the globe. Why does the environment vary from equator to midlatitudes, and between deserts and polar regions? How does solar energy influence the distribution of trees, soils, climates, and lifestyles? What produces the patterns of wind, weather, and ocean currents? Why are global sea levels on the rise? How do natural systems affect human populations, and, in turn, what impact are humans having on natural systems? Why are record levels of plants and animals facing extinction? In this book, we explore those questions, and more, through geography's unique perspective.

Perhaps more than any other issue, climate change has become an overriding focus of the study of Earth systems. The past decade experienced the highest temperatures over land and water in the instrumental record. The year 2010 tied 2005 as the warmest for global temperatures. In response, the extent of sea ice in the Arctic Ocean continues to decline to record lows—the 2012 summer sea ice extent was the lowest since satellite measurements began in 1979. Between 1992 and 2011, melting of the Greenland and Antarctica ice sheets accelerated; together they now lose more than three times the ice they lost annually 20 years ago and contribute about 20% of current sea-level rise. Elsewhere, intense weather events, drought, and flooding continue to increase.

The Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/), the lead international scientific body assessing the current state of knowledge about climate change and its impacts on society and the environment, completed its *Fourth Assessment Report* in 2007, and released the *Fifth Assessment Report* in 2014. The overwhelming scientific consensus is that human activities are forcing climate change. The first edition of *Geosystems* in 1992 featured the findings of the initial *First Assessment Report* from the IPCC, and the current edition continues to survey climate change evidence and consider its implications. In every chapter, *Geosystems* presents up-to-date science and information to help you understand our dynamic Earth systems. Welcome to an exploration of physical geography!

In this chapter: Our study of geosystems—Earth systems—begins with a look at the science of physical geography and the geographic tools it uses. Physical geography uses an integrative spatial approach, guided by the scientific process, to study entire Earth systems. The role of humans is an increasingly important focus of physical geography, as are questions of global sustainability as Earth's population grows.

Physical geographers study the environment by analyzing air, water, land, and living systems. Therefore, we discuss systems and the feedback mechanisms that influence system operations. We then consider location on Earth as determined by the coordinated grid system of latitude and longitude, and the determination of world time zones. Next, we examine maps as critical tools that geographers use to display physical and cultural information. This chapter concludes with an overview of new and widely accessible technologies that are adding exciting new dimensions to geographic science: Global Positioning System, remote sensing from space, and geographic information systems.

The Science of Geography

A common idea about geography is that it is chiefly concerned with place names. Although location and place are important geographic concepts, geography as a science encompasses much more. **Geography** (from *geo*, "Earth," and *graphein*, "to write") is the science that studies the relationships among natural systems, geographic areas, society, and cultural activities, and the interdependence of all of these, *over space.* These last two words are key, for geography is a science that is in part defined by its method—a special way of analyzing phenomena over space. In geography, the term **spatial** refers to the nature and character of physical space, its measurement, and the distribution of things within it.

Geographic concepts pertain to distributions and movement across Earth. For example, to the patterns of air and ocean currents over Earth's surface, and how these currents affect the dispersal of pollutants, such as nuclear radiation or oil spills. Geography, then, is the spatial consideration of Earth processes interacting with human actions.

Although geography is not limited to place names, maps and location are central to the discipline and are important tools for conveying geographic data. Evolving technologies such as geographic information systems (GIS) and the Global Positioning System (GPS) are widely used for scientific applications and in today's society as hundreds of millions of people access maps and locational information every day on computers and mobile devices.

For educational purposes, the concerns of geographic science have traditionally been divided into five spatial themes: **location**, **region**, **human–Earth relationships**, **movement**, and **place,** each illustrated and defined in Figure 1.2. These themes, first implemented in 1984, are still used as a framework for understanding geographic concepts at all levels, and *Geosystems* draws on each. At the same time, the National Center for Geographic Education (NCGE) has updated the geography education guidelines (most recently in 2012) in response to increasing globalization and environmental change, redefining the essential elements of geography and expanding their number to six: *the spatial world*, *places and regions*, *physical systems*, *human systems*, *environment and society*, and *uses of geography in today's society*. These categories emphasize the spatial and environmental perspectives within the discipline and reflect the growing importance of human–environment interactions.

The Geographic Continuum

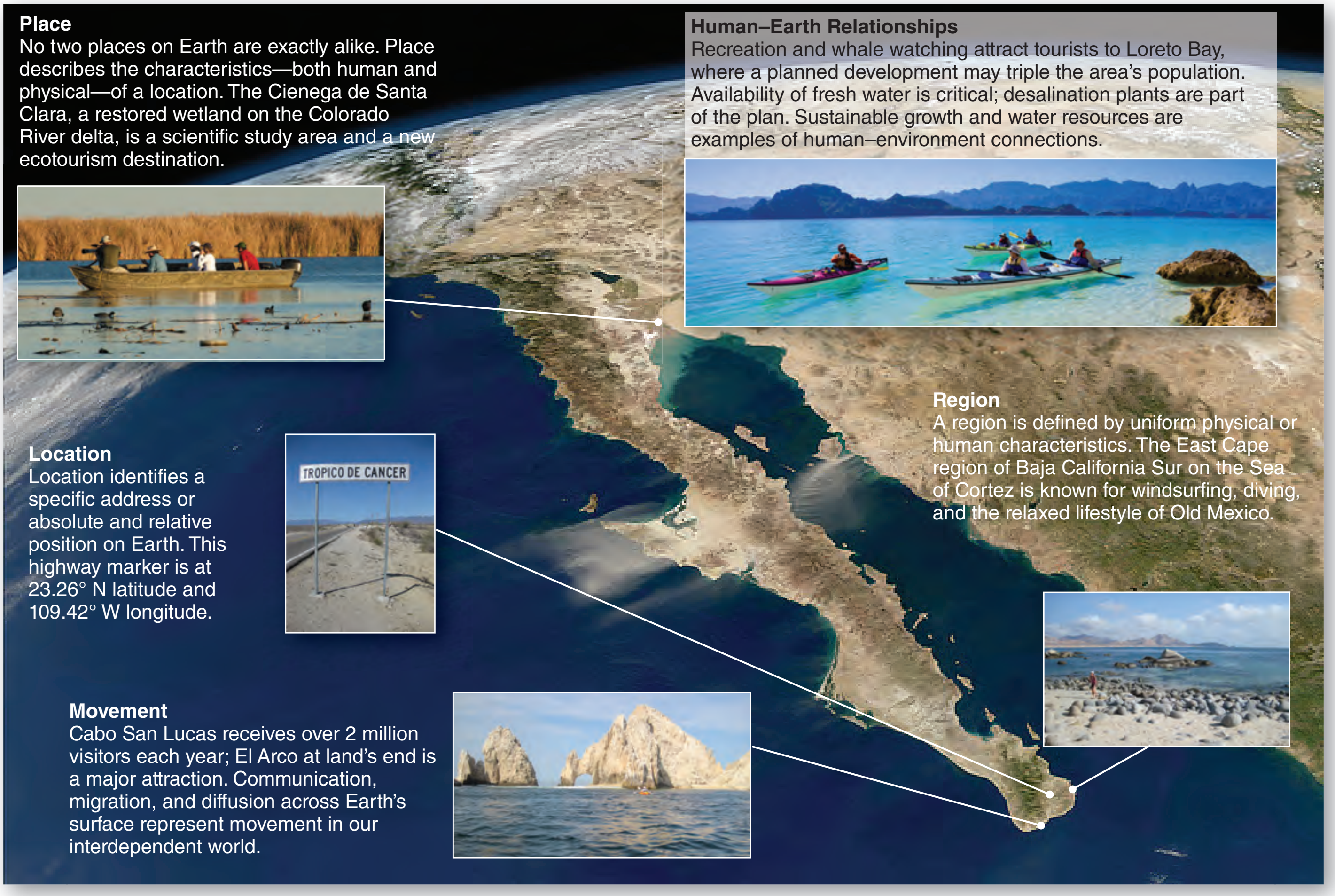
Because many subjects can be examined geographically, geography is an eclectic science that integrates subject matter from a wide range of disciplines. Even so, it splits broadly into two primary fields: *physical geography*, comprising specialty areas that draw largely on the physical and life sciences; and *human geography*, comprising specialty areas that draw largely on the social and cultural sciences. Prior to this century, scientific studies tended to fall onto one end of this continuum or the other. Humans tended at times to think of themselves as exempt from physical Earth processes—like actors not paying attention to their stage, props, and lighting.

However, as global population, communication, and movement increase, so does awareness that we all depend on Earth's systems to provide oxygen, water, nutrients, energy, and materials to support life. The growing complexity of the human–Earth relationship in the twenty-first century has shifted the study of geographic processes toward the center of the continuum in Figure 1.3 to attain a more balanced perspective—such is the thrust of *Geosystems*. This more balanced synthesis is reflected in geographic subfields such as natural resource geography and environmental planning, and in technologies such as geographic information science (GISci), used by both physical and human geographers.

Within physical geography, research now emphasizes human influences on natural systems in all specialty areas, effectively moving this end of the continuum closer to the middle. For example, physical geographers monitor air pollution, examine the vulnerability of human populations to climate change, study impacts of human activities on forest health and the movement of invasive species, study changes in river systems caused by dams and dam removal, and examine the response of glacial ice to changing climate.

Geographic Analysis

As mentioned earlier, the science of geography is unified more by its method than by a specific body of knowledge.



Place
No two places on Earth are exactly alike. Place describes the characteristics—both human and physical—of a location. The Cienega de Santa Clara, a restored wetland on the Colorado River delta, is a scientific study area and a new ecotourism destination.

Human–Earth Relationships
Recreation and whale watching attract tourists to Loreto Bay, where a planned development may triple the area's population. Availability of fresh water is critical; desalination plants are part of the plan. Sustainable growth and water resources are examples of human–environment connections.

Region
A region is defined by uniform physical or human characteristics. The East Cape region of Baja California Sur on the Sea of Cortez is known for windsurfing, diving, and the relaxed lifestyle of Old Mexico.

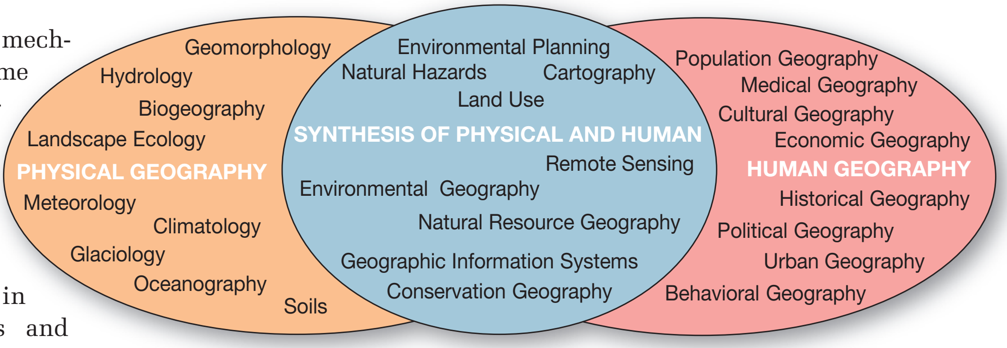
Location
Location identifies a specific address or absolute and relative position on Earth. This highway marker is at 23.26° N latitude and 109.42° W longitude.

Movement
Cabo San Lucas receives over 2 million visitors each year; El Arco at land's end is a major attraction. Communication, migration, and diffusion across Earth's surface represent movement in our interdependent world.

▲**Figure 1.2 Five themes of geographic science.** Drawing from your own experience, can you think of examples of each theme? This 2011 satellite image shows the entire length of Mexico's Baja peninsula, including Earth's curvature. [Photos by Karl Birkeland, except Place by Cheryl Zook/National Geographic and Human–Earth by Gary Luhm/garyluhm.net. Image from *Aqua* satellite/Norman Kuring, Ocean Color Team. NASA/GSFC.]

The method is **spatial analysis**. Using this method, geography synthesizes (brings together) topics from many fields, integrating information to form a whole-Earth concept. Geographers view phenomena as occurring across spaces, areas, and locations. The language of geography reflects this spatial view: territory, zone, pattern, distribution, place, location, region, sphere, province, and distance. Geographers analyze the differences and similarities between places.

Process, a set of actions or mechanisms that operate in some special order, is a central concept of geographic analysis. Among the examples you encounter in *Geosystems* are the numerous processes involved in Earth's vast water–atmosphere–weather system; in continental crust movements and earthquake occurrences; in ecosystem functions; or in river channel dynamics. Geographers use spatial analysis to examine how Earth's processes interact through space or over areas.



▲**Figure 1.3 The content of geography.** Geography synthesizes Earth topics and human topics, blending ideas from many different sciences. This book focuses on physical geography, but integrates pertinent human and cultural content for a whole-Earth perspective.

Therefore, **physical geography** is the spatial analysis of all the physical elements, processes, and systems that make up the environment: energy, air, water, weather, climate, landforms, soils, animals, plants, microorganisms, and Earth itself. Today, in addition to its place in the geographic continuum, physical geography also forms part of the broad field of **Earth systems science**, the area of study that seeks to understand Earth as a complete entity, an interacting set of physical, chemical, and biological systems. With these definitions in mind, we now discuss the general process and methods used by scientists, including geographers.

The Scientific Process

The process of science consists of observing, questioning, testing, and understanding elements of the natural world. The **scientific method** is the traditional recipe of a scientific investigation; it can be thought of as simple, organized steps leading toward concrete, objective conclusions. A scientist observes and asks questions, makes a general statement to summarize the observations, formulates a hypothesis (a logical explanation), conducts experiments or collects data to test the hypothesis, and interprets results. Repeated testing and support of a hypothesis leads to a scientific theory. Sir Isaac Newton (1642–1727) developed this method of discovering the patterns of nature, although the term *scientific method* was applied later.

While the scientific method is of fundamental importance in guiding scientific investigation, the real process of science is more dynamic and less linear, leaving room for questioning and thinking “out of the box.” Flexibility and creativity are essential to the scientific process, which may not always follow the same sequence of steps or use the same methods for each experiment or research project. There is no single, definitive method for doing science; scientists in different fields and even in different subfields of physical geography may approach their scientific testing in different ways. However, the end result must be a conclusion that can be tested repeatedly and possibly shown as true, or as false. Without this characteristic, it is not science.

Using the Scientific Method

Figure 1.4 illustrates steps of the scientific method and outlines a simple application examining cottonwood tree distributions. The scientific method begins with our perception of the real world. Scientists who study the physical environment begin with the clues they see in nature. The process begins as scientists question and analyze their observations and explore the relevant published scientific literature on their topic. Brainstorming with others, continued observation, and preliminary data collection may occur at this stage.

Questions and observations identify variables, which are the conditions that change in an experiment or model. Scientists often seek to reduce the number of variables when formulating a *hypothesis*—a tentative explanation for the phenomena observed. Since natural systems are complex, controlling or eliminating variables helps simplify research questions and predictions.

Scientists test hypotheses using experimental studies in laboratories or natural settings. Correlational studies, which look for associations between variables, are common in many scientific fields, including physical geography. The methods used for these studies must be reproducible so that repeat testing can occur. Results may support or disprove the hypothesis, or predictions made according to it may prove accurate or inaccurate. If the results disprove the hypothesis, the researcher will need to adjust data-collection methods or refine the hypothesis statement. If the results support the hypothesis, repeated testing and verification may lead to its elevation to the status of a *theory*.

Reporting research results is also part of the scientific method. For scientific work to reach other scientists and eventually the public at large, it must be described in a scientific paper and published in one of many scientific journals. Critical to the process is *peer review*, in which other members of the scientific or professional community critique the methods and interpretation of results. This process also helps detect any personal or political bias by the scientist. When a paper is submitted to a scientific journal, it is sent to reviewers, who may recommend rejecting the paper or accepting and revising it for publication. Once a number of papers are published with similar results and conclusions, the building of a theory begins.

The word *theory* can be confusing as used by the media and general public. A scientific theory is constructed on the basis of several extensively tested hypotheses and can be reevaluated or expanded according to new evidence. Thus, a scientific theory is not absolute truth; the possibility always exists that the theory could be proved wrong. However, theories represent truly broad general principles—unifying concepts that tie together the laws that govern nature. Examples include the theory of relativity, theory of evolution, and plate tectonics theory. A scientific theory reinforces our perception of the real world and is the basis for predictions to be made about things not yet known. The value of a scientific theory is that it stimulates continued observation, testing, understanding, and pursuit of knowledge within scientific fields.

Applying Scientific Results

Scientific studies described as “basic” are designed largely to help advance knowledge and build scientific theories. Other research is designed to produce “applied” results tied directly to real-world problem solving. Applied scientific research may advance new technologies, affect natural resource policy, or directly impact management strategies. Scientists share the results of both basic and applied research at conferences as well as in published papers, and they may take leadership roles in policy and planning. For example, the awareness that human activity is producing global climate change places increasing pressure on scientists to participate in decision making. Numerous editorials in scientific journals have called for such practical scientific involvement.

The nature of science is objective and does not make value judgments. Instead, pure science provides people and their institutions with objective information on which to base their own value judgments. Social and political judgments about the applications of science are increasingly important as Earth’s natural systems respond to the impacts of modern civilization.

(a) **Scientific Process Flow Chart**

Real World Observations
- Observe nature, ask questions, collect preliminary data
- Search for patterns, build conceptual or numerical models of natural systems

Hypothesis and Predictions
- Formulate hypothesis (a logical explanation)
- Identify variables and determine data needed and collection methods

Experimentation and Measurement
- Conduct tests to verify hypothesis; called "hypothesis testing"

Results support hypothesis

Results prove hypothesis false
- Reject hypothesis

Peer Review
- Communicate findings for evaluation by other scientists

Reject methods or results

Scientific Paper Published
- Revise and approve paper
- Follow with further research

Scientific Theory Development
- Hypothesis survives repeated testing without being shown false
- Comprehensive explanation for real world observation is widely accepted and supported by research

(b) **Using the Scientific Process to Study Cottonwood Tree Distribution**

1. Observations
In the dry climates of the western United States, cottonwood trees grow only along rivers. These trees are not found away from watercourses. What environmental factors influence their spatial distribution?

2. Questions and Variables
Are temperatures near rivers favorable for cottonwood growth?
Is consistent moisture needed for tree survival?
Do cottonwood roots grow only in river gravels or only in sediments with specific nutrients?
Have humans removed all the cottonwoods except along rivers?
Cottonwood trees are the *dependent variable* because their distribution is dependent on some environmental factor. Temperature, sunlight, moisture, sediment type, nutrients, and human actions are *independent variables*; any or all of these may be found to determine patterns of cottonwood distribution.

3. Hypothesis
One possible explanation for the observed pattern of tree distribution is that cottonwoods require consistent moisture in their root zone.
We can test the hypothesis that the number of cottonwoods decreases as one moves away from a river channel because there the tree roots are out of the reach of surface flows and groundwater.

4. Testing
Collect data from natural systems for a natural experiment. Establish vegetation plots (small areas of ground). Sample, or count, trees within plots and measure the distance of each tree from the main channel. Control other variables as much as possible.

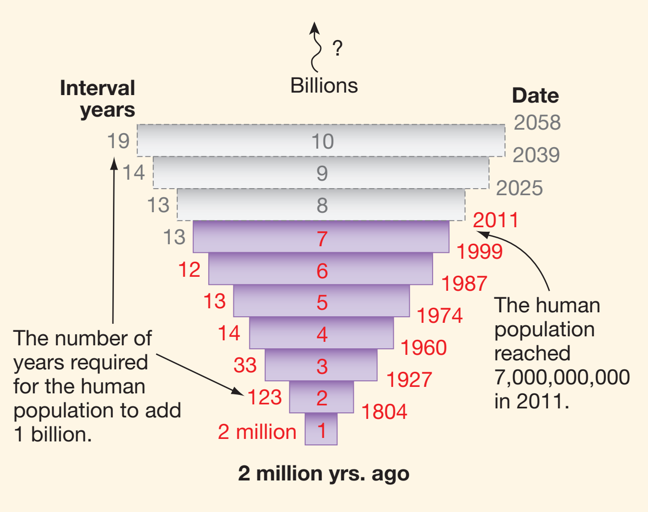
5. Results
A natural experiment often reveals a *correlation*, or a statistical relationship. If a correlation shows that the number of cottonwoods decreases away from the stream channel, then the hypothesis is supported. Continued investigation might repeat the same procedure in a different environment or expand the study to a larger region, and lead to a theory. However, if results show that cottonwoods grow at a variety of distances from the main channel, then we reject the hypothesis, replacing or refining it with another possible explanation (see questions above).

6. Theory Development
If we find that the distribution of cottonwoods is correlated with the presence of surface or subsurface water, we may also conclude that cottonwoods are an easily observable indicator of surface flow and available groundwater in dry or semi-dry regions.

▲Figure 1.4 **The scientific process.** (a) Scientific method flow chart and (b) example application to cottonwood distribution. [Ginger Birkeland photograph.]

Human–Earth Interactions in the 21st Century

Issues surrounding the growing influence of humans on Earth systems are central concerns of physical geography; we discuss them in every chapter of *Geosystems*. Human influence on Earth is now pervasive. The global human population passed 6 billion in August 1999 and continued to grow at the rate of 82 million per year, adding another billion by 2011, when the 7 billionth human was born. More people are alive today than at any previous moment in the planet's long history, unevenly distributed among 193 countries and numerous colonies. Virtually all new population growth is in the less-developed countries (LDCs), which now possess 81%, or about 5.75 billion, of the total population. Over the span of human history, billion-mark milestones occurred at ever closer intervals through the sixth-billion milestone; the interval is now slightly increasing. (Figure 1.5).



▲**Figure 1.5 Human population growth.** Note the population forecasts for the next half century.

The Human Denominator We consider the totality of human impact on Earth as the *human denominator.* Just as the denominator in a fraction tells how many parts a whole is divided into, so the growing human population and its increasing demand for resources and rising planetary impact suggest the stresses on the whole Earth system to provide support. Yet Earth's resource base remains relatively fixed.

The population in just two countries makes up 37% of Earth's human count: 19.1% live in China and 17.9% in India—2.61 billion people combined. Considered overall, the planetary population is young, with some 26% still under the age of 15 (2012 data from the Population Reference Bureau, at http://www.prb.org and the U.S. Census Bureau's *POPClock Projection,* at http://www.census.gov/popclock).

