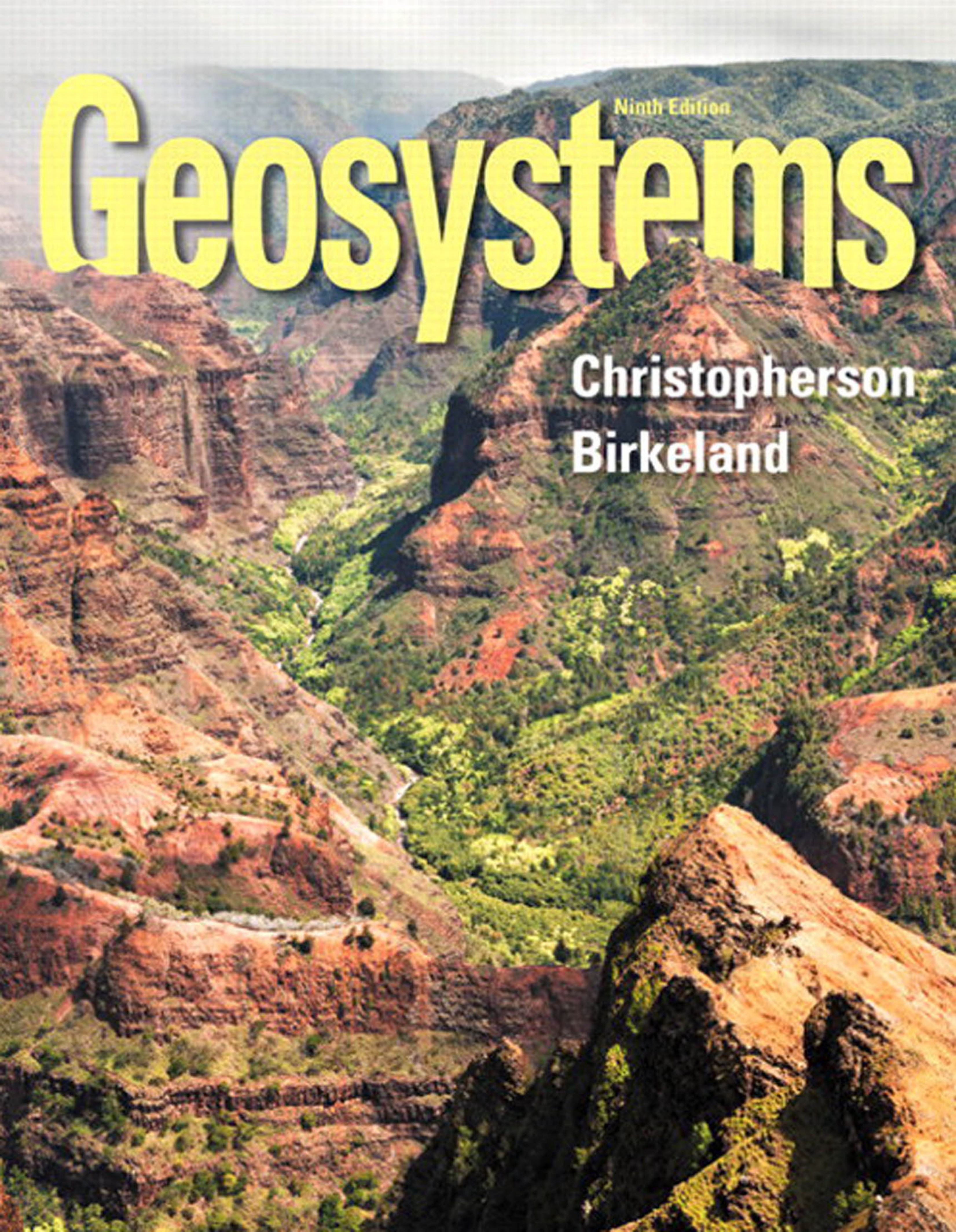