Population in most of the more-developed countries (MDCs) is no longer increasing. In fact, some European countries are actually declining in growth or are near replacement levels. However, people in these developed countries have a greater impact on the planet per person and therefore constitute a population impact crisis. The United States and Canada, with about 5% of the world's population, produce more than 25.8% ($14.7 trillion and $1.6 trillion in 2010, respectively) of the world's gross domestic product (GDP), the United States increasing to $15,094 billion GDP for 2011. These two countries use more than 2 times the energy per capita of Europeans, more than 7 times that of Latin Americans, 10 times that of Asians, and 20 times that of Africans. Therefore, the impact of this 5% on the state of Earth systems, natural resources, and sustainability of current practices in the MDCs is critical.

Global Sustainability Recently, **sustainability science** emerged as a new, integrative discipline, broadly based on concepts of sustainable development related to functioning Earth systems. Geographic concepts are fundamental to this new science, with its emphasis on human well-being, Earth systems, and human–environment interactions. Geographers are leading the effort to articulate this emerging field that seeks to directly link science and technology with sustainability.

Geographer Carol Harden, geomorphologist and past president of the Association of American Geographers, pointed out the important role of geographical concepts in sustainability science in 2009. She wrote that the idea of a human "footprint," representing the human impact on Earth systems, relates to sustainability and geography. When the human population of over 7 billion is taken into account, the human footprint on Earth is enormous, both in terms of its spatial extent and the strength of its influence. Shrinking this footprint ties to sustainability science in all of its forms—for example, sustainable development, sustainable resources, sustainable energy, and sustainable agriculture. Especially in the face of today's rapidly changing technological and environmental systems, geographers are poised to contribute to this emerging field.

If we consider some of the key issues for this century, many of them fall beneath the umbrella of sustainability science, such as feeding the world's population, energy

GEOreport 1.1 Welcome to the Anthropocene

The human population on Earth reached 7 billion in 2011. Many scientists now agree that the *Anthropocene,* a term coined by Nobel Prize–winning scientist Paul Crutzen, is an appropriate name for the most recent years of geologic history, when humans have influenced Earth's climate and ecosystems. Some scientists mark the beginning of agriculture, about 5000 years ago, as the start of the Anthropocene; others place the start at the dawn of the Industrial Revolution, in the 18th century. To see a video charting the growth of humans as a planetary force, go to http://www.anthropocene.info.

supplies and demands, climate change, loss of biodiversity, and air and water pollution. These are issues that need to be addressed in new ways if we are to achieve sustainability for both human and Earth systems. Understanding Earth's physical geography and geographic science informs your thinking on these issues.

CRITICALthinking 1.1
What is Your Footprint?

The concept of an individual's "footprint" has become popular—ecological footprint, carbon footprint, lifestyle footprint. The term has come to represent the costs of affluence and modern technology to our planetary systems. Footprint assessments are gross simplifications, but they can give you an idea of your impact and even an estimate of how many planets it would take to sustain that lifestyle and economy if everyone lived like you. Calculate your carbon footprint online at http://www.epa.gov/climatechange/ghgemissions/ind-calculator.html, one of many such websites, for housing, transportation, or food consumption. How can you reduce your footprint at home, at school, at work, or on the road? How does your footprint compare to the U.S. and worldwide average footprints? ●

Earth Systems Concepts

The word *system* is in our lives daily: "Check the car's cooling system"; "How does the grading system work?"; "A weather system is approaching." *Systems analysis* techniques in science began with studies of energy and temperature (thermodynamics) in the 19th century and were further developed in engineering studies during World War II. Systems methodology is an important analytical tool. In this book's 4 parts and 20 chapters, the content is organized along logical flow paths consistent with systems thinking.

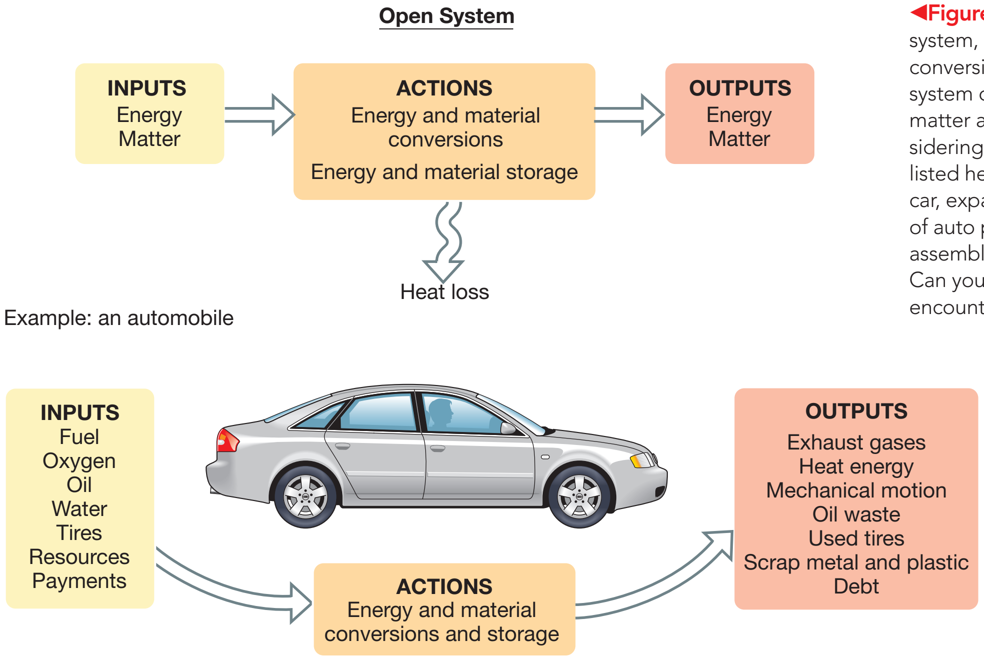
Systems Theory

Simply stated, a **system** is any set of ordered, interrelated components and their attributes, linked by flows of energy and matter, as distinct from the surrounding environment outside the system. The elements within a system may be arranged in a series or intermingled. A system may comprise any number of subsystems. Within Earth's systems, both matter and energy are stored and retrieved, and energy is transformed from one type to another. (Remember: *Matter* is mass that assumes a physical shape and occupies space; *energy* is a capacity to change the motion of, or to do work on, matter.)

Open Systems

Systems in nature are generally not self-contained: Inputs of energy and matter flow into the system, and outputs of energy and matter flow from the system. Such a system is an **open system** (Figure 1.6). Within a system, the parts function in an interrelated manner, acting together in a way that gives each system its operational character. Earth is an open system in terms of energy because solar energy enters freely and heat energy leaves, going back into space.

Within the Earth system, many subsystems are interconnected. Free-flowing rivers are open systems: inputs consist of solar energy, precipitation, and soil and rock particles; outputs are water and sediments to the ocean. Changes to a river system may affect the nearby coastal system; for example, an increase in a river's sediment load may change the shape of a river mouth or spread pollutants along a coastline. Most natural systems are open in terms of energy. Examples of open atmospheric subsystems include hurricanes and tornadoes.



◀**Figure 1.6 An open system.** In an open system, inputs of energy and matter undergo conversions and are stored or released as the system operates. Outputs include energy and matter and heat energy (waste). After considering how the various inputs and outputs listed here are related to the operation of the car, expand your thinking to the entire system of auto production, from raw materials to assembly to sales to car accidents to junkyards. Can you identify other open systems that you encounter in your daily life?

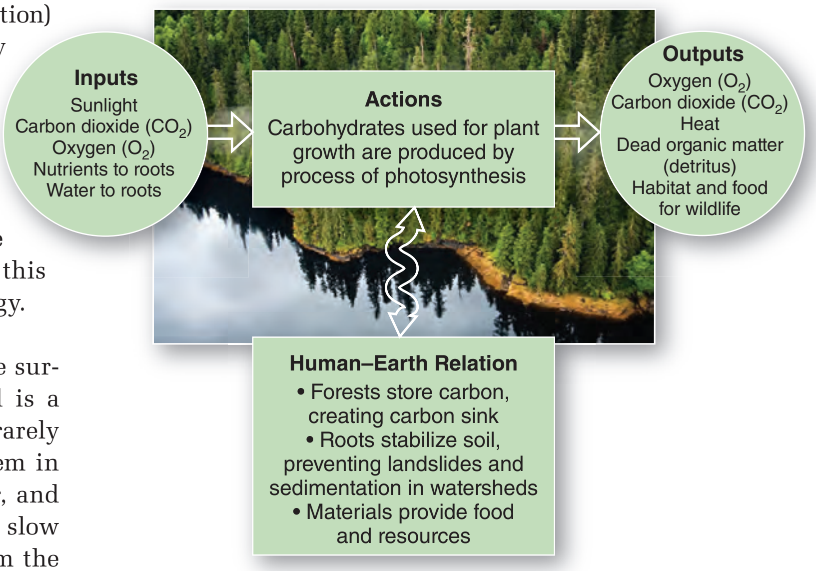
Earth systems are dynamic (energetic, in motion) because of the tremendous infusion of radiant energy from the Sun. As this energy passes through the outermost edge of Earth's atmosphere, it is transformed into various kinds of energy that power terrestrial systems, such as kinetic energy (of motion), potential energy (of position), or chemical or mechanical energy—setting the fluid atmosphere and ocean in motion. Eventually, Earth radiates this energy back to the cold vacuum of space as heat energy.

Closed Systems A system that is shut off from the surrounding environment so that it is self-contained is a **closed system**. Although such closed systems are rarely found in nature, Earth is essentially a closed system in terms of physical matter and resources—air, water, and material resources. The only exceptions are the slow escape of lightweight gases (such as hydrogen) from the atmosphere into space and the input of frequent, but tiny, meteors and cosmic dust. The fact that Earth is a closed material system makes recycling efforts inevitable if we want a sustainable global economy.

Natural System Example A forest is an example of an open system (Figure 1.7). Through the process of photosynthesis, trees and other plants use sunlight as an energy input and water, nutrients, and carbon dioxide as material inputs. The photosynthetic process converts these inputs to stored chemical energy in the form of plant sugars (carbohydrates). The process also releases an output from the forest system: the oxygen that we breathe.

Forest outputs also include products and activities that link to other broad-scale Earth systems. For example, forests store carbon and are thus referred to as "carbon sinks." A 2011 study found that forests absorb about one-third of the carbon dioxide released through the burning of fossil fuels, making them a critical part of the climate system as global carbon dioxide levels rise. Forest roots stabilize soil on hillslopes and stream banks, connecting them to land and water systems. Finally, the food and habitat resources provided by forests link them closely to other living systems, including humans. (Chapters 10, 13, 19, and 20 discuss these processes and interactions.)

The connection of human activities to inputs, actions, and outputs of forest systems is indicated by the double-headed arrow in Figure 1.7. This interaction has two causal directions, since forest processes affect humans, and humans influence forests. Forests affect humans through the outputs of carbon storage (which mitigates climate change), soil stabilization (which prevents erosion and sedimentation into source areas for drinking water), and food and resources. Human influences on forests include direct impacts such as logging for wood resources, burning to make way for agriculture, and clearing for development, as well as indirect impacts from human-caused climate change, which may enhance the spread of disease and insects and pollution, which affects tree health.



▲**Figure 1.7 Example of a natural open system: a forest.** [USDA Forest Service.]

System Feedback As a system operates, it generates outputs that influence its own operations. These outputs function as "information" that returns to various points in the system via pathways called **feedback loops**. Feedback information can guide, and sometimes control, further system operations. For the forest system in Figure 1.7, any increase or decrease in daylength (sunlight availability), carbon dioxide, or water produces feedback that causes specific responses in the individual trees and plants. For example, decreasing the water input slows the growth process; increasing daylength increases the growth process, within limits.

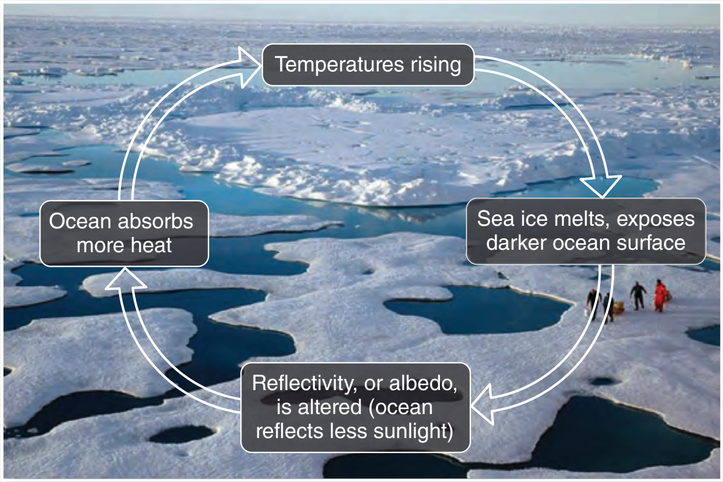
If the feedback information discourages change in the system, it is **negative feedback**. Further production of such feedback opposes system changes and leads to stability. Such negative feedback causes self-regulation in a natural system. Negative feedback loops are common in nature. In our forest, for example, healthy trees produce roots that stabilize hillslopes and inhibit erosion, providing a negative feedback. If the forest is damaged or removed, perhaps by fire or logging practices, the hillslope may become unstable and subject to landslides or mudslides. This instability affects nearby systems as sediment is deposited into streams, along coastlines, or into developed areas.

In many ecosystems, predator populations provide negative feedback for populations of other animals; the size of the prey population tends to achieve a balance with the number of predators. If a predator population drops abruptly, prey populations increase and cause ecosystem instability. After wolves were exterminated from Yellowstone National Park in Wyoming and Montana in the late 1800s, the unnaturally high elk population stripped many areas of natural vegetation. After the 1995 reintroduction of Canadian wolves into Yellowstone, elk numbers declined with wolf predation. Since then, aspens and willow are returning, improving habitat for birds and small mammals and providing other ecosystem benefits.

If feedback information encourages change in the system, it is **positive feedback**. Further production of positive feedback stimulates system changes. Unchecked positive feedback in a system can create a runaway ("snowballing") condition. In natural systems, such unchecked system changes can reach a critical limit, leading to instability, disruption, or death of organisms.

Global climate change creates an example of positive feedback as summer sea ice melts in the Arctic Region (discussed in Chapter 4). As arctic temperatures rise, summer sea ice and glacial melting accelerate. This causes light-colored snow and sea-ice surfaces, which reflect sunlight and so remain cooler, to be replaced by darker-colored open ocean surfaces, which absorb sunlight and become warmer. As a result, the ocean absorbs more solar energy, which raises the temperature, which, in turn, melts more ice, and so forth (Figure 1.8). This is a positive feedback loop, further enhancing the effects of higher temperatures and warming trends.

The acceleration of change in a positive feedback loop can be dramatic. Scientists have found that the *extent* of sea ice has decreased in area, and that the *volume* has dropped at an accelerating rate. Volume, a better indicator than extent for existing sea ice, has dropped by half since 1980; however, the rate of decrease was 2.5 times faster during the decade from 2000 to 2012 than it was from 1980 to 1990. As the feedback loop accelerates, the possibility of complete summer ice melt in the Arctic may become reality sooner than predicted—September is normally the month for lowest sea-ice extent; in 2012 this happened in August.



▲**Figure 1.8 The Arctic sea ice–albedo positive feedback loop.** Average ice thickness in the Arctic summer has dropped dramatically, leaving thinner ice that melts more easily. Since 2000, 70% of the September ice volume has disappeared. If this rate of ice volume loss continues, the first ice-free Arctic September might happen before 2017. [NOAA.]

System Equilibrium Most systems maintain structure and character over time. An energy and material system that remains balanced over time, in which conditions are constant or recur, is in a *steady-state condition.* When the rates of inputs and outputs in the system are equal and the amounts of energy and matter in storage within the system are constant (or more realistically, fluctuate around a stable average), the system is in **steady-state equilibrium**. For example, river channels commonly adjust their form in response to inputs of water and sediment; these inputs may change in amount from year to year, but the channel form represents a stable average—a steady-state condition.

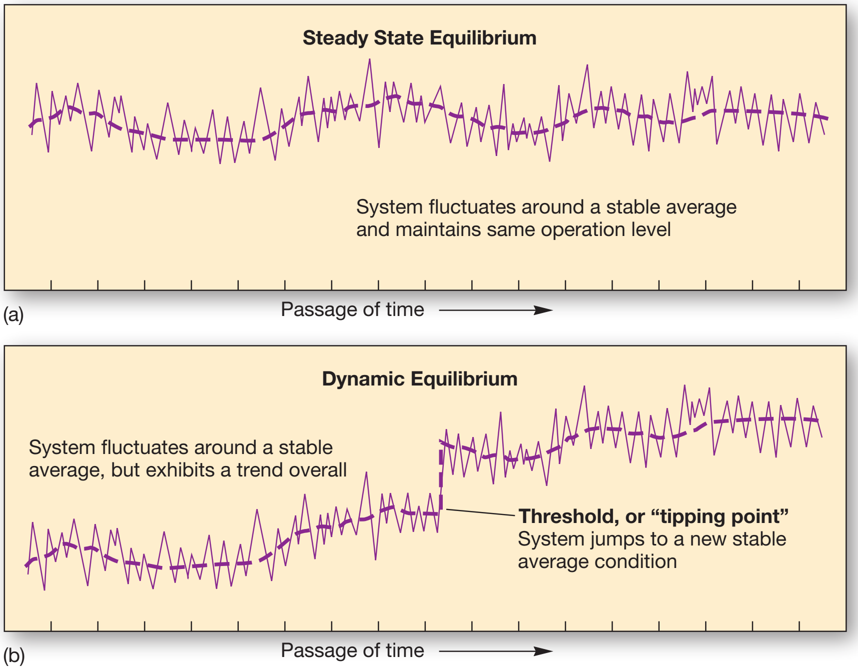
However, a steady-state system may demonstrate a changing trend over time, a condition described as **dynamic equilibrium**. These changing trends may appear gradually and are compensated for by the system. A river may tend toward channel widening as it adjusts to greater inputs of sediment over some time scale, but the overall system will adjust to this new condition and thus maintain a dynamic equilibrium. Figure 1.9 illustrates these two equilibrium conditions, steady-state and dynamic.

Note that systems in equilibrium tend to maintain their functional operations and resist abrupt change. However, a system may reach a **threshold**, or *tipping point*, where it can no longer maintain its character, so it lurches to a new operational level. A large flood in a river system may push the river channel to a threshold where it abruptly shifts, carving a new channel. Another example of such a condition is a hillside or coastal bluff that adjusts after a sudden landslide. A new equilibrium is eventually achieved among slope, materials, and energy over time. High-latitude climate change has caused threshold events such as the relatively sudden collapse of ice shelves surrounding a portion of Antarctica and the crack-up of ice shelves on the north coast of Ellesmere Island, Canada, and Greenland.

Also, plant and animal communities can reach thresholds. After 1997, warming conditions in oceans combined with pollution to accelerate the bleaching of living coral reefs worldwide—taking coral systems to a threshold. Bleaching is the loss of colorful

GEOreport 1.2 Amphibians at thresholds

Amphibian species are a threatened group of animals, with approximately one-third of recognized species now at risk of extinction. According to the International Union for Conservation of Nature (IUCN) Amphibian Specialist Group, two new initiatives are aimed at stopping the amphibian decline: increased habitat protection for species that are found in only a single location and stepped-up efforts at testing antifungal drugs to halt the killer frog disease favored by the temperature increases. Read more about the current amphibian extinction crisis at http://www.amphibians.org/.




(c) Wave action and heavy rainfall caused slope instability along the Pacific Coast of south of San Francisco in January 2010. When a threshold was reached, the bluffs collapsed and the cliff face retreated inland some 30.5 m (100 ft.)

▲Figure 1.9 **System equilibria: steady-state and dynamic.** The vertical axis represents the value of a typical systems variable, such as stream channel width or hillslope angle. [Bobbé Christopherson photograph.]

algae, food source for the coral, causing the eventual death of the coral colonies making up the reef. In some areas, 50% of regional coral reefs experienced bleaching. On the Great Barrier Reef in Australia, coral die-off of up to 90% occurred during the worst years. Today, about 50% of the corals on Earth are ailing; more on this in Chapter 16. Harlequin frogs of tropical Central and South America are another example of species reaching a tipping point, with increased extinctions since 1986 related directly to climate change; discussed in Chapter 19 and GeoReport 1.2.

Models of Systems

A **model** is a simplified, idealized representation of part of the real world. Scientists design models with varying degrees of specificity. A conceptual model is usually the most generalized and focuses on how processes interact within a system. A numerical model is more specific and is usually based on data collected from field or laboratory work. The simplicity of a model makes a system easier to understand and to simulate in experiments. A good example is a model of the *hydrologic system*, which represents Earth's entire water system, its related energy flows, and the atmosphere, surface, and subsurface environments through which water moves (see Figure 9.4 in Chapter 9). Predictions associated with climate change are often based on computer models of atmospheric processes, discussed in Chapter 11. We discuss many system models in this text.

Adjusting the variables in a model simulates differing conditions and allows predictions of possible system operations. However, predictions are only as good as the assumptions and accuracy built into the model. A model is best viewed for what it is—a simplification to help us understand complex processes.

Systems Organization in *Geosystems*

From general layout to presentation of specific topics, *Geosystems* follows a systems flow. The part structure is designed around Earth systems pertaining to air, water, land, and living organisms. These are Earth's four "spheres" and represent the broadest level of organization within the book. Within each part, chapters and topics are arranged according to systems thinking, focusing on inputs, actions, and outputs, with an emphasis on human–Earth interactions and on interrelations among the parts and chapters. Specific subjects, such as the eruption of Mount Pinatubo in the Philippines discussed just ahead, recur in many chapters, illustrating systems connections. The *Geosystems in Action* illustration on the following pages outlines the part structure and chapter content within Earth's four spheres.

Earth's Four "Spheres"

Earth's surface is a vast area of 500 million km^2 (193 million mi^2) where four immense open systems interact. The Geosystems in Action feature (pp. 40–41) shows the three **abiotic**, or nonliving, systems forming the realm of the **biotic**, or living, system. The abiotic spheres are the *atmosphere*, *hydrosphere*, and *lithosphere*. The biotic sphere is the *biosphere*. Together, these spheres form a simplified model of Earth systems.

(text continued on page 42)

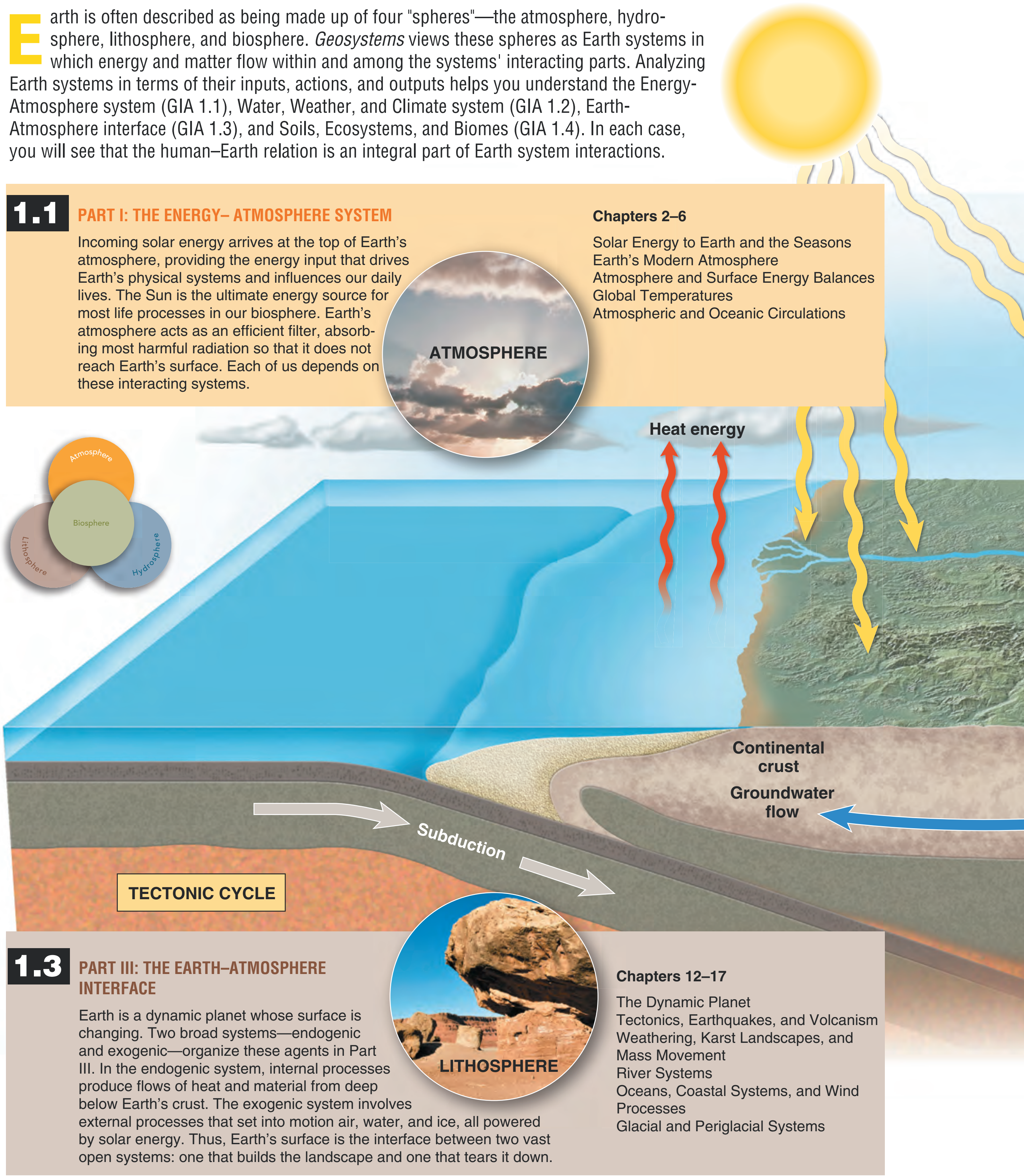
Earth is often described as being made up of four "spheres"—the atmosphere, hydrosphere, lithosphere, and biosphere. *Geosystems* views these spheres as Earth systems in which energy and matter flow within and among the systems' interacting parts. Analyzing Earth systems in terms of their inputs, actions, and outputs helps you understand the Energy-Atmosphere system (GIA 1.1), Water, Weather, and Climate system (GIA 1.2), Earth-Atmosphere interface (GIA 1.3), and Soils, Ecosystems, and Biomes (GIA 1.4). In each case, you will see that the human–Earth relation is an integral part of Earth system interactions.

1.1 PART I: THE ENERGY– ATMOSPHERE SYSTEM

Incoming solar energy arrives at the top of Earth's atmosphere, providing the energy input that drives Earth's physical systems and influences our daily lives. The Sun is the ultimate energy source for most life processes in our biosphere. Earth's atmosphere acts as an efficient filter, absorbing most harmful radiation so that it does not reach Earth's surface. Each of us depends on these interacting systems.

Chapters 2–6

Solar Energy to Earth and the Seasons
Earth's Modern Atmosphere
Atmosphere and Surface Energy Balances
Global Temperatures
Atmospheric and Oceanic Circulations



1.3 PART III: THE EARTH–ATMOSPHERE INTERFACE

Earth is a dynamic planet whose surface is changing. Two broad systems—endogenic and exogenic—organize these agents in Part III. In the endogenic system, internal processes produce flows of heat and material from deep below Earth's crust. The exogenic system involves external processes that set into motion air, water, and ice, all powered by solar energy. Thus, Earth's surface is the interface between two vast open systems: one that builds the landscape and one that tears it down.

Chapters 12–17

The Dynamic Planet
Tectonics, Earthquakes, and Volcanism
Weathering, Karst Landscapes, and Mass Movement
River Systems
Oceans, Coastal Systems, and Wind Processes
Glacial and Periglacial Systems

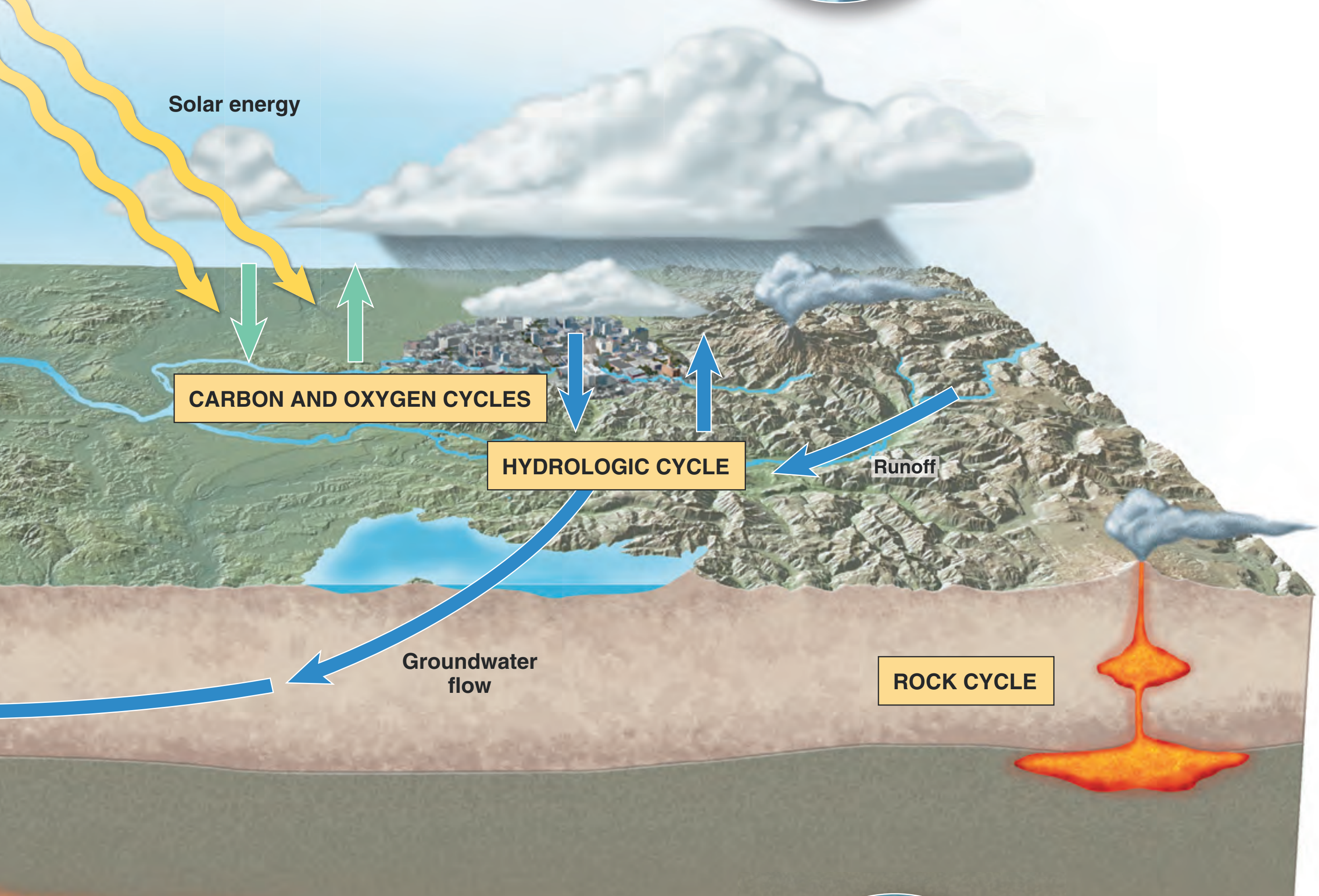
Video
The Changing Face of Earth

1.2 PART II: WATER, WEATHER, AND CLIMATE SYSTEMS

Earth is the water planet. Part II describes the distribution of water on Earth, including water circulation in the hydrologic cycle. Part II also describes the daily dynamics of the atmosphere as it interacts with the hydrosphere to produce weather. Outputs of the water–weather system range from climate patterns to our water resources. Part II concludes with an examination of global climate change, the impacts that are occurring, and forecasts of future changes.

Chapters 7–11

Water and Atmospheric Moisture
Weather
Water Resources
Global Climate Systems
Climate Change



1.4 PART IV: SOILS, ECOSYSTEMS, AND BIOMES

Energy enters the biosphere through conversion of solar energy by photosynthesis in the leaves of plants. Soil is the essential link among the lithosphere, plants, and the rest of Earth's physical systems. Thus, soil helps sustain life and is a bridge between Parts III and IV of this text. Together, soils, plants, animals, and the physical environment make up ecosystems, which are grouped together in biomes.

Chapters 18–20

The Geography of Soils
Ecosystem Essentials
Terrestrial Biomes
Human–Earth Interactions: all chapters

GEOquiz

1. Explain: Explain how the Sun is involved in Earth's physical systems. What is the Sun's role in the biosphere?

2. Compare: How are endogenic and exogenic systems similar? How are they different? Based on the illustration, give an example of each type of system.

- **Atmosphere (Part I, Chapters 2–6)** The **atmosphere** is a thin, gaseous veil surrounding Earth, held to the planet by the force of gravity. Formed by gases arising from within Earth's crust and interior and the exhalations of all life over time, the lower atmosphere is unique in the Solar System. It is a combination of nitrogen, oxygen, argon, carbon dioxide, water vapor, and trace gases.
- **Hydrosphere (Part II, Chapters 7–11)** Earth's waters exist in the atmosphere, on the surface, and in the crust near the surface. Collectively, these waters form the **hydrosphere**. That portion of the hydrosphere that is frozen is the **cryosphere**—ice sheets, ice caps and fields, glaciers, ice shelves, sea ice, and subsurface ground ice. Water of the hydrosphere exists in three states: liquid, solid (the frozen cryosphere), and gaseous (water vapor). Water occurs in two general chemical conditions, fresh and saline (salty).
- **Lithosphere (Part III, Chapters 12–17)** Earth's crust and a portion of the upper mantle directly below the crust form the **lithosphere**. The crust is quite brittle compared with the layers deep beneath the surface, which move slowly in response to an uneven distribution of heat energy and pressure. In a broad sense, the term *lithosphere* sometimes refers to the entire solid planet. The soil layer is the *edaphosphere* and generally covers Earth's land surfaces. In this text, soils represent the bridge between the lithosphere (Part III) and biosphere (Part IV).
- **Biosphere (Part IV, Chapters 18–20)** The intricate, interconnected web that links all organisms with their physical environment is the **biosphere**, or **ecosphere**. The biosphere is the area in which physical and chemical factors form the context of life. The biosphere exists in the overlap of the three abiotic, or nonliving, spheres, extending from the seafloor, the upper layers of the crustal rock, to about 8 km (5 mi) into the atmosphere. Life is sustainable within these natural limits. The biosphere evolves, reorganizes itself at times, undergoes extinctions, and manages to flourish.

Within each part, the sequence of chapters generally follows a systems flow of energy, materials, and information. Each of the four part-opening page spreads summarizes the main system linkages; these diagrams are presented together in Figure 1.10. As an example of our systems organization, Part I, "The Energy–Atmosphere System," begins with the Sun (Chapter 2). The Sun's energy flows across space to the top of the atmosphere and through the atmosphere to Earth's surface, where it is balanced by outgoing energy from Earth (Chapters 3 and 4). Then we look at system outputs of temperature (Chapter 5) and winds and ocean currents (Chapter 6). Note the same logical systems flow in the other three parts of this text. The organization of many chapters also follows this systems flow.

Mount Pinatubo—Global System Impact A dramatic example of interactions between Earth systems in response to a volcanic eruption illustrates the strength of the systems approach used throughout this textbook. Mount Pinatubo in the Philippines erupted violently in 1991, injecting 15–20 million tons of ash and sulfuric acid mist into the upper atmosphere (Figure 1.11). This was the second greatest eruption during the 20th century; Mount Katmai in Alaska in 1912 was the only one greater. The eruption materials from Mount Pinatubo affected Earth systems in several ways, as noted on the map. For comparison, the 2010 eruption of Eyjafjallajökull in Iceland was about 100 times smaller in terms of the volume of material ejected, with debris reaching only the lower atmosphere.

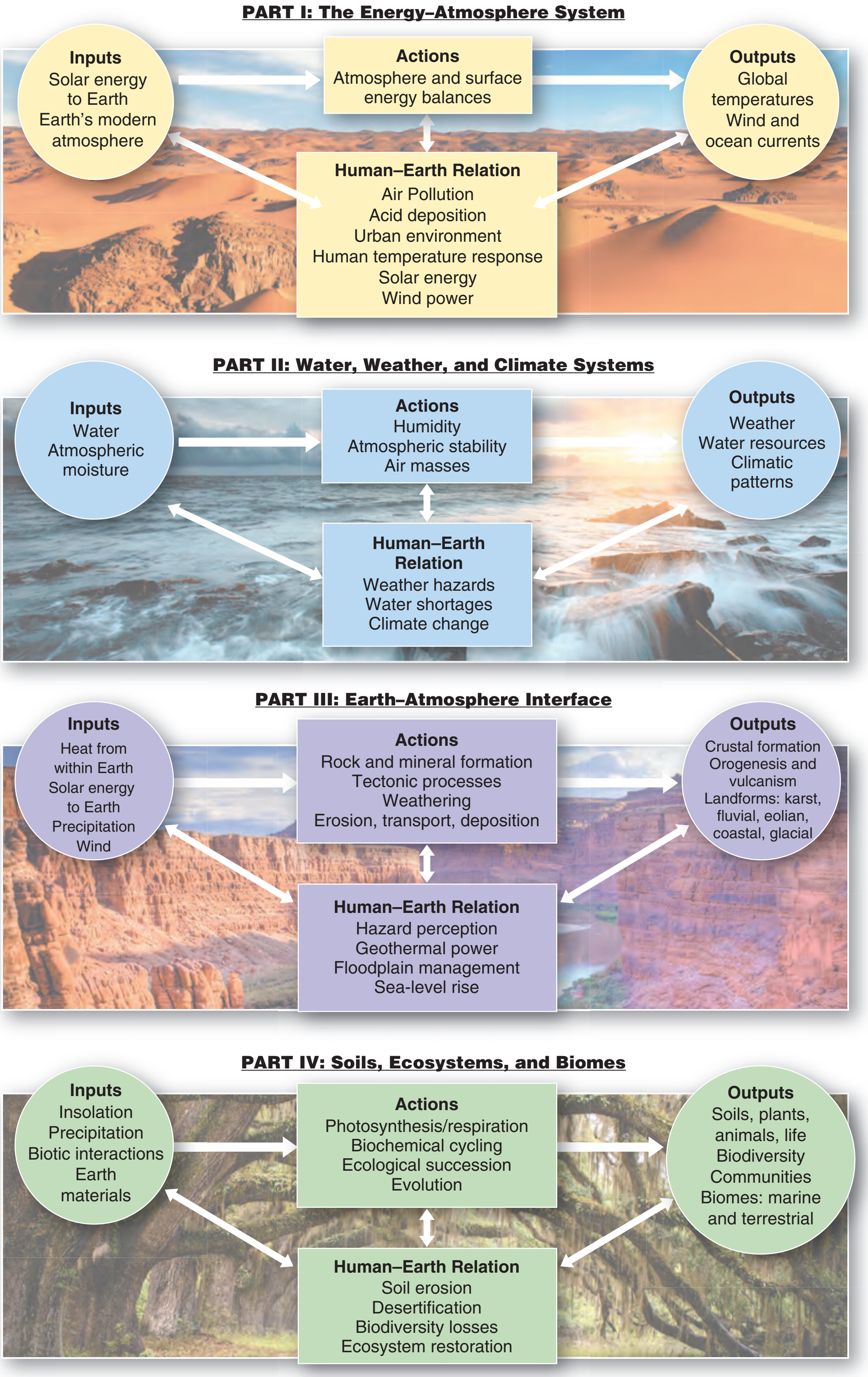
As you progress through this book, you see the story of Mount Pinatubo and its implications woven through eight chapters: Chapter 1 (discussion of systems theory), Chapter 4 (effects on energy budgets in the atmosphere), Chapter 6 (satellite images of the spread of debris by atmospheric winds), Chapter 11 (temporary effect on global atmospheric temperatures), Chapter 13 (volcanic process) and Chapter 19 (effects on net photosynthesis). Instead of simply describing the eruption, we see the linkages and global impacts of such a volcanic explosion.

Earth's Dimensions

We all have heard that some people in the past believed Earth was flat. Yet Earth's *sphericity*, or roundness, is not as modern an idea as many think. For instance, more than two millennia ago, the Greek mathematician and philosopher Pythagoras (ca. 580–500 B.C.) determined through observation that Earth is spherical. We do not know what observations led Pythagoras to this conclusion. Can you guess at what he saw to deduce Earth's roundness?

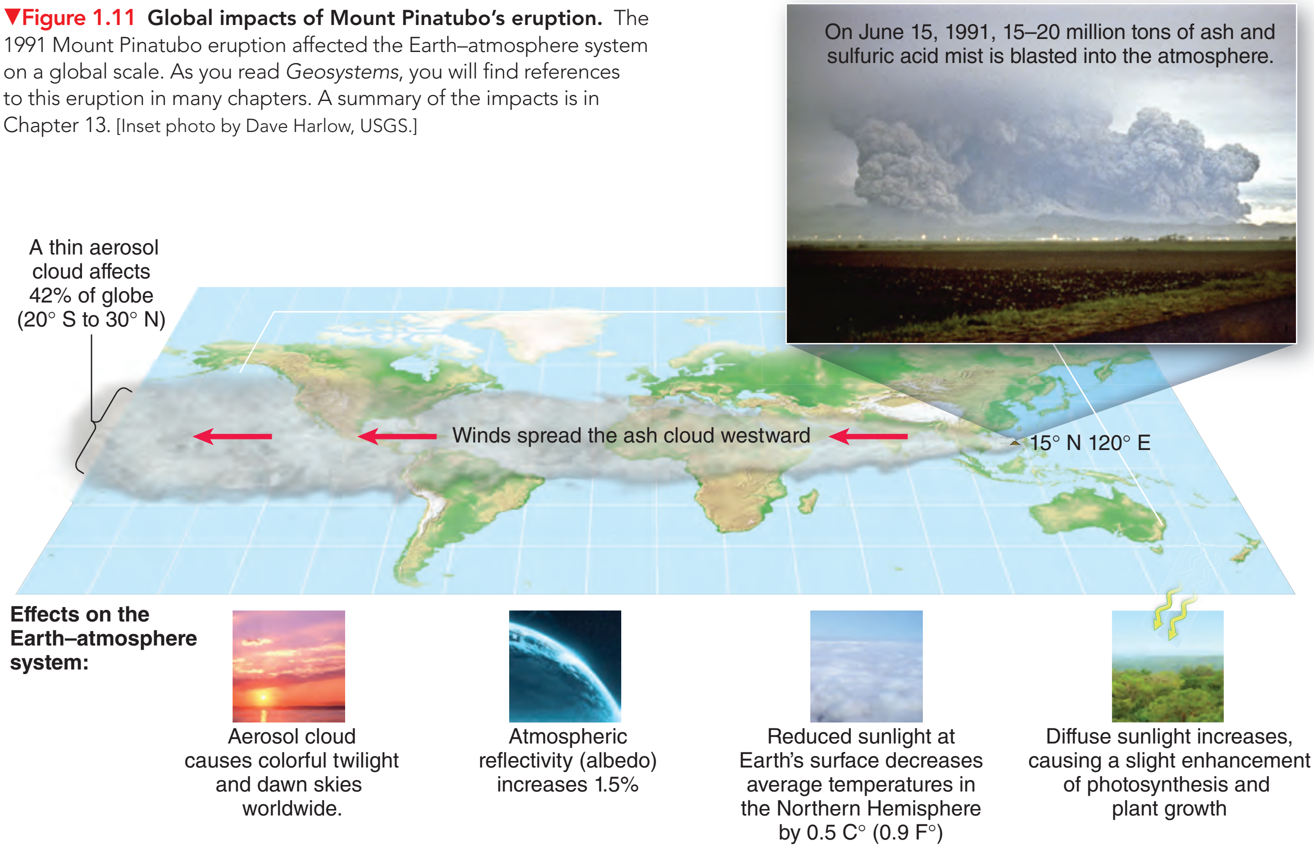
GEOreport 1.3 Earth's unique hydrosphere

The hydrosphere on Earth is unique among the planets in the Solar System: only Earth possesses surface water in such quantity, some 1.36 billion km^3 (0.33 billion mi^3). Subsurface water exists on other planets, discovered on the Moon and on the planet Mercury in their polar areas, Mars, Jupiter's moon Europa, and Saturn's moons Enceladus and Titan. In the Martian polar region, remote spacecraft are studying ground ice and patterned ground phenomena caused by freezing and thawing water, as discussed for Earth in Chapter 17. The *Curiosity* rover in 2012 landed in an area of Mars that billions of years ago was flooded with waist-deep water. In the Universe, deep-space telescopes reveal traces of water in nebulae and on distant planetary objects.



▲Figure 1.10 **The systems in *Geosystems*.** The sequence of systems flow in the organization of Parts I, II, III, and IV.

▼**Figure 1.11 Global impacts of Mount Pinatubo's eruption.** The 1991 Mount Pinatubo eruption affected the Earth–atmosphere system on a global scale. As you read *Geosystems*, you will find references to this eruption in many chapters. A summary of the impacts is in Chapter 13. [Inset photo by Dave Harlow, USGS.]



Evidence of Sphericity He might have noticed ships sailing beyond the horizon and apparently sinking below the water's surface, only to arrive back at port with dry decks. Perhaps he noticed Earth's curved shadow cast on the lunar surface during an eclipse of the Moon. He might have deduced that the Sun and Moon are not really the flat disks they appear to be in the sky, but are spherical, and that Earth must be a sphere as well.

Earth's sphericity was generally accepted by the educated populace as early as the first century A.D. Christopher Columbus, for example, knew he was sailing around a sphere in 1492; this is one reason why he thought he had arrived in the East Indies.

Earth as a Geoid Until 1687, the spherical-perfection model was a basic assumption of **geodesy**, the science that determines Earth's shape and size by surveys and mathematical calculations. But in that year, Sir Isaac Newton postulated that Earth, along with the other planets, could not be perfectly spherical. Newton reasoned that the more rapid rotational speed at the equator—the part of the planet farthest from the central axis and therefore the fastest moving—produces an equatorial bulge as centrifugal force pulls Earth's surface outward. He was convinced that Earth is slightly misshapen into an *oblate spheroid*, or, more correctly, an *oblate ellipsoid* (*oblate* means "flattened"), with the oblateness occurring at the poles.

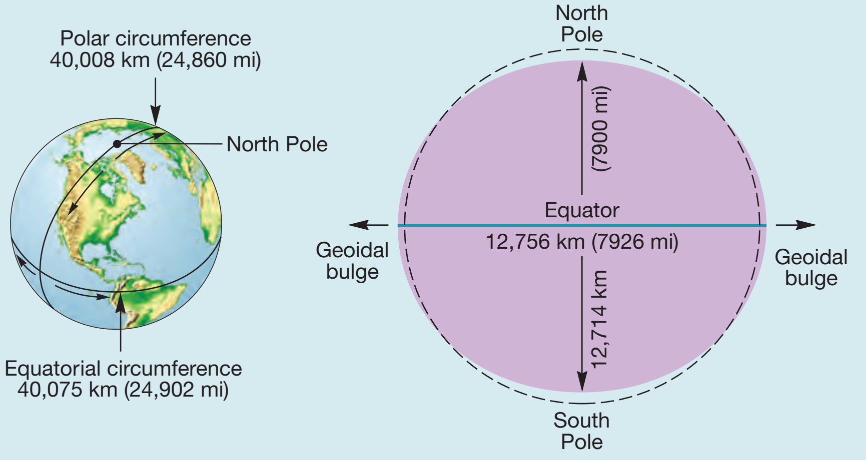
Earth's equatorial bulge and its polar oblateness are today universally accepted and confirmed with tremendous precision by satellite observations. The unique, irregular shape of Earth's surface, coinciding with mean sea level and perpendicular to the direction of gravity, is described as a **geoid**. Imagine Earth's geoid as a sea-level surface that extends uniformly worldwide, beneath the continents. Both heights on land and depths in the oceans measure from this hypothetical surface. Think of the geoid surface as a balance among the gravitational attraction of Earth's mass, the distribution of water and ice along its surface, and the outward centrifugal pull caused by Earth's rotation. Figure 1.12 gives Earth's polar and equatorial circumferences and diameters.

Location and Time on Earth

Fundamental to geographic science is a coordinated grid system that is internationally accepted to determine location on Earth. The terms *latitude* and *longitude* for the lines of this grid were in use on maps as early as the first century A.D., with the concepts themselves dating to earlier times.

The geographer, astronomer, and mathematician Ptolemy (ca. A.D. 90–168) contributed greatly to the development of modern maps, and many of his terms are still used today. Ptolemy divided the circle into

▶Figure 1.12 **Earth's dimensions.** The dashed line is a perfect circle for comparison to Earth's geoid.



(a) Equatorial and polar circumference

(b) Equatorial and polar diameters

360 degrees (360°), with each degree having 60 minutes (60′) and each minute having 60 seconds (60″) in a manner adapted from the ancient Babylonians. He located places using these degrees, minutes, and seconds. However, the precise length of a degree of latitude and a degree of longitude remained unresolved for the next 17 centuries.

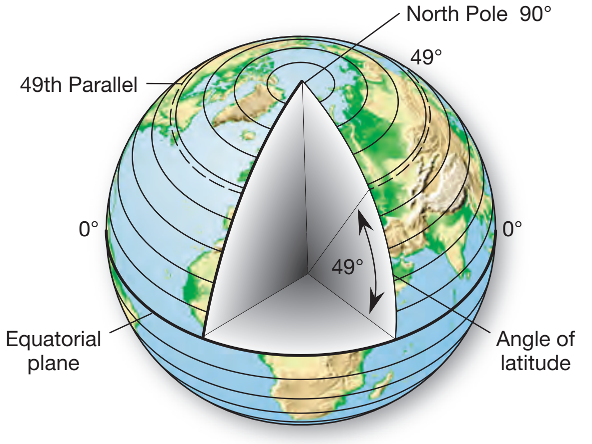
Latitude

Latitude is an angular distance north or south of the equator, measured from the center of Earth (Figure 1.13a). On a map or globe, the lines designating these angles of latitude run east and west, parallel to the equator (Figure 1.13b). Because Earth's equator divides the distance between the North Pole and the South Pole exactly in half, it is assigned the value of 0° latitude. Thus, latitude increases from the equator northward to the North Pole, at 90° north latitude, and southward to the South Pole, at 90° south latitude.

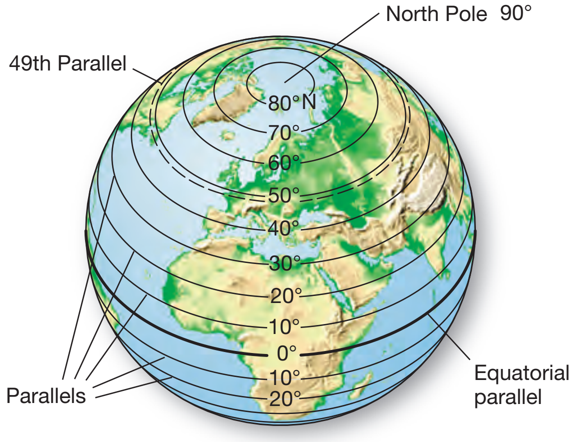
A line connecting all points along the same latitudinal angle is a **parallel**. In the figure, an angle of 49° north latitude is measured, and, by connecting all points at this latitude, we have the 49th parallel. Thus, *latitude* is the name of the angle (49° north latitude), *parallel* names the line (49th parallel), and both indicate distance north of the equator.

From equator to poles, the distance represented by a degree of latitude is fairly consistent, about 100 km (69 mi); at the poles, a degree of latitude is only slightly larger (about 1.12 km, or 0.70 mi) than at the equator (Figure 1.14). To pinpoint location more precisely, we divide degrees into 60 minutes, and minutes into 60 seconds. For example, Cabo San Lucas, Baja California, Mexico, in Figure 1.2 is located at 22 degrees, 53 minutes, 23 seconds (22° 53′ 23″) south latitude. Alternatively, many geographic information systems (GIS) and Earth visualization programs such as Google Earth™ use decimal notation for latitude and longitude degrees (an online conversion is at http://www.csgnetwork.com/gpscoordconv.html). In decimal units, Cabo San Lucas is at +22.8897° latitude—the positive sign is for north latitude, a negative sign for south latitude.

Latitude is readily determined by observing fixed celestial objects such as the Sun or the stars, a method dating to ancient times.

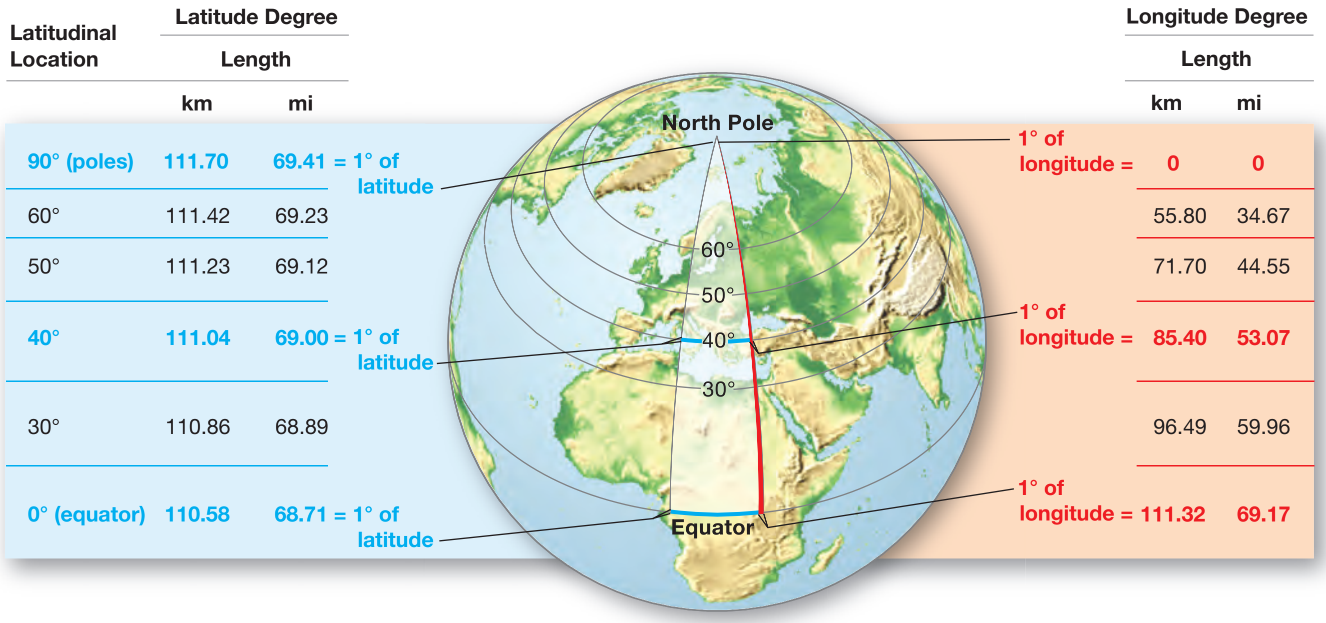


(a) Latitude is measured in degrees north or south of the Equator (0°). Earth's poles are at 90°. Note the measurement of 49° latitude.



(b) These angles of latitude determine parallels along Earth's surface.

▲Figure 1.13 **Parallels of latitude.** Do you know your present latitude?

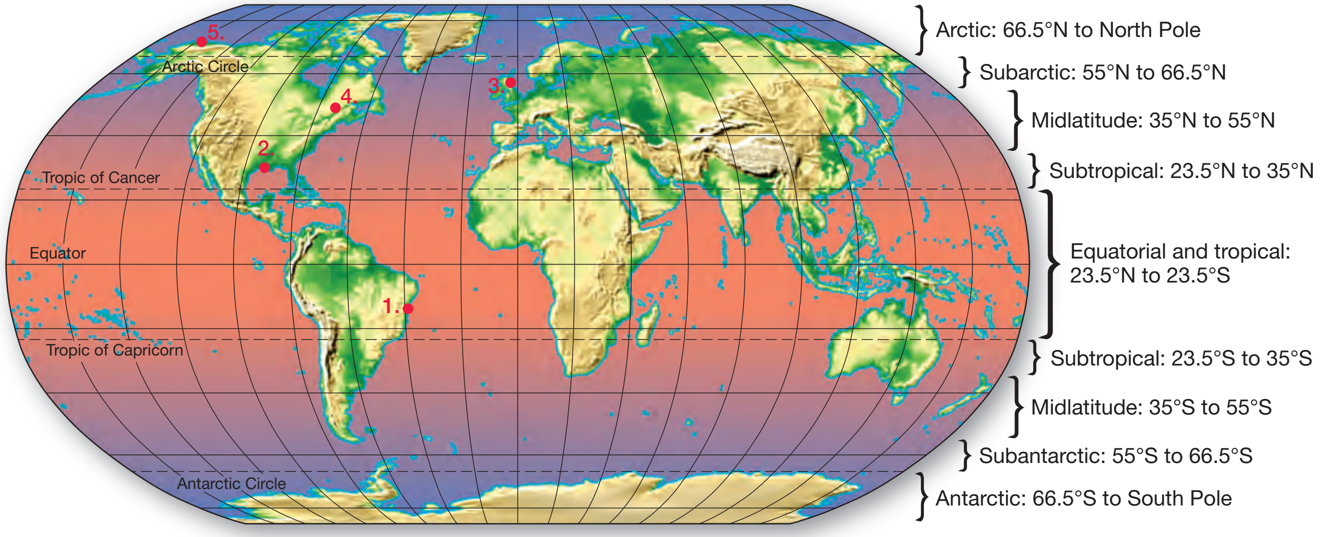


Latitudinal Location	Latitude Degree Length km	Latitude Degree Length mi	Longitude Degree Length km	Longitude Degree Length mi
90° (poles)	111.70	69.41 = 1° of latitude	1° of longitude = 0	0
60°	111.42	69.23	55.80	34.67
50°	111.23	69.12	71.70	44.55
40°	111.04	69.00 = 1° of latitude	1° of longitude = 85.40	53.07
30°	110.86	68.89	96.49	59.96
0° (equator)	110.58	68.71 = 1° of latitude	1° of longitude = 111.32	69.17

▲Figure 1.14 **Physical distances represented by degrees of latitude and longitude.**

"Lower latitudes" are those nearer the equator, whereas "higher latitudes" are those nearer the poles. You may be familiar with other general names describing regions related to latitude, such as "the tropics" and "the Arctic." Such terms refer to natural environ-ments that differ dramatically from the equator to the poles. These differences result from the amount of solar energy received, which varies by latitude and season of the year.

Figure 1.15 displays the names and locations of the *latitudinal geographic zones* used by geographers: *equatorial* and *tropical*, *subtropical*, *midlatitude*, *subarctic* or *subantarctic*, and *arctic* or *antarctic*. These generalized latitudinal zones are useful for reference and comparison, but they do not have rigid boundaries; rather, think of them as transitioning one to another. We will discuss specific lines of latitude, such as the Tropic of Cancer and the Arctic Circle, in Chapter 2 as we learn about the seasons.



▲Figure 1.15 **Latitudinal geographic zones.** Geographic zones are generalizations that characterize various regions by latitude. Noted cities: 1. Salvador, Brazil; 2. New Orleans, Louisiana; 3. Edinburgh, Scotland; 4. Montreal, Quebec; 5. Barrow, Alaska; see Critical Thinking 1.2.

CRITICALthinking 1.2
Latitudinal Geographic Zones and Temperature

Refer to the graph in Figure 5.5 that plots annual temperature data for five cities from near the equator to beyond the Arctic Circle. Note the geographic location for each of the five cities on the latitudinal geographic zone map in Figure 1.15. In which zone is each city located? Roughly characterize changing temperature patterns through the seasons as you move away from the equator. Describe what you discover. ●

Longitude

Longitude is an angular distance east or west of a point on Earth's surface, measured from the center of Earth (Figure 1.16a). On a map or globe, the lines designating these angles of longitude run north and south (Figure 1.16b). A line connecting all points along the same longitude is a **meridian**. In the figure, a longitudinal angle of 60° E is measured. These meridians run at right angles (90°) to all parallels, including the equator.

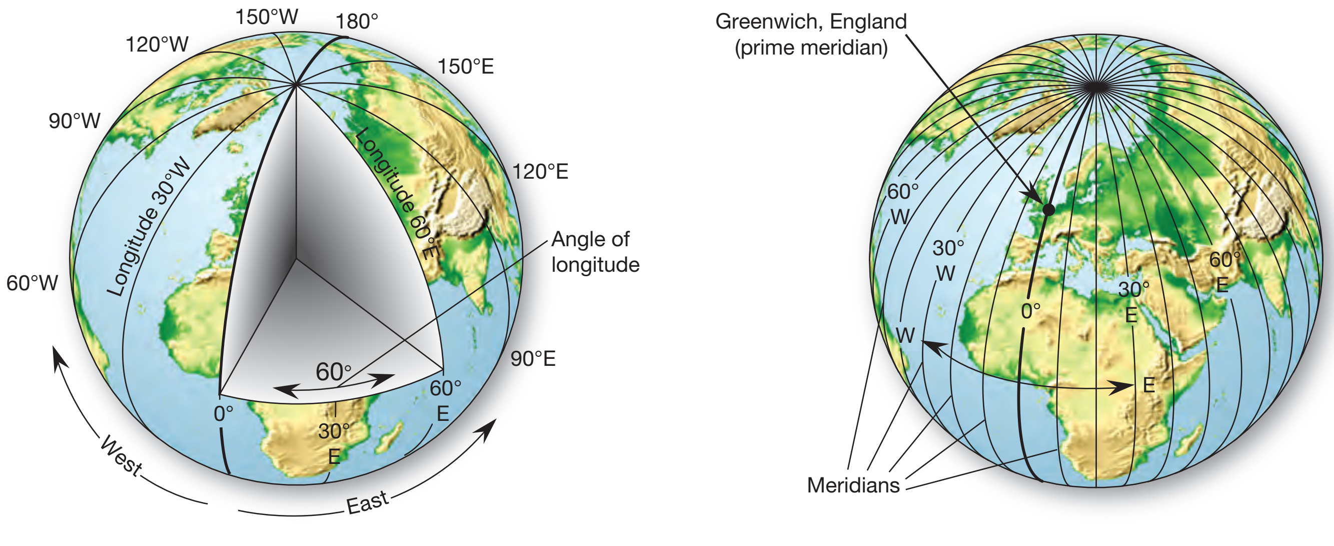
Thus, *longitude* is the name of the angle, *meridian* names the line, and both indicate distance east or west of an arbitrary **prime meridian**—a meridian designated as 0° (Figure 1.16b). Earth's prime meridian passes through the old Royal Observatory at Greenwich, England, as set by an 1884 treaty; this is the *Greenwich prime meridian.* Because meridians of longitude converge toward the poles, the actual distance on the ground spanned by a degree of longitude is greatest at the equator (where meridians separate to their widest distance apart) and diminishes to zero at the poles (where meridians converge; Figure 1.14). As with latitude, longitude is expressed in degrees, minutes, and seconds or in decimal degrees. Cabo San Lucas in Figure 1.2 is located at 109° 54′ 56″ W longitude, or –109.9156°; east longitude has a positive value, while west longitude is negative.

We noted that latitude is determined easily by sighting the Sun or the North Star as a pointer. In contrast, a method of accurately determining longitude, especially at sea, remained a major difficulty in navigation until after 1760. The key to measuring the longitude of a place lies in accurately knowing time and required the invention of a clock without a pendulum.

Great Circles and Small Circles

Great circles and small circles are important navigational concepts that help summarize latitude and longitude (Figure 1.17). A **great circle** is any circle of Earth's circumference whose center coincides with the center of Earth. An infinite number of great circles can be drawn on Earth. Every meridian is one-half of a great circle that passes through the poles. On flat maps, airline and shipping routes appear to arch their way across oceans and landmasses. These are *great circle routes*, tracing the shortest distances between two points on Earth (see Figure 1.24).

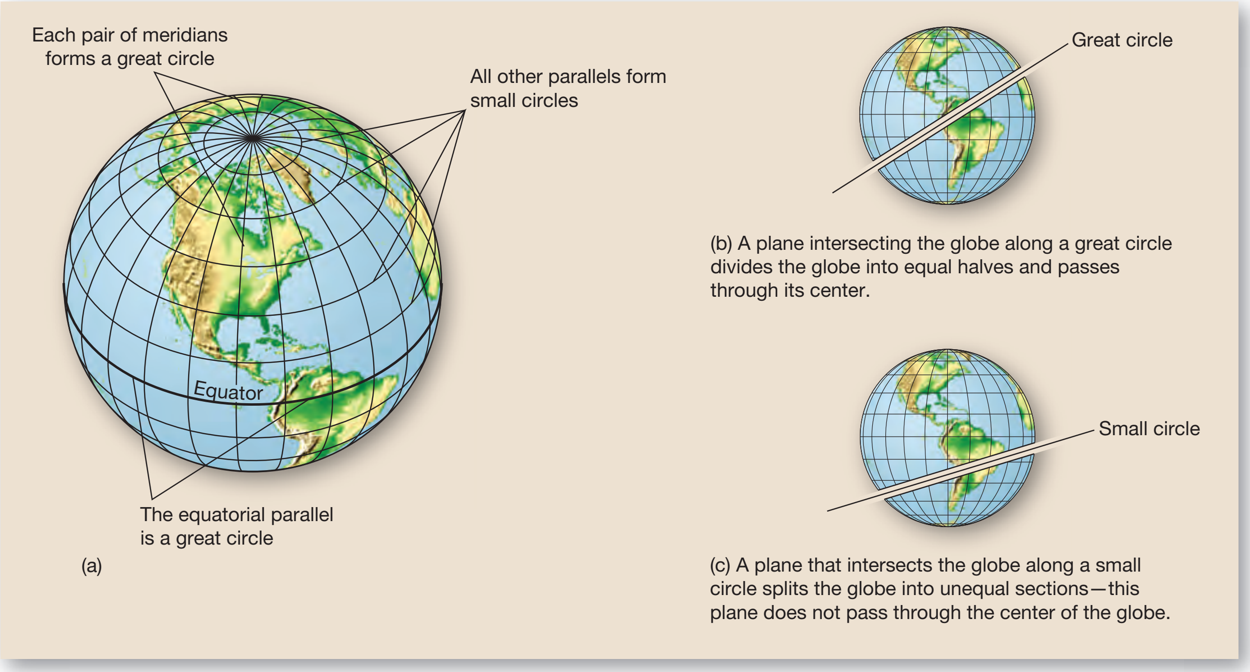
In contrast to meridians, only one parallel is a great circle—the *equatorial parallel.* All other parallels diminish in length toward the poles and, along with any other non–great circles that one might draw, constitute **small**



(a) Longitude is measured in degrees east or west of a 0° starting line, the prime meridian. Note the measurement of 60°E longitude

(b) Angles of longitude measured from the prime meridian determine other meridians. North America is west of Greenwich; therefore, it is in the Western Hemisphere.

▲**Figure 1.16 Meridians of longitude.** Do you know your present longitude?



(b) A plane intersecting the globe along a great circle divides the globe into equal halves and passes through its center.

(c) A plane that intersects the globe along a small circle splits the globe into unequal sections—this plane does not pass through the center of the globe.

▲Figure 1.17 **Great circles and small circles.**

circles. These circles have centers that do not coincide with Earth's center.

Figure 1.18 combines latitude and parallels with longitude and meridians to illustrate Earth's complete coordinate grid system. Note the red dot that marks our measurement of 49° N and 60° E, a location in western Kazakhstan. Next time you look at a world globe, follow the parallel and meridian that converge on your location.

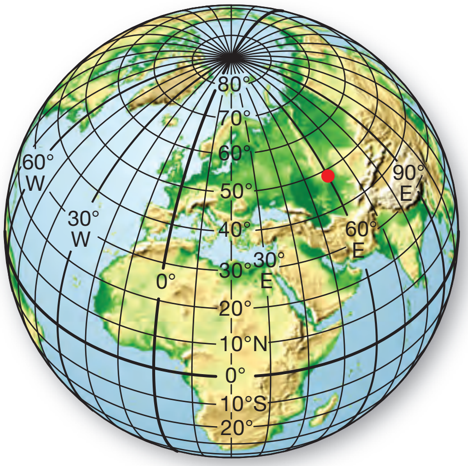
CRITICALthinking 1.3
Where are You?

Select a location (for example, your campus, home, or workplace or a city) and determine its latitude and longitude—both in degrees, minutes, and seconds and as decimal degrees. Describe the resources you used to gather this geographic information, such as an atlas, website, Google Earth™, or GPS measurement. Consult Figure 1.14 to find the approximate lengths of the latitude and longitude degrees at that location. ●

Meridians and Global Time

A worldwide time system is necessary to coordinate international trade, airline schedules, business and agricultural activities, and daily life. Our time system is based on longitude, the prime meridian, and the fact that Earth rotates on its own axis, revolving 360° every 24 hours, or 15° per hour (360° ÷ 24 = 15°).

In 1884 at the International Meridian Conference in Washington, DC, the prime meridian was set as the official standard for the world time zone system—**Greenwich Mean Time (GMT)** (see http://wwp.greenwich-meantime.com/). This standard time system established 24 standard meridians around the globe at equal intervals from the prime meridian, with a time zone of 1 hour spanning 7.5° on either side of these *central meridians*. Before this universal system, time zones were problematic, especially in large countries. In 1870, railroad travelers going from Maine to San Francisco made 22 adjustments to their watches to stay consistent with local time! Today, only three adjustments are needed in the continental United States—from Eastern Standard Time to Central, Mountain, and Pacific—and four changes across Canada.



▲Figure 1.18 **Earth's coordinate grid system.** Latitude and parallels and longitude and meridians allow us to locate all places on Earth precisely. The red dot is at 49° N latitude and 60° E longitude.

As illustrated in Figure 1.19, when it is 9:00 P.M. in Greenwich, then it is 4:00 P.M. in Baltimore (–5 hr), 3:00 P.M. in Oklahoma City (–6 hr), 2:00 P.M. in Salt Lake City (–7 hr), 1:00 P.M. in Seattle and Los Angeles (–8 hr), noon in Anchorage (–9 hr), and 11:00 A.M. in Honolulu (–10 hr). To the east, it is midnight in Ar Riyāḑ, Saudi Arabia (+3 hr). The designation A.M. is for *ante meridiem*, “before noon,” whereas P.M. is for *post meridiem*, “after noon.” A 24-hour clock avoids the use of these designations: 3 P.M. is stated as 15:00 hours; 3 A.M. is 3:00 hours.

As you can see from the modern international time zones in Figure 1.19, national or state boundaries and political considerations distort time boundaries. For example, China spans four time zones, but its government decided to keep the entire country operating at the same time. Thus, in some parts of China clocks are several hours off from what the Sun is doing. In the United States, parts of Florida and west Texas are in the same time zone.

Coordinated Universal Time

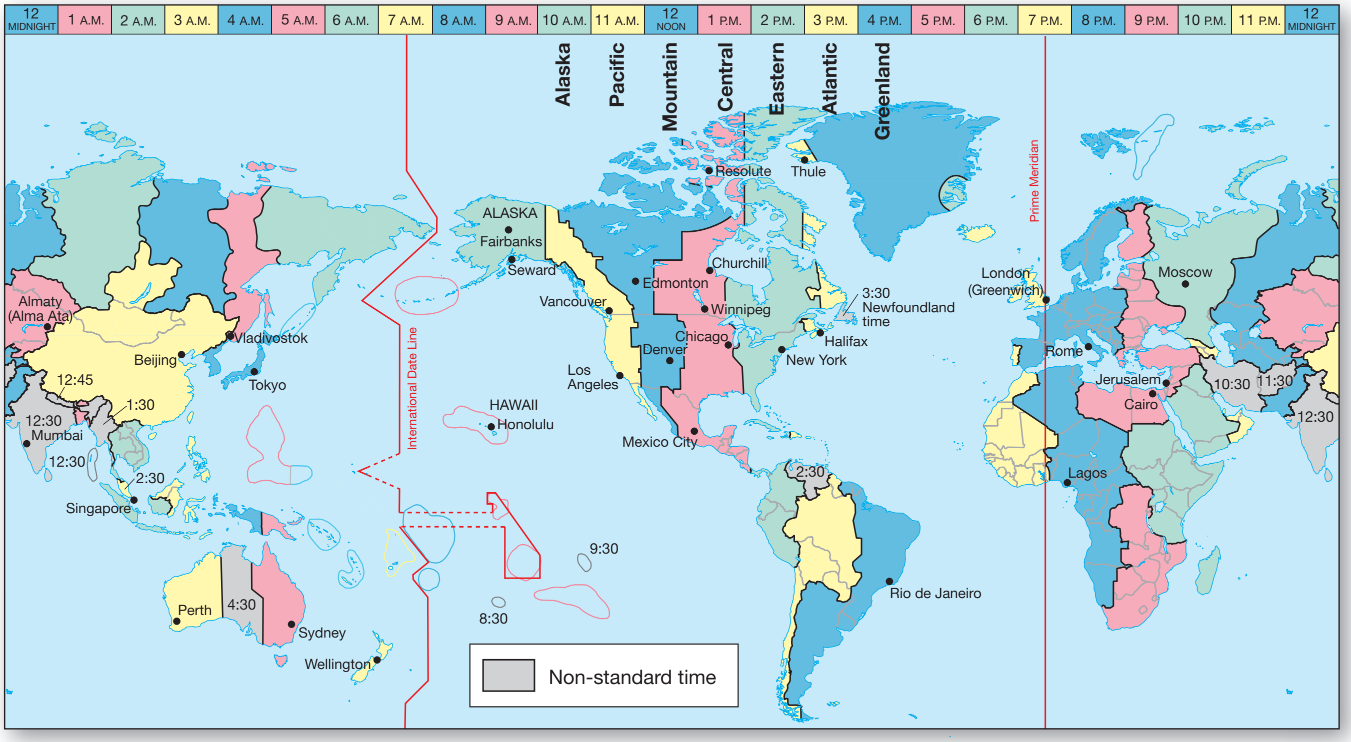
For decades, GMT was determined using the Royal Observatory’s astronomical clocks and was the world’s standard for accuracy. However, Earth rotation, on which those clocks were based, varies slightly over time, making it unreliable as a basis for timekeeping. Note that 150 million years ago, a “day” was 22 hours long, and 150 million years in the future, a “day” will be approaching 27 hours in length.

The invention of a quartz clock in 1939 and atomic clocks in the early 1950s improved the accuracy of measuring time. In 1972, the **Coordinated Universal Time (UTC)*** time-signal system replaced GMT and became the legal reference for official time in all countries. UTC is based on average time calculations from atomic clocks collected worldwide. You might still see official UTC referred to as GMT or Zulu time.

International Date Line

An important corollary of the prime meridian is the 180° meridian on the opposite side of the planet. This meridian is the **International Date Line (IDL)**, which marks the place where each day officially begins (at 12:01 A.M.). From this “line,” the new day sweeps westward. This *westward* movement of time is created by Earth’s turning *eastward* on its axis. Locating the date line in the sparsely populated Pacific Ocean minimizes most local confusion (Figure 1.20).

At the IDL, the west side of the line is always one day ahead of the east side. No matter what time of day it is when the line is crossed, the calendar changes a day



▲**Figure 1.19 Modern international standard time zones.** If it is 7 p.m. in Greenwich, determine the present time in Moscow, London, Halifax, Chicago, Winnipeg, Denver, Los Angeles, Fairbanks, Honolulu, Tokyo, and Singapore. [Adapted from Defense Mapping Agency. See http://aa.usno.navy.mil/faq/docs/world_tzones.html.]

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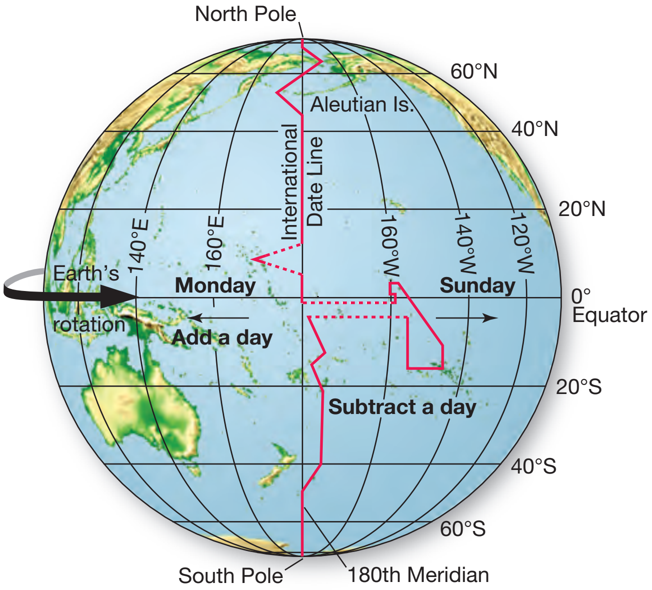
*UTC is in use because agreement was not reached on whether to use English word order, CUT, or the French order, TUC. UTC was the compromise and is recommended for all timekeeping applications; use of the term *GMT* is discouraged.



▲**Figure 1.20** **International Date Line.** The IDL location is approximately along the 180th meridian (see Figure 1.19). The dotted lines on the map show where island countries have set their own time zones, but their political control extends only 3.5 nautical miles (4 mi) offshore. Officially, you gain 1 day crossing the IDL from east to west. (See GeoReport 1.5)

(Figure 1.20). Note in the illustration the departures from the IDL and the 180° meridian; this deviation is due to local administrative and political preferences.

Daylight Saving Time In 70 countries, mainly in the temperate latitudes, time is set ahead 1 hour in the spring and set back 1 hour in the fall—a practice known as **daylight saving time**. The idea to extend daylight for early evening activities at the expense of daylight in the morning, first proposed by Benjamin Franklin, was not adopted until World War I and again in World War II, when Great Britain, Australia, Germany, Canada, and the United States used the practice to save energy (1 less hour of artificial lighting needed).

In 1986 and again in 2007, the United States and Canada increased daylight saving time. Time "springs forward" 1 hour on the second Sunday in March and "falls back" 1 hour on the first Sunday in November, except in a few places that do not use daylight saving time (Hawai'i, Arizona, and Saskatchewan). In Europe, the last Sundays in March and October are used to begin and end the "summer-time period" (see http://webexhibits.org/daylightsaving/).

Maps and Cartography

For centuries, geographers have used maps as tools to display spatial information and analyze spatial relationships. A **map** is a generalized view of an area, usually some portion of Earth's surface, as seen from above and greatly reduced in size. A map usually represents a specific characteristic of a place, such as rainfall, airline routes, or political features such as state boundaries and place names. **Cartography** is the science and art of mapmaking, often blending aspects of geography, engineering, mathematics, computer science, and art. It is similar in ways to architecture, in which aesthetics and utility combine to produce a useful product.

We all use maps to visualize our location in relation to other places, or maybe to plan a trip, or to understand a news story or current event. Maps are wonderful tools! Understanding a few basics about maps is essential to our study of physical geography.

The Scale of Maps

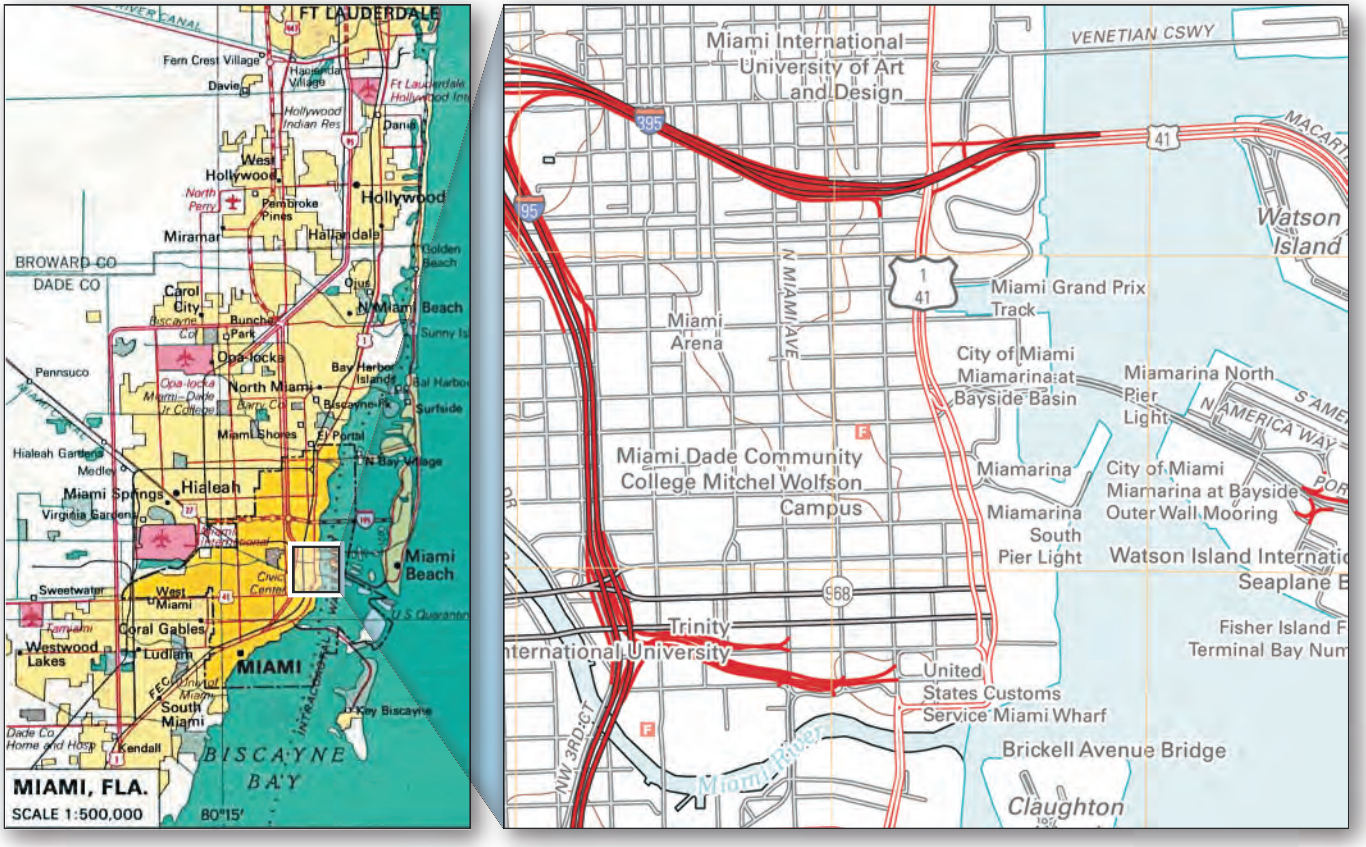
Architects, toy designers, and mapmakers have something in common: They all represent real things and places with the convenience of a model; examples are a drawing; a pretend car, train, or plane; a diagram; or a map. In most cases, the model is smaller than the reality. For example, an architect renders a blueprint of a structure to guide the building contractors, preparing the drawing so that a centimeter (or inch) on the blueprint represents so many meters (or feet) on the proposed building. Often, the drawing is 1/50 or 1/100 real size.

The cartographer does the same thing in preparing a map. The ratio of the image on a map to the real world is the map's **scale**; it relates the size of a unit on the map to the size of a similar unit on the ground. A 1:1 scale means that any unit (for example, a centimeter) on the map represents that same unit (a centimeter) on the ground, although this is an impractical map scale, since the map is as large as the area mapped! A more appropriate scale for a local map is 1:24,000, in which 1 unit on the map represents 24,000 identical units on the ground.

Cartographers express map scale as a representative fraction, a graphic scale, or a written scale (Figure 1.21). A *representative fraction* (*RF*, or *fractional scale*) is expressed with either a colon or a slash, as in 1:125,000 or 1/125,000. No actual units of measurement are mentioned because any unit is applicable as long as both parts of the fraction are in the same unit: 1 cm to 125,000 cm, 1 in. to 125,000 in., or even 1 arm length to 125,000 arm lengths.

GEOreport 1.4 The world's most accurate clock

Time and Frequency Services of the National Institute for Standards and Technology (NIST), U.S. Department of Commerce, operates several of the most advanced clocks currently in use. The NIST-F1 cesium atomic clock is the most accurate clock in the world. Housed in Boulder, Colorado, it will not gain or lose a second in nearly 20 million years. For accurate time in the United States, see http://www.time.gov, operated by NIST and the U.S. Naval Observatory. In Canada, the Institute for Measurement Standards, National Research Council Canada, participates in determining UTC; see http://time5.nrc.ca/webclock_e.shtml.



Representative fraction:	1:500,000 or 1/500,000
Written scale:	1 inch = 8 miles 1 cm = 5.0 km
Graphic scale:	0 4 8 MILES 0 5 10 KILOMETERS

Representative fraction:	1:24,000 or 1/24,000
Written scale:	1 inch = 2000 feet 1 cm = 0.25 km
Graphic scale:	0 1000 2000 FEET 0 0.25 0.5 KILOMETERS

(a) Relatively small scale map of Miami area shows less detail.

(b) Relatively large scale map of the same area shows a higher level of detail.

▲**Figure 1.21 Map scale.** Examples of maps at different scales, with three common expressions of map scale—representative fraction, graphic scale, and written scale. Both maps are enlarged to show detail. [USGS. Courtesy of the University of Texas Libraries, The University of Texas at Austin.]

A *graphic scale*, or *bar scale*, is a bar graph with units to allow measurement of distances on the map. An important advantage of a graphic scale is that, if the map is enlarged or reduced, the graphic scale enlarges or reduces along with the map. In contrast, written and fractional scales become incorrect with enlargement or reduction. As an example, if you shrink a map from 1:24,000 to 1:63,360, the written scale "1 in. to 2000 ft" will no longer be correct. The new correct written scale is 1 in. to 5280 ft (1 mi).

Scales are *small*, *medium*, and *large*, depending on the ratio described. In relative terms, a scale of 1:24,000 is a large scale, whereas a scale of 1:50,000,000 is a small scale. The greater the denominator in a fractional scale (or the number on the right in a ratio expression), the smaller the scale of the map. Table 1.1 lists examples of selected representative fractions and written scales for small-, medium-, and large-scale maps.

Small-scale maps show a greater area in less detail; a small-scale map of the world is little help in finding an exact location, but works well for illustrating global wind patterns or ocean currents. Large-scale maps show a smaller area in more detail and are useful for applications needing precise location or navigation over short distances.

GEOreport 1.5 Magellan's crew loses a day

Early explorers had a problem before the date-line concept was developed. For example, Magellan's crew returned from the first circumnavigation of Earth in 1522, confident from their ship's log that it was Wednesday, September 7. They were shocked when informed by local residents that it was actually Thursday, September 8. Without an International Date Line, they had no idea that they must advance their calendars by a day when sailing around the world in a westward direction.

TABLE 1.1 Sample Representative Fractions and Written Scales for Small-, Medium-, and Large-Scale Maps

System	Scale Size	Representative Fraction	Written System Scale
English	Small	1:3,168,000	1 in. = 50 mi
		1:1,000,000	1 in. = 16 mi
		1:250,000	1 in. = 4 mi
	Medium	1:125,000	1 in. = 2 mi
		1:63,360 (or 1:62,500)	1 in. = 1 mi
	Large	1:24,000	1 in. = 2000 ft
Metric	Small	1:1,000,000	1 cm = 10.0 km
	Medium	1:25,000	1 cm = 0.25 km
	Large	1:10,000	1 cm = 0.10 km

CRITICALthinking 1.4
Find and Calculate Map Scales

Find globes or maps in the library or geography department and check the scales at which they were drawn. See if you can find examples of fractional, graphic, and written scales on wall maps, on highway maps, and in atlases. Find some examples of small- and large-scale maps, and note the different subject matter they portray.

Look at a world globe that is 61 cm (24 in.) in diameter (or adapt the following values to whatever globe you are using). We know that Earth has an equatorial diameter of 12,756 km (7926 mi), so the scale of such a globe is the ratio of 61 cm to 12,756 km. To calculate the representative fraction for the globe in centimeters, divide Earth's actual diameter by the globe's diameter (12,756 km ÷ 61 cm). (Hint: 1 km = 1000 m, 1 m = 100 cm; therefore, Earth's diameter of 12,756 km represents 1,275,600,000 cm; and the globe's diameter is 61 cm.) In general, do you think a world globe is a small- or a large-scale map of Earth's surface? ●

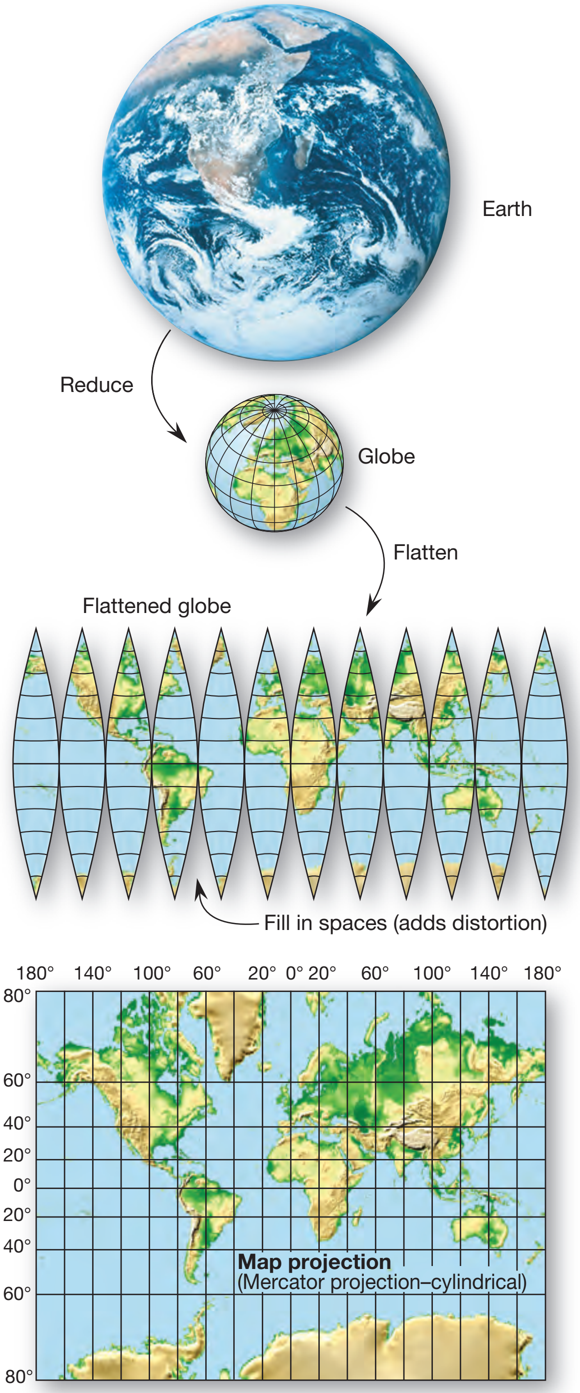
Map Projections

A globe is not always a helpful map representation of Earth. When you go on a trip, you need more-detailed information than a globe can provide. To provide local detail, cartographers prepare large-scale *flat maps*, which are two-dimensional representations (scale models) of our three-dimensional Earth. Unfortunately, such conversion from three dimensions to two causes distortion.

A globe is the only true representation of *distance*, *direction*, *area*, *shape*, and *proximity* on Earth. A flat map distorts these properties. Therefore, in preparing a flat map, the cartographer must decide which characteristic to preserve, which to distort, and how much distortion is acceptable. To understand this problem, consider these important properties of a globe:

- Parallels always are parallel to each other, always are evenly spaced along meridians, and always decrease in length toward the poles.
- Meridians always converge at both poles and always are evenly spaced along any individual parallel.
- The distance between meridians decreases toward poles, with the spacing between meridians at the 60th parallel equal to one-half the equatorial spacing.
- Parallels and meridians always cross each other at right angles.

The problem is that all these qualities cannot be reproduced simultaneously on a flat surface. Simply taking a globe apart and laying it flat on a table illustrates the challenge faced by cartographers (Figure 1.22). You can see the empty spaces that open up between the sections, or gores,



▲**Figure 1.22 From globe to flat map.** Conversion of the globe to a flat map projection requires a decision about which properties to preserve and the amount of distortion that is acceptable. [NASA astronaut photo from *Apollo 17*, 1972.]

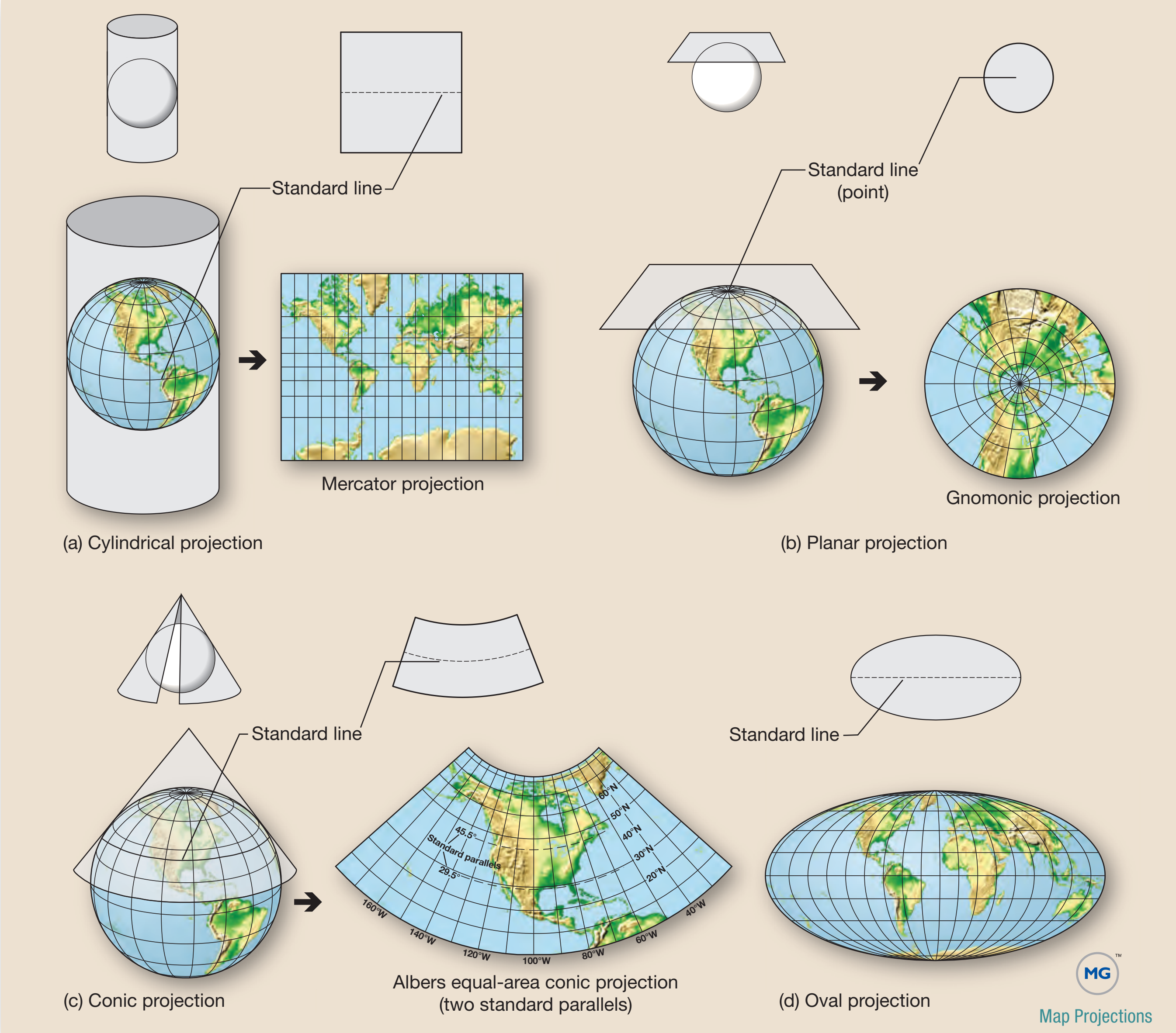
Map Projections

of the globe. This reduction of the spherical Earth to a flat surface is a **map projection**, and no flat map projection of Earth can ever have all the features of a globe. Flat maps always possess some degree of distortion—much less for large-scale maps representing a few kilometers; much more for small-scale maps covering individual countries, continents, or the entire world.

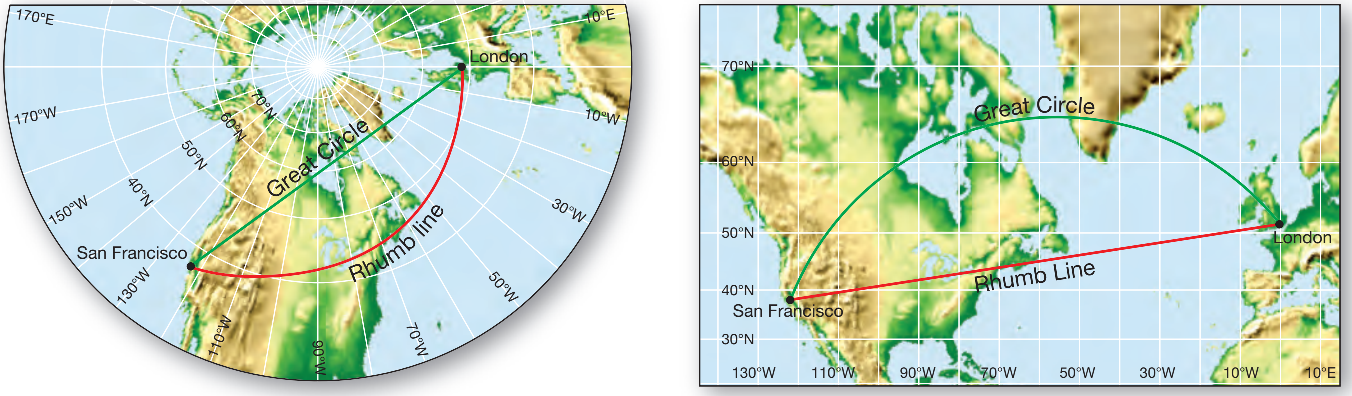
Equal Area or True Shape? There are four general classes of map projections, shown in Figure 1.23. The best projection is always determined by the intended use of the map. The major decisions in selecting a map projection involve the properties of **equal area** (equivalence) and **true shape** (conformality). A decision favoring one property sacrifices the other, for they cannot be shown together on the same flat map.

If a cartographer selects equal area as the desired trait—for example, for a map showing the distribution of world climates—then true shape must be sacrificed by stretching and shearing, which allow parallels and meridians to cross at other than right angles. On an equal-area map, a coin covers the same amount of surface area no matter where you place it on the map. In contrast, if a cartographer selects the property of true shape, such as for a map used for navigational purposes, then equal area must be sacrificed, and the scale will actually change from one region of the map to another.

Classes of Projections Figure 1.23 illustrates the classes of map projections and the perspective from which each class is generated. Despite the fact that modern cartographic technology uses mathematical constructions and computer-assisted graphics, the word *projection* is still used. The term comes from times past, when geographers actually projected the shadow of a wire-skeleton globe onto a geometric surface, such as



▲Figure 1.23 Classes of map projections.



(a) The gnomonic projection is used to determine the shortest distance (great circle route) between San Francisco and London because on this projection the arc of a great circle is a straight line.

(b) The great circle route is then plotted on a Mercator projection, which has true compass direction. Note that straight lines or bearings on a Mercator projection (rhumb lines) are not the shortest route.

▲**Figure 1.24 Determining great circle routes.**

a *cylinder*, *plane*, or *cone*. The wires represented parallels, meridians, and outlines of the continents. A light source cast a shadow pattern of these lines from the globe onto the chosen geometric surface.

The main map projection classes include the cylindrical, planar (or azimuthal), and conic. Another class of projections, which cannot be derived from this physical-perspective approach, is the nonperspective oval shape. Still other projections derive from purely mathematical calculations.

With projections, the contact line or contact point between the wire globe and the projection surface—a *standard line* or *standard point*—is the only place where all globe properties are preserved. Thus, a *standard parallel* or *standard meridian* is a standard line true to scale along its entire length without any distortion. Areas away from this critical tangent line or point become increasingly distorted. Consequently, this line or point of accurate spatial properties should be centered by the cartographer on the area of interest.

The commonly used **Mercator projection** (invented by Gerardus Mercator in 1569) is a cylindrical projection (Figure 1.23a). The Mercator is a conformal projection, with meridians appearing as equally spaced straight lines and parallels appearing as straight lines that are spaced closer together near the equator. The poles are infinitely stretched, with the 84th N parallel and 84th S parallel fixed at the same length as that of the equator. Note in Figures 1.22 and 1.23a that the Mercator projection is cut off near the 80th parallel in each hemisphere because of the severe distortion at higher latitudes.

Unfortunately, Mercator classroom maps present false notions of the size (area) of midlatitude and poleward landmasses. A dramatic example on the Mercator projection is Greenland, which looks bigger than all of South America. In reality, Greenland is an island only one-eighth the size of South America and is actually 20% smaller than Argentina alone.

The advantage of the Mercator projection is that a line of constant direction, known as a **rhumb line**, is straight and therefore facilitates plotting directions between two points (Figure 1.24). Thus, the Mercator projection is useful in navigation and is standard for nautical charts prepared by the National Ocean Service.

The *gnomonic*, or *planar, projection* in Figure 1.23b is generated by projecting a light source at the center of a globe onto a plane that is tangent to (touching) the globe's surface. The resulting severe distortion prevents showing a full hemisphere on one projection. However, a valuable feature is derived: All great circle routes, which are the shortest distance between two points on Earth's surface, are projected as straight lines (Figure 1.24a). The great circle routes plotted on a gnomonic projection then can be transferred to a true-direction projection, such as the Mercator, for determination of precise compass headings (Figure 1.24b).

For more information on maps used in this text and standard map symbols, turn to Appendix A, Maps in This Text and Topographic Maps. Topographic maps are essential tools for landscape analysis and are used by scientists, travelers, and others using the outdoors—perhaps you have used a "topo" map. The U.S. Geological Survey (USGS) *National Map* (available at http://nationalmap.gov/) provides downloadable digital topographic data for the entire United States. USGS topographic maps appear in several chapters of this text.

Modern Tools and Techniques for Geoscience

Geographers and Earth scientists analyze and map our home planet using a number of relatively recent and evolving technologies—the Global Positioning System (GPS), remote sensing, and geographic information systems (GIS). GPS relies on satellites in orbit to provide precise location and elevation. Remote sensing utilizes spacecraft, aircraft, and ground-based sensors to provide visual data that enhance our understanding of Earth. GIS is a means for storing and processing large amounts of spatial data as separate layers of geographic information; GISci is the geographic subfield that uses this technique.

Global Positioning System

Using an instrument that receives radio signals from satellites, you can accurately determine latitude, longitude, and elevation anywhere on or near the surface of Earth. The **Global Positioning System (GPS)** comprises at least 27 orbiting satellites, in 6 orbital planes, that transmit navigational signals to Earth-bound receivers (backup GPS satellites are in orbital storage as replacements). Think of the satellites as a constellation of navigational beacons with which you interact to determine your unique location. As we know, every possible square meter of Earth's surface has its own address relative to the latitude–longitude grid.

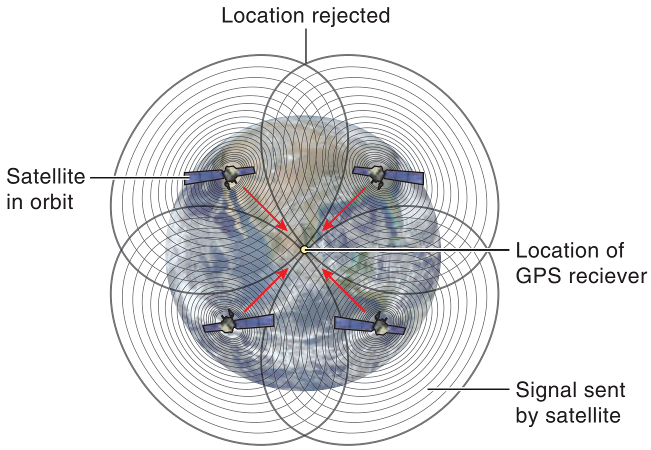
A GPS receiver senses signals from at least four satellites—a minimum of three satellites for location and a fourth to determine accurate time. The distance between each satellite and the GPS receiver is calculated using clocks built into each instrument that time radio signals traveling at the speed of light between them (Figure 1.24). The receiver calculates its true position using trilateration so that it reports latitude, longitude, and elevation. GPS units also report accurate time to within 100 billionths of a second. This allows GPS base stations to have perfectly synchronized timing, essential to worldwide communication, finance, and many industries.

GPS receivers are built into many smartphones, wristwatches, and motor vehicles, and can be bought as handheld units. Standard cell phones not equipped with a GPS receiver determine location based on the position of cell phone towers—a process not as accurate as GPS measurement.

The GPS is useful for diverse applications, such as navigating on the ocean, managing the movement of fleets of trucks, mining and mapping of resources, tracking wildlife migration and behavior, carrying out police and security work, and conducting environmental planning. Commercial airlines use the GPS to improve accuracy of routes flown and thus increase fuel efficiency.

Scientific applications of GPS technology are extensive. Consider these examples:

- In geodesy, GPS helps refine knowledge of Earth's exact shape and how this shape is changing.
- Scientists used GPS technology in 1998 to accurately determine the height of Mount Everest in the Himalayan Mountains, raising its elevation by 2 m (6 ft).
- On Mount St. Helens in Washington, a network of GPS stations measure ground deformation associated with earthquake activity (Figure 1.26). In



▲**Figure 1.25 Using satellites to determine location through GPS.** Imagine a ranging sphere around each of four GPS satellites. These spheres intersect at two points, one easily rejected because it is some distance above Earth and the other at the true location of the GPS receiver. In this way, signals from four satellites can reveal the receiver's location and elevation. [Based on J. Amos, "Galileo sat-nav in decisive phase," BBC News, March 2007, available at http://news.bbc.co.uk/2/hi/science/nature/6450367.stm]

▲**Figure 1.26 GPS application on Mount St. Helens.** [Mike Poland, USGS.]

GEOreport 1.6 GPS origins

Originally devised in the 1970s by the U.S. Department of Defense for military purposes, GPS is now commercially available worldwide. In 2000, the Pentagon shut down its Pentagon Selective Availability security control, making commercial resolution the same as military applications. Additional frequencies were added in 2003 and 2006, which increased accuracy significantly, to less than 10 m (33 ft). *Differential GPS (DGPS)* achieves accuracy of 1 to 3 m by comparing readings with another base station (reference receiver) for a differential correction. For a GPS overview, see http://www.gps.gov/.

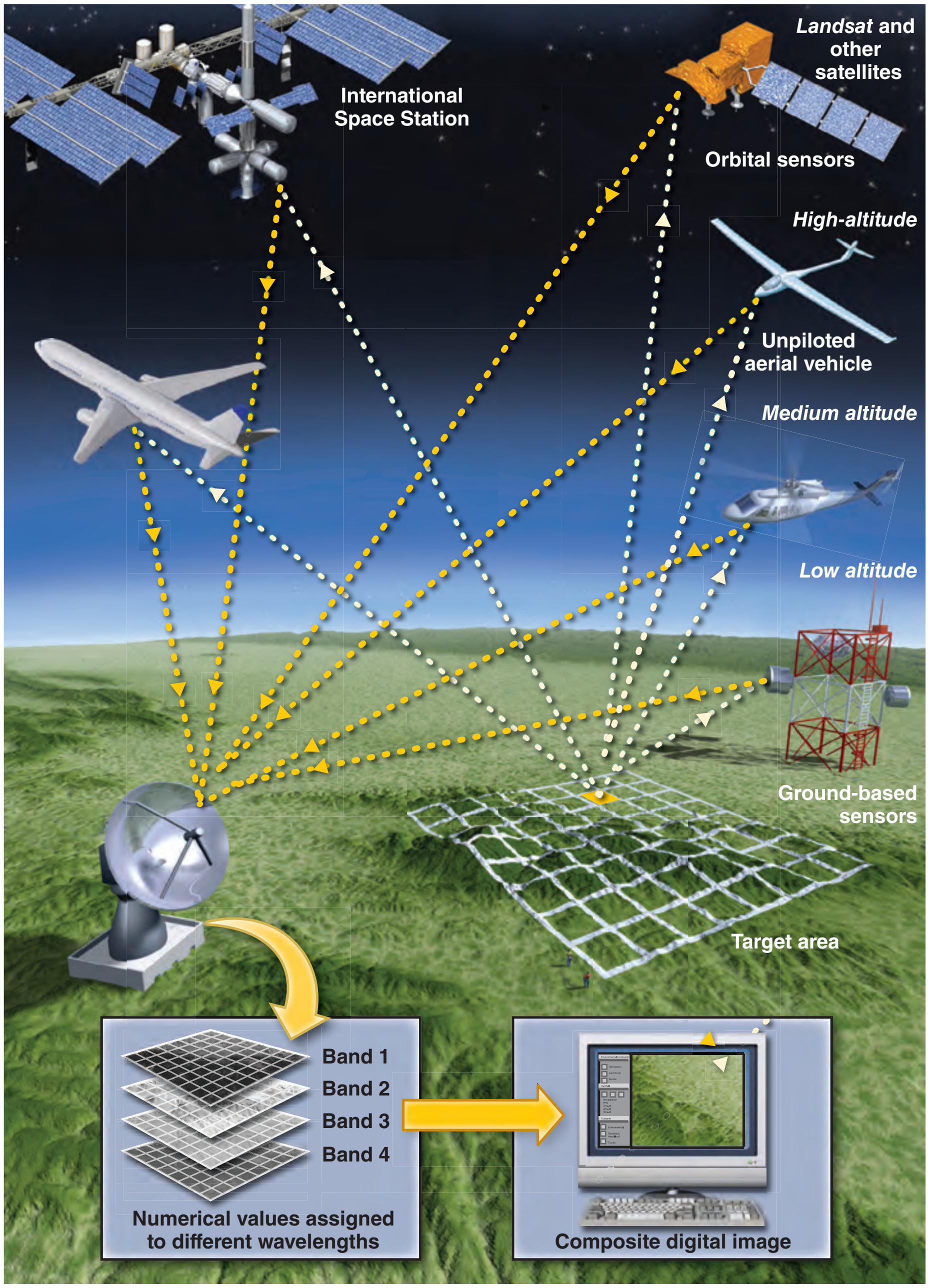
southern California, a similar GPS system can record fault movement as small as 1 mm (0.04 in.).

- GPS units attached to buoys in the Gulf of Mexico helped track the spread of the 2010 *Deepwater Horizon* oil spill.
- In Virunga National Park, Rwanda, rangers use handheld GPS units to track and protect mountain gorillas from poaching.

For scientists, this important technology provides a convenient, precise way to determine location, reducing the need for traditional land surveys requiring point-to-point line-of-sight measurements on the ground. In your daily life and travels, have you ever used a GPS unit? How did GPS assist you?

Remote Sensing

The acquisition of information about distant objects without having physical contact is **remote sensing**. In this era of observations from satellites outside the atmosphere, from aircraft within it, and from remote submersibles in the oceans, scientists obtain a wide array of remotely sensed data (Figure 1.27). Remote sensing is nothing new to humans; we do it with our eyes as we scan the environment, sensing the shape, size, and color of objects



A sample of orbital platforms:
CloudSat: Studies cloud extent, distribution, radiative properties, and structure.
ENVISAT: ESA environment-monitoring satellite; 10 sensors, including next generation radar.
GOES: Weather monitoring and Forecasting; *GOES-11*, *-12*, *-13*, and *-14*.
GRACE: Accurately maps Earth's gravitational field.
JASON-1, -2: Measures sea-level heights.
Landsat: *Landsat-1* in 1972 to *Landsat-7* in 1999, and *Landsat-8* in 2013, provides millions of images for Earth systems science and global change.
NOAA: First in 1978 through *NOAA-15*, *-16*, *-17*, *-18*, and *-19* now in operation, global data gathering, short- and long-term weather forecasts.
RADARSAT-1, -2: Synthetic Aperture Radar in near-polar orbit, operated by Canadian Space Agency.
SciSat-1: Analyzes trace gases, thin clouds, atmospheric aerosols with Arctic focus.
SeaStar: Carries the *SeaWiFS* (Sea-viewing Wide Field-of-View instrument) to observe Earth's oceans and microscopic marine plants.
Terra* and *Aqua: Environmental change, error-free surface images, cloud properties, through five instrument packages.
TOMS-EP: Total Ozone Mapping Spectrometer, monitoring stratospheric ozone, similar instruments on *NIMBUS-7* and *Meteor-3*.
***TOPEX-POSEIDON*:** Measures sea-level heights.
***TRMM*:** Tropical Rainfall Measuring Mission, includes lightning detection and global energy budget measurements.

For more info see:
http://www.nasa.gov/centers/goddard/missions/index.html

▲**Figure 1.27 Remote-sensing technology.** Remote-sensing technology measures and monitors Earth's systems from orbiting spacecraft, aircraft, and ground-based sensors. Various wavelengths (bands) are collected from sensors; computers process these data and produce digital images for analysis. A sample of remote-sensing platforms is listed along the side of the illustration. (Illustration is not to scale.)

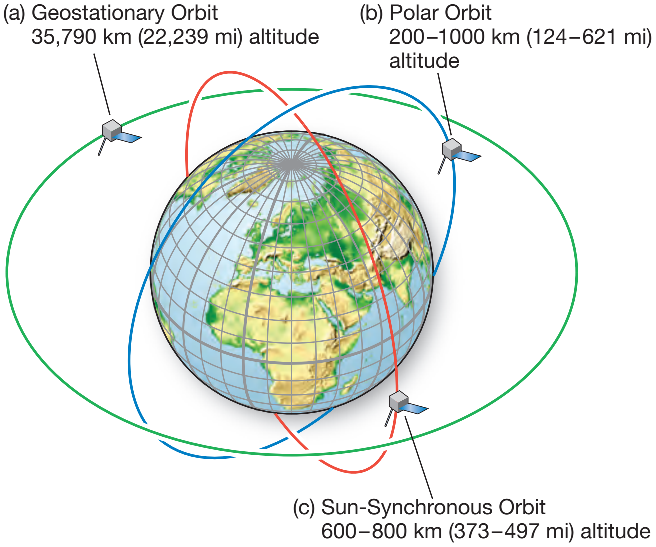
from a distance by registering energy from the visible-wavelength portion of the electromagnetic spectrum (discussed in Chapter 2). Similarly, when a camera views the wavelengths for which its film or sensor is designed, it remotely senses energy that is reflected or emitted from a scene.

Aerial photographs from balloons and aircraft were the first type of remote sensing, used for many years to improve the accuracy of surface maps more efficiently than can be done by on-site surveys. Deriving accurate measurements from photographs is the realm of **photogrammetry**, an important application of remote sensing. Later, remote sensors on satellites, the International Space Station, and other craft were used to sense a broader range of wavelengths beyond the visible range of our eyes. These sensors can be designed to "see" wavelengths shorter than visible light (such as ultraviolet) and wavelengths longer than visible light (such as infrared and microwave radar). As examples, infrared sensing produces images based on the temperature of objects on the ground, microwave sensing reveals features below Earth's surface, and radar sensing shows land-surface elevations, even in areas that are obscured by clouds.

Satellite Imaging During the last 50 years, satellite remote sensing has transformed Earth observation. Physical elements of Earth's surface emit radiant energy in wavelengths that are sensed by satellites and other craft and sent to receiving stations on the ground. The receiving stations sort these wavelengths into specific bands, or ranges. A scene is scanned and broken down into pixels (*pic*ture *el*ements), each identified by coordinates named *lines* (horizontal rows) and *samples* (vertical columns). For example, a grid of 6000 lines and 7000 samples forms 42,000,000 pixels, providing an image of great detail when the pixels are matched to the wavelengths they emit.

A large amount of data is needed to produce a single remotely sensed image; these data are recorded in digital form for later processing, enhancement, and image generation. Digital data are processed in many ways to enhance their utility: with simulated natural color, "false" color to highlight a particular feature, enhanced contrast, signal filtering, and different levels of sampling and resolution.

Satellites can be set in specific orbital paths (Figure 1.28) that affect the type of data and imagery produced. Geostationary (or geosynchronous) orbits, typically at an altitude of 35,790 km (22,239 mi), are *high Earth orbits* that effectively match Earth's rotation speed so that one orbit is completed in about 24 hours. Satellites can therefore remain "parked" above a specific location, usually the equator (Figure 1.28a). This "fixed" position means that satellite antennas on Earth can be pointed permanently at one position in the sky where the satellite is located; many communications and weather satellites use these high Earth orbits.



▲**Figure 1.28** **Three satellite orbital paths.**

Some satellites orbit at lower altitudes. The pull of Earth's gravity means that the closer to Earth they are, the faster their orbiting speed. For example, GPS satellites, at altitudes of about 20,200 km (12,552 mi), have *medium Earth orbits* that move more quickly than high Earth orbits. *Low Earth orbits*, at altitudes less than 1000 km (621 mi), are the most useful for scientific monitoring. Several of the National Aeronautics and Space Administration (NASA) environmental satellites in low Earth orbit are at altitudes of about 700 km (435 mi), completing one orbit every 99 minutes.

The angle of a satellite's orbit in relation to Earth's equator is its *inclination*, another factor affecting remotely sensed data. Some satellites orbit near the equator to monitor Earth's tropical regions; this low-inclination orbit acquires data only from low latitudes. An example is the *Tropical Rainfall Measuring Mission* (TRMM) satellite, which provides data for mapping water vapor and rainfall patterns in the tropics and subtropics. Monitoring the polar regions requires

GEOreport 1.7 Polar-orbiting satellites predict Hurricane Sandy's path

Scientists at the European Centre for Medium-Range Weather Forecasts report that polar-orbiting satellites, such as the National Oceanic and Atmospheric Administration (NOAA) *Suomi NPP* satellite, were critical for predicting Hurricane Sandy's track. Without data from these satellites, predictions for Hurricane Sandy would have been off by hundreds of miles, showing the storm heading out to sea rather than turning toward the New Jersey coast. *Suomi* orbits Earth about 14 times each day, collecting data from nearly the entire planet (find out more at http://npp.gsfc.nasa.gov/).

a satellite in polar orbit, with a higher inclination of about 90° (Figure 1.28b).

One type of polar orbit important for scientific observation is a Sun-synchronous orbit (Figure 1.28c). This low Earth orbit is synchronous with the Sun, so that the satellite crosses the equator at the same local solar time each day. Ground observation is maximized in Sun-synchronous orbit because Earth surfaces viewed from the satellite are illuminated by the Sun at a consistent angle. This enables better comparison of images from year to year because lighting and shadows do not change.

Passive Remote Sensing Passive remote-sensing systems record wavelengths of energy radiated from a surface, particularly visible light and infrared. Our own eyes are passive remote sensors, as was the *Apollo 17* astronaut camera that made the film photograph of Earth on the back cover of this book.

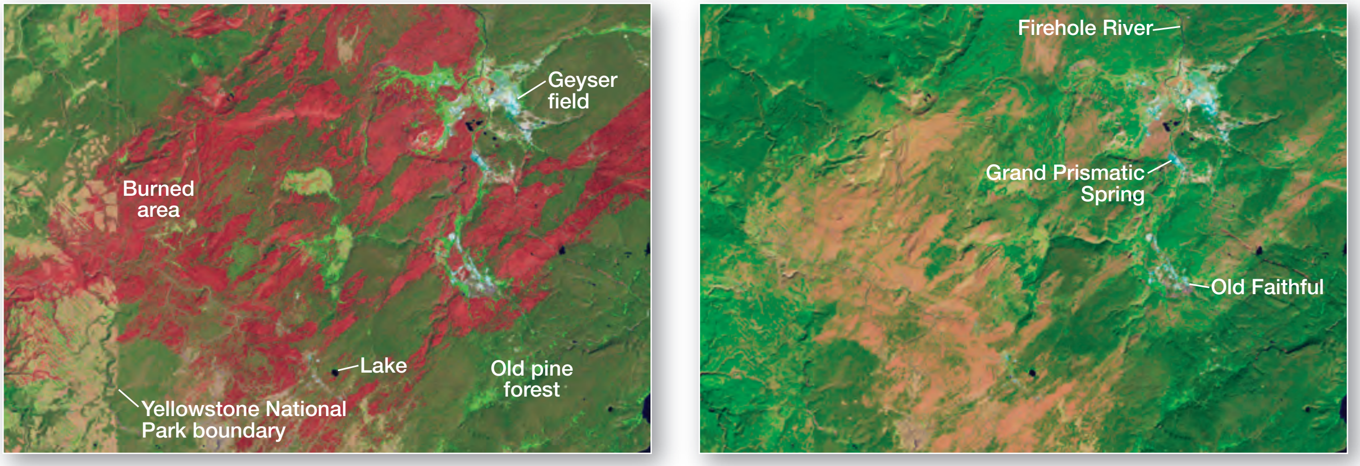
A number of satellites carry passive remote sensors for weather forecasting. The *Geostationary Operational Environmental Satellites*, known as *GOES*, became operational in 1994 and provide the images you see on television weather reports. *GOES-12*, *-13*, and *-15* are operational; *GOES-12* sits at 60° W longitude to monitor the Caribbean and South America. Think of these satellites as hovering over these meridians for continuous coverage, using visual wavelengths for daylight hours and infrared for nighttime views. *GOES-14*, parked in orbit since 2009, replaced *GOES-13* in 2012 when that satellite experienced technical problems.

Landsat satellites, which began imaging Earth in the 1970s, are used extensively for comparison of changing Earth landscapes over time, among other applications (Figure 1.29; more images of changing Earth systems at http://earthobservatory.nasa.gov). *Landsat-5* was retired in 2012 after 29 years, the longest-running Earth-observing mission in history; *Landsat-7* remains operational as part of NASA's ongoing Landsat Data Continuity Mission. Landsat-8 was launched in 2013, beginning the new Landsat program managed by the U.S. Geological Survey.

Although the *Landsat* satellites far surpassed their predicted lifespans, most satellites are removed from orbit after 3 to 5 years. Launched in 2011, *Suomi NPP* is part of the National Polar-orbiting Partnership (NPP), the next generation of satellites that will replace NASA's aging Earth Observation Satellite satellite fleet. *Suomi NPP*'s Visible Infrared Imaging Radiometer Suite (VIIRS) imaged Hurricane Sandy along the U.S. East Coast in October 2012, as seen on the half title page of this book. Many of the beautiful NASA "Blue Marble" Earth composite images are from the *Suomi* satellite (Figure 1.30).

Active Remote Sensing Active remote-sensing systems direct a beam of energy at a surface and analyze the energy reflected back. An example is *radar* (*ra*dio *d*etection *a*nd *r*anging). A radar transmitter emits short bursts of energy that have relatively long wavelengths (0.3 to 10 cm) toward the subject terrain, penetrating clouds and darkness. Energy reflected back to a radar receiver for analysis is known as *backscatter*. Radar images collected in a time series allow scientists to make pixel-by-pixel comparisons to detect Earth movement, such as elevation changes along earthquake faults (images and discussion in Chapter 13).

Another active remote-sensing technology is airborne LiDAR, or light detection and ranging. LiDAR systems collect highly detailed and accurate data for surface terrain using a laser scanner, with up to 150,000 pulses per second, 8 pulses or more per square meter, providing 15-m (49.2-ft) resolution. GPS and navigation systems onboard the aircraft determine the location of



(a) A year after the 1988 wildfires, burned land is deep red. Old pine forest is dark green; geyser fields are pale blue; lakes are dark blue.

(b) By the end of 2011, fire scars have faded to orange as grass and young trees emerge. Recovery is slow on this high-elevation plateau.

▲**Figure 1.29 Landscape recovery from fire in Yellowstone National Park, Wyoming.** *Landsat-5* images contrast the 1989 and 2011 landscapes of Yellowstone, using a combination of visible and infrared light to highlight the burned area and changes in vegetation. [NASA.]

▲Figure 1.30 ***Suomi NPP* Blue Marble image.** This composite view of Earth was imaged January 2, 2012. NASA scientist Norman Kuring combined VIIRS instrument data from 6 orbits of the *Suomi NPP* satellite. VIIRS acquires data in 22 bands covering visible, near-infrared, and thermal infrared wavelengths. [NASA.]

each pulse. LiDAR datasets are often shared between private, public, and scientific users for multiple applications. Scientists are presently studying the effects of Hurricane Sandy along the U.S. East Coast using LiDAR (see discussion in Chapter 16).

Geographic Information Systems

Techniques such as remote sensing acquire large volumes of spatial data that must be stored, processed, and retrieved in useful ways. A **geographic information system (GIS)** is a computer-based data-processing tool for gathering, manipulating, and analyzing geographic information. Today's sophisticated computer systems allow the integration of geographic information from direct surveys (on-the-ground mapping) and remote sensing in complex ways never before possible. Whereas printed maps are fixed at time of publication, GIS maps can be easily modified and evolve instantly.

In a GIS, spatial data can be arranged in layers, or planes, containing different kinds of data (Figure 1.31). The beginning component for any GIS is a map, with its associated coordinate system, such as latitude–longitude provided by GPS locations or digital surveys (the top layer in Figure 1.31a). This map establishes reference points against which to accurately position other data, such as remotely sensed imagery.

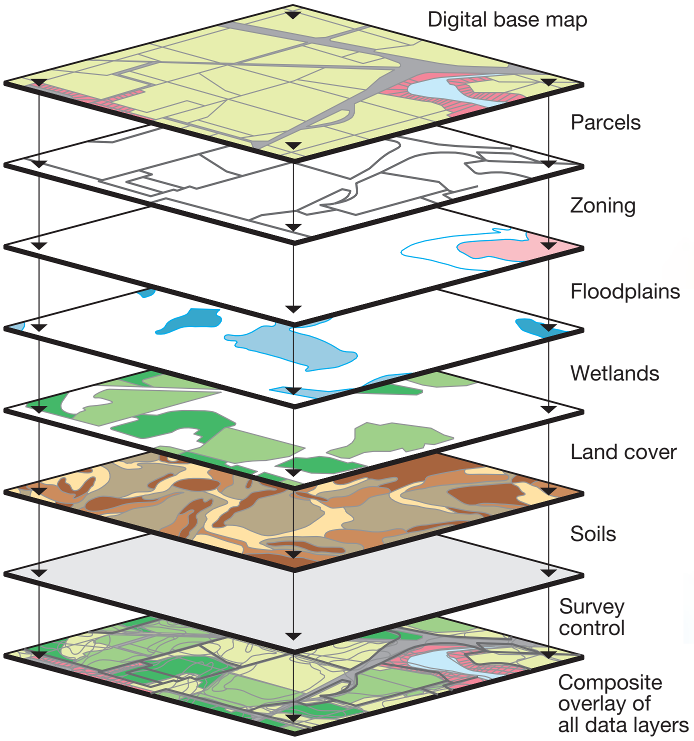
CRITICALthinking 1.5
Test Your Knowledge about Satellite Imagery

Go to the NASA, USGS (http://eros.usgs.gov/), or ESA (European Space Agency; http://www.esa.int/Our_Activities/Observing_the_Earth) website and view some satellite images. Then examine the image in Figure CT 1.5.1. Was this made by an aircraft, a ground-based sensor, or a satellite? Is this a natural-color or false-color image? Can you determine what the colors represent? Can you identify the location, the land and water bodies, and other physical features? Finally, based on your research and examples in this text, can you determine the specific source (LiDAR aircraft, *GOES* or *Landsat* satellite, etc.) of the data that made this image? (Find the answers at the end of the Chapter 1 Key Learning Concept Review.) ●

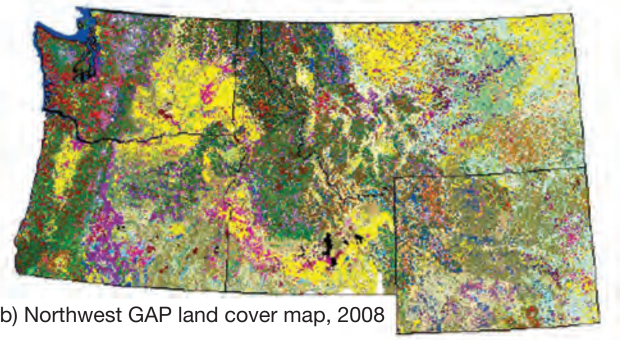
▲Figure CT 1.5.1 Can you describe this image? [NASA.]

A GIS is capable of analyzing patterns and relationships within a single data plane, such as the floodplain or soil layer in Figure 1.31a. A GIS also can generate an overlay analysis where two or more data planes interact. When the layers are combined, the resulting synthesis—a *composite overlay*—is ready for use in analyzing complex problems. The utility of a GIS is its ability to manipulate data and bring together several variables for analysis.

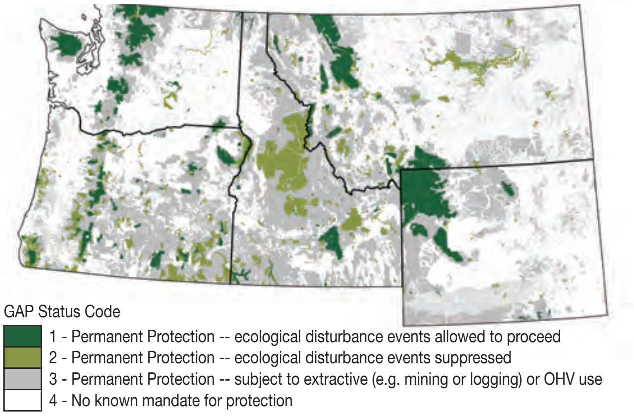
Figures 1.31b and c show two GIS map layers included in the Northwest Gap Analysis Program (GAP), a five-state assessment of terrestrial species and habitat, land stewardship, and management status, which began in 2004. The Northwest project is part of a nationwide GAP environmental quality assessment by the USGS for species conservation; critical data layers are vegetation



(a) Layered spatial data in a GIS format.



(b) Northwest GAP land cover map, 2008



(c) Northwest GAP protected areas map, 2008

▲**Figure 1.31 A geographic information system (GIS) model.** [(a) After USGS. (b) and (c) University of Idaho, Northwest Gap Analysis Project.]

type, species range, and land ownership, among other environmental variables. (See http://gapanalysis.usgs.gov/ or http://gap.uidaho.edu for a project overview and to access interactive maps.)

Geographic information science (GISci) is the field that develops the capabilities of GIS for use within geography and other disciplines. GISci analyzes Earth and human phenomena over time. This can include the study and forecasting of diseases, the population displacement caused by Hurricane Sandy, the destruction from the Japan earthquake and tsunami in 2011, or the status of endangered species and ecosystems, to name a few examples.

One widely used application of GIS technology is in the creation of maps with a three-dimensional perspective. These maps are produced by combining *digital elevation models* (DEMs), which provide the base elevation data, with satellite-image overlay (see examples in Chapter 13). Through the GIS, these data are available for multiple displays, animations, and other scientific analyses.

Google Earth™ and similar programs that can be downloaded from the Internet provide three-dimensional viewing of the globe, as well as geographic information (http://earth.google.com/). Google Earth™ allows the user to "fly" anywhere on Earth and zoom in on landscapes and features of interest, using satellite imagery and aerial photography at varying resolutions. Users can select layers, as in a GIS model, depending on the task at hand and the composite overlay displayed. NASA's World Wind software is another open-source browser with access to high-resolution satellite images and multiple data layers suitable for scientific applications.

Geovisualization is the technique of adjusting geospatial data sets in real time, so that users can instantly make changes to maps and other visual models. Geovisual tools are important for translating scientific knowledge into resources that nonscientists can use for decision making and planning. At East Carolina University, scientists are developing geovisual tools to assess the effects of sea level rise along the North Carolina coast, in partnership with state, local, and nonprofit organizations (see http://www.ecu.edu/renci/Technology/GIS.html).

Access to GIS is expanding and becoming more user-friendly with the increased availability of numerous open-source GIS software packages. These are usually free, have online support systems, and are updated frequently (see http://opensourcegis.org/). In addition, public access to large remote-sensing data sets for analyses and display is now available, without the need to download large amounts of data (see examples of research applications at http://disc.sci.gsfc.nasa.gov/).

GEOSYSTEMS**connection**

With this overview of geography, the scientific process, and the *Geosystems* approach in mind, we now embark on a journey through each of Earth's four spheres—Part I, Atmosphere; Part II, Hydrosphere; Part III, Lithosphere; and Part IV, Biosphere. Chapter 2 begins at the Sun, including its place in the Universe and seasonal changes in the distribution of its energy flow to Earth. In Chapter 3, we follow solar energy through Earth's atmosphere to the surface, and in Chapters 4 through 6 examine global temperature patterns and the circulation of air and water in Earth's vast wind and ocean currents.

At the end of each chapter, you find a *Geosystems Connection* to act as a bridge from one chapter to the next, helping you to cross to the next topic.

KEY LEARNING concepts review

Here is a handy summary designed to help you review the Key Learning Concepts listed on this chapter's title page. The recap of each concept concludes with a list of the key terms from that portion of the chapter, their page numbers, and review questions pertaining to the concept. Similar summary and review sections follow each chapter in the book.

■ *Define* geography in general and physical geography in particular.

Geography combines disciplines from the physical and life sciences with the human and cultural sciences to attain a holistic view of Earth. Geography's **spatial** viewpoint examines the nature and character of physical space and the distribution of things within it. Geography integrates a wide range of subject matter, and geographic education recognizes five major themes: **location**, **region**, **human–Earth relationships**, **movement**, and **place**. A method, **spatial analysis**, ties together this diverse field, focusing on the interdependence among geographic areas, natural systems, society, and cultural activities over space or area. The analysis of **process**—a set of actions or mechanisms that operate in some special order—is also central to geographic understanding.

Physical geography applies spatial analysis to all the physical components and process systems that make up the environment: energy, air, water, weather, climate, landforms, soils, animals, plants, microorganisms, and Earth itself. Physical geography is an essential aspect of **Earth systems science.** The science of physical geography is uniquely qualified to synthesize the spatial, environmental, and human aspects of our increasingly complex relationship with our home planet—Earth.

geography (p. 31)
spatial (p. 31)
location (p. 31)
region (p. 31)
human–Earth relationships (p. 31)
movement (p. 31)
place (p. 31)
spatial analysis (p. 32)
process (p. 32)
physical geography (p. 32)
Earth systems science (p. 33)

1. Define the feedback mechanisms that influence the system operations.
2. How will you synthesize physical and human geography? What are the processes and elements that make up the environment?
3. Have you made decisions today that involve geographic concepts discussed within the five themes presented? Explain briefly.
4. What are the different spatial themes of geographic science? Provide examples for each theme according to your own experience.

■ *Discuss* human activities and human population growth as they relate to geographic science, and *summarize* the scientific process.

Understanding the complex relations between Earth's physical systems and human society is important to human survival. Hypotheses and theories about the Universe, Earth, and life are developed through the scientific process, which relies on a general series of steps that make up the **scientific method**. Results and conclusions from scientific experiments can lead to basic theories, as well as applied uses for the general public.

Awareness of the human denominator, the role of humans on Earth, has led to physical geography's increasing emphasis on human–environment interactions. Recently, **sustainability science** has become an important new discipline, integrating sustainable development and functioning Earth systems.

scientific method (p. 33)
sustainability science (p. 35)

5. Sketch a flow diagram of the scientific process and method, beginning with observations and ending with the development of theories and laws.
6. Summarize population-growth issues: population size, the impact per person, and future projections. What strategies do you see as important for global sustainability?

■ *Describe* systems analysis, open and closed systems, and feedback information, and *relate* these concepts to Earth systems.

A **system** is any ordered set of interacting components and their attributes, as distinct from their surrounding environment. Systems analysis is an important organizational and analytical tool used by geographers. Earth is an **open system** in terms of energy, receiving energy from the Sun, but it is essentially a **closed system** in terms of matter and physical resources.

As a system operates, "information" is returned to various points in the operational process via pathways of **feedback loops**. If the feedback information discourages change in the system, it is **negative feedback**. Further production of such feedback opposes system changes. Such negative feedback causes self-regulation in a natural system, stabilizing the system. If feedback information encourages change in the system, it is **positive feedback**. Further production of positive feedback stimulates system changes. Unchecked positive feedback in a system can create a runaway ("snowballing") condition. When the rates of inputs and outputs in the system are equal and the amounts of energy and matter in storage within the system are constant (or when they fluctuate around a stable average), the system is in **steady-state equilibrium**. A system showing a steady increase or decrease in some operation over time (a trend) is in **dynamic equilibrium**. A **threshold**, or tipping point, is the moment at which a system can no longer maintain its character and lurches to a new operational level. Geographers often construct a simplified **model** of natural systems to better understand them.

Four immense open systems powerfully interact at Earth's surface: three **abiotic**, or nonliving, systems—the **atmosphere**, **hydrosphere** (including the **cryosphere**), and **lithosphere—**and a **biotic**, or living, system—the **biosphere**, or **ecosphere**.

system (p. 36)
open system (p. 36)
closed system (p. 37)
feedback loop (p. 37)
negative feedback (p. 37)
positive feedback (p. 38)
steady-state equilibrium (p. 38)
dynamic equilibrium (p. 38)
threshold (p. 38)
model (p. 39)
abiotic (p. 39)
biotic (p. 39)
atmosphere (p. 42)
hydrosphere (p. 42)
cryosphere (p. 42)
lithosphere (p. 42)
biosphere (p. 42)
ecosphere (p. 42)

7. Describe the difference between open and closed Earth systems. How do open systems affect the Earth's environment and equilibrium?
8. Describe Earth as a system in terms of both energy and matter; use simple diagrams to illustrate your description.
9. What are the three abiotic spheres that make up Earth's environment? Relate these to the biotic sphere, the biosphere.

■ *Explain* Earth's reference grid: latitude and longitude and latitudinal geographic zones and time.

The science that studies Earth's shape and size is **geodesy**. Earth bulges slightly through the equator and is oblate (flattened) at the poles, producing a misshapen spheroid, or **geoid**. Absolute location on Earth is described with a specific reference grid of **parallels** of **latitude** (measuring distances north and south of the equator) and **meridians** of **longitude** (measuring distances east and west of a prime meridian). A historic breakthrough in navigation occurred with the establishment of an international **prime meridian** (0° through Greenwich, England). A **great circle** is any circle of Earth's circumference whose center coincides with the center of Earth. Great circle routes are the shortest distance between two points on Earth. **Small circles** are those whose centers do not coincide with Earth's center.

The prime meridian provided the basis for **Greenwich Mean Time** (**GMT**), the world's first universal time system. Today, **Coordinated Universal Time** (**UTC**) is the worldwide standard and the basis for international time zones. A corollary of the prime meridian is the 180° meridian, the **International Date Line (IDL)**, which marks the place where each day officially begins. **Daylight saving time** is a seasonal change of clocks by 1 hour in summer months.

geodesy (p. 44)
geoid (p. 44)
latitude (p. 45)
parallel (p. 45)
longitude (p. 47)
meridian (p. 47)
prime meridian (p. 47)
great circle (p. 47)
small circle (p. 47)
Greenwich Mean Time (GMT) (p. 48)
Coordinated Universal Time (UTC) (p. 49)
International Date Line (IDL) (p. 49)
daylight saving time (p. 50)

10. Draw a simple sketch describing Earth's shape and size.
11. What are the ellipsoid, geoid, and spheroid? How are they used to determine the Earth's surface?
12. Define the great circle and small circle. How do these circles help to establish the shortest route from one place to another?
13. Discuss the physical distances represented by degrees of latitude and longitude. How does the distance between degrees vary while moving toward the poles?
14. What does timekeeping have to do with longitude? Explain this relationship. How is Coordinated Universal Time (UTC) determined on Earth?
15. What and where is the prime meridian? How was the location originally selected? Describe the meridian that is opposite the prime meridian on Earth's surface.

■ *Define* cartography and mapping basics: map scale and map projections.

A **map** is a generalized depiction of the layout of an area, usually some portion of Earth's surface, as seen from above and greatly reduced in size. **Cartography** is the science and art of mapmaking. For the spatial portrayal of Earth's physical systems, geographers use maps. **Scale** is the ratio of the image on a map to the real world; it relates a unit on the map to a corresponding unit on the ground. When creating a **map projection**, cartographers select the class of projection that is the best compromise for the map's specific purpose. Compromise is always necessary because Earth's roughly spherical three-dimensional surface cannot be exactly duplicated on a flat, two-dimensional map. Relative abilities to portray **equal area** (equivalence), **true shape** (conformality), true direction, and true distance are all considerations in selecting a projection. The **Mercator projection** is in the cylindrical class; it has true-shape qualities and straight lines that show constant direction. A **rhumb line** denotes constant direction and appears as a straight line on the Mercator.

map (p. 50)
cartography (p. 50)
scale (p. 50)
map projection (p. 53)
equal area (p. 53)
true shape (p. 53)
Mercator projection (p. 54)
rhumb line (p. 54)

16. Define cartography. Explain why it is an integrative discipline.
17. Assess your geographic literacy by examining atlases and maps. What types of maps have you used: Political? Physical? Topographic? Do you know what map projections they employed? Do you know the names and locations of the four oceans, the seven continents, and most individual countries? Can you identify the new countries that have emerged since 1990?
18. What is map scale? In what three ways may it be expressed on a map?
19. Differentiate between small- and large-scale maps. Where and in which kind of application can you utilize a map having a small area of coverage and providing detailed information about objects? Support your answer with examples.
20. Describe the differences between the characteristics of a globe and those that result when a flat map is prepared.
21. Discuss the advantages and disadvantages of different projections. Which projection system would you choose for your country? Explain.

- *Describe* modern geoscience techniques—the Global Positioning System (GPS), remote sensing, and the geographic information system (GIS)—and *explain* how these tools are used in geographic analysis.

Latitude, longitude, and elevation are accurately measured using a handheld **Global Positioning System** (**GPS**) instrument that reads radio signals from satellites. Orbital and aerial **remote sensing** obtains information about Earth systems from great distances without the need for physical contact. Satellites do not take photographs but instead record images that are transmitted to Earth-based receivers. Satellite data are recorded in digital form for later processing, enhancement, and image generation. Aerial photographs are used to improve the accuracy of surface maps, an application of remote sensing called **photogrammetry**.

Satellite and other data may be analyzed using **geographic information system** (**GIS**) technology. Computers process geographic information from direct ground surveys and remote sensing in complex layers of spatial data. Digital elevation models are three-dimensional products of GIS technology. Open-source GIS is increasingly available to scientists and the public for many applications, including spatial analysis in geography and the better understanding of Earth's systems.

Global Positioning System (GPS) (p. 55)
remote sensing (p. 56)
photogrammetry (p. 57)
geographic information system (GIS) (p. 59)

22. What is the minimum number of Global Positioning System (GPS) satellites required to calculate a position? Explain the process of positioning using GPS.
23. What is remote sensing? What are you viewing when you observe a weather satellite image on TV or in the newspaper? Explain.
24. If you were in charge of planning the human development of a large tract of land, how would GIS methodologies assist you? How might planning and zoning be affected if a portion of the tract in the GIS is a floodplain or prime agricultural land?

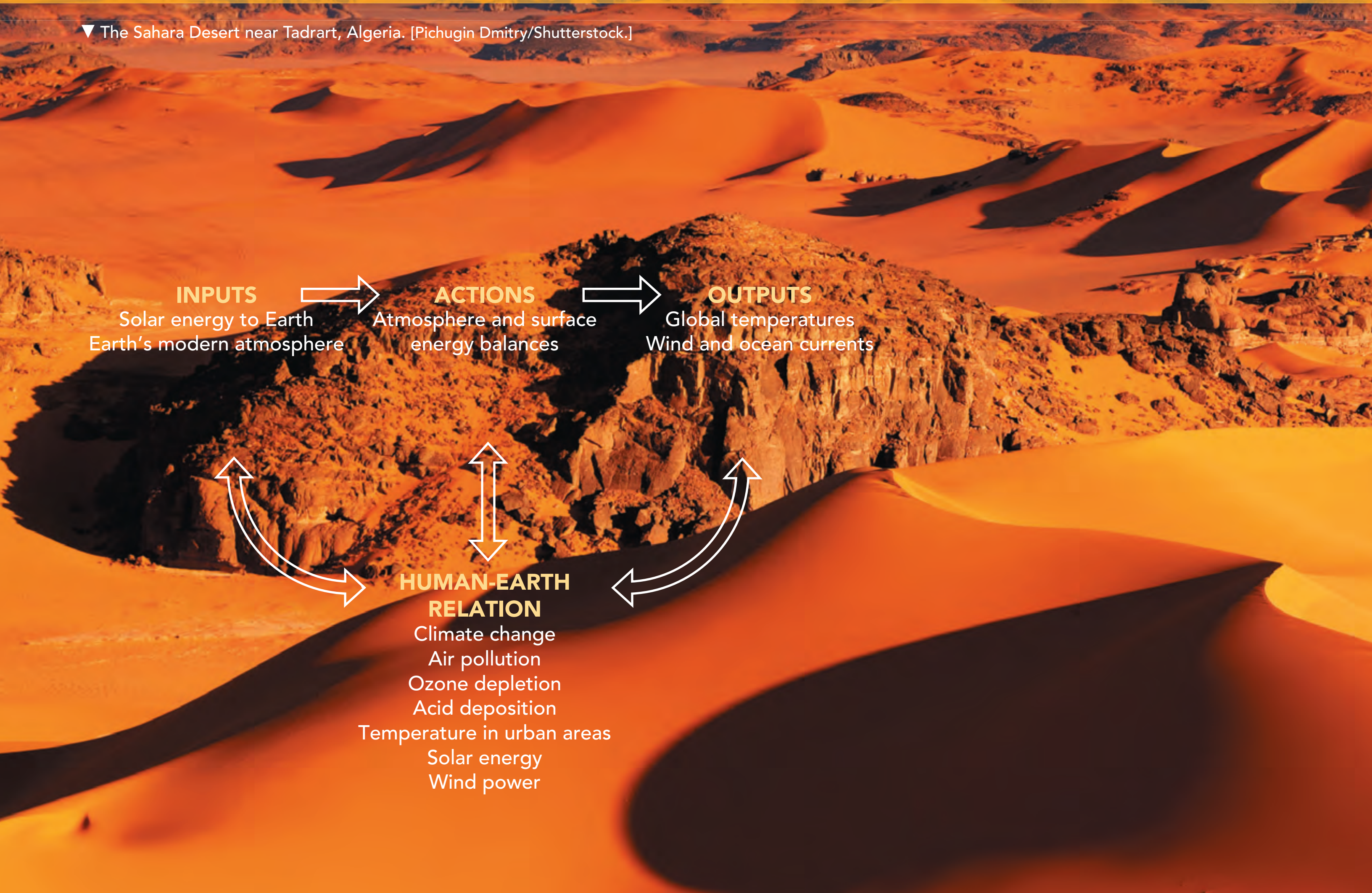
Answer for Critical Thinking 1.5, Figure CT 1.5.1: This natural, true-color image is a composite mosaic of numerous images captured between 2000 and 2002 from NASA satellite *Terra*. The location it depicts is the meeting of the European and African continents at the Strait of Gibraltar, extending from France and Spain across the Mediterranean to Morocco and Algeria.

I

The Energy–Atmosphere System

For more than 4.6 billion years, solar energy has traveled across interplanetary space to Earth, where a small portion of the solar output is intercepted. Our planet and our lives are powered by this radiant energy from the Sun. Because of Earth's curvature, the arriving energy is unevenly distributed at the top of the atmosphere, creating energy imbalances over the Earth's surface—the equatorial region experiences surpluses, receiving more energy than

▼ The Sahara Desert near Tadrart, Algeria. [Pichugin Dmitry/Shutterstock.]

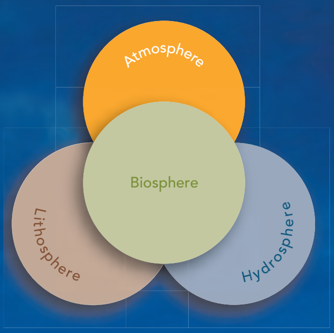


INPUTS
Solar energy to Earth
Earth's modern atmosphere

ACTIONS
Atmosphere and surface energy balances

OUTPUTS
Global temperatures
Wind and ocean currents

HUMAN-EARTH RELATION
Climate change
Air pollution
Ozone depletion
Acid deposition
Temperature in urban areas
Solar energy
Wind power



it emits; the polar regions experience deficits, emitting more energy than they receive. Also, the annual pulse of seasonal change varies the distribution of energy during the year.

Earth's atmosphere acts as an efficient filter, absorbing most harmful radiation, charged particles, and space debris so that they do not reach Earth's surface. In the lower atmosphere the unevenness of daily energy receipt gives rise to global patterns of temperature and the circulation of wind and ocean currents, driving weather and climate. Each of us depends on these interacting systems that are set into motion by energy from the Sun. These are the systems of Part I.

2

Solar Energy to Earth and the Seasons

On Fogo Island in the Cape Verde archipelago, a small village lies within the Cha Caldera, a large depression formed when the volcanic summit of Pico de Fogo collapsed after an eruption. On the date of this photo, your author and his wife were close to the subsolar point, the latitude on Earth where the Sun's rays are perpendicular to the surface at local noon. Looking closely, you can see shadows cast directly below the trees in this courtyard. The caldera wall is visible in the background.

Geosystems Now describes the author's chase of the subsolar point from aboard a ship in the Atlantic Ocean; the chase ended here at Fogo Island on May 1 at 14.8 N latitude. Chapter 2 discusses energy from the Sun and the seasonal changes we experience on Earth. [Bobbé Christopherson.]

KEY LEARNING concepts

After reading the chapter, you should be able to:

- ***Distinguish*** between galaxies, stars, and planets, and ***locate*** Earth.
- ***Summarize*** the origin, formation, and development of Earth, and ***reconstruct*** Earth's annual orbit about the Sun.
- ***Describe*** the Sun's operation, and ***explain*** the characteristics of the solar wind and the electromagnetic spectrum of radiant energy.
- ***Illustrate*** the interception of solar energy and its uneven distribution at the top of the atmosphere.
- ***Define*** solar altitude, solar declination, and daylength, and ***describe*** the annual variability of each—Earth's seasonality.

Chasing the Subsolar Point

April 2010 in the Atlantic Ocean: After a month at sea traveling from the Antarctic region, our ship moves northward toward the equator in the Atlantic Ocean. We have no readily accessible news or Wi-Fi; our views are of ocean horizons in every direction. Our research ship carries crew and 48 passengers. On 24 April, I swam at the Earth's equator, no land in sight for thousands of kilometers and water 3 to 4 km deep. Looking through a mask toward the seafloor the view is an infinite blue, creating both an awesome and scary feeling.

On our 5-week expedition, your author and his wife traveled from the Weddell Sea, Antarctica, at 63° S latitude, to the Cape Verde islands off the West African coast, at 14° N latitude (Figure GN 2.1). As we passed over the equator into the Northern Hemisphere, our chase of the subsolar point began.

▲Figure GN 2.1 **The 2010 author's expedition map.** See *Geosystems Now* in Chapters 6 and 20 for a description of events occurring on the island of Tristan de Cunha, another stop on the expedition.

What is the subsolar point? Every day at noon, there is some latitude on Earth at which the Sun is "directly" overhead at nearly a 90° angle. During the spring months (March–June), the latitude receiving the "direct" rays of the Sun shifts from the equator, at 0°, to the Tropic of Cancer, at 23.5° N. The exact latitude receiving these direct 90° rays is the *subsolar point*. Think of this point as the latitude where the Sun is highest in the sky and its rays are perpendicular to the Earth's surface.

Each year, around March 22, the subsolar point is on the equator; this is the *March equinox*, when daylength is equal for all latitudes on Earth. In summer, around June 21, the subsolar point is on the Tropic of Cancer; this is the *June solstice*, when daylength is longest for northern hemisphere latitudes and shortest for southern hemisphere latitudes. Around September 22, the Sun's subsolar point returns to the equator (the September equinox), and by December it is on the Tropic of Capricorn, at 23.5° S (the December solstice). Outside of the tropics, the Sun is never directly overhead. For example, at 40° N latitude the noon Sun's altitude ranges from 26° above the horizon in December to 73° in June, and is never at 90°.

Catching up to the Sun's direct rays On our expedition ship, we chased the subsolar point as it moved from the equator to the Tropic of Cancer between the March equinox and the June solstice. As we traveled, we tracked our route and that of the Sun to determine the closest we could get to this point, either on our ship or on an island in the Atlantic Ocean.

▲Figure GN 2.2 **Near the subsolar point, Fogo Island, Cape Verde.** Note that the boys' shadow is cast almost directly beneath them. [Bobbé Christopherson.]

The subsolar point occurs at 1° N latitude on March 23, moving close to 15° N on May 1. When did we come closest? On May 1, we arrived at 14.8° N, on Fogo Island, Cape Verde. We saw two boys and a donkey hauling water around local noon. Note that their shadow is cast directly beneath them, under the nearly perpendicular rays of the overhead Sun (Figure GN 2.2 and the chapter-opening photo).

In this chapter we track the march of the seasons, marked by changes in daylength and the angle of the Sun's rays. We can calculate the latitude of the subsolar point at any time during the year using a chart called the *analemma*, which appears on most globes in the area of the Southeast Pacific. An example of this figure-8 shaped chart is provided toward the end of the chapter (see Figure CT 2.3.1, p. 54).). After learning about Earth's seasonality in relation to Sun angle, you can use the analemma to determine the subsolar point for any day of the year. Check this analemma for May 1st.

GEOSYSTEMS NOW ONLINE For the current location of the subsolar point, go to http://www.timeanddate.com/worldclock/sunearth.html. MG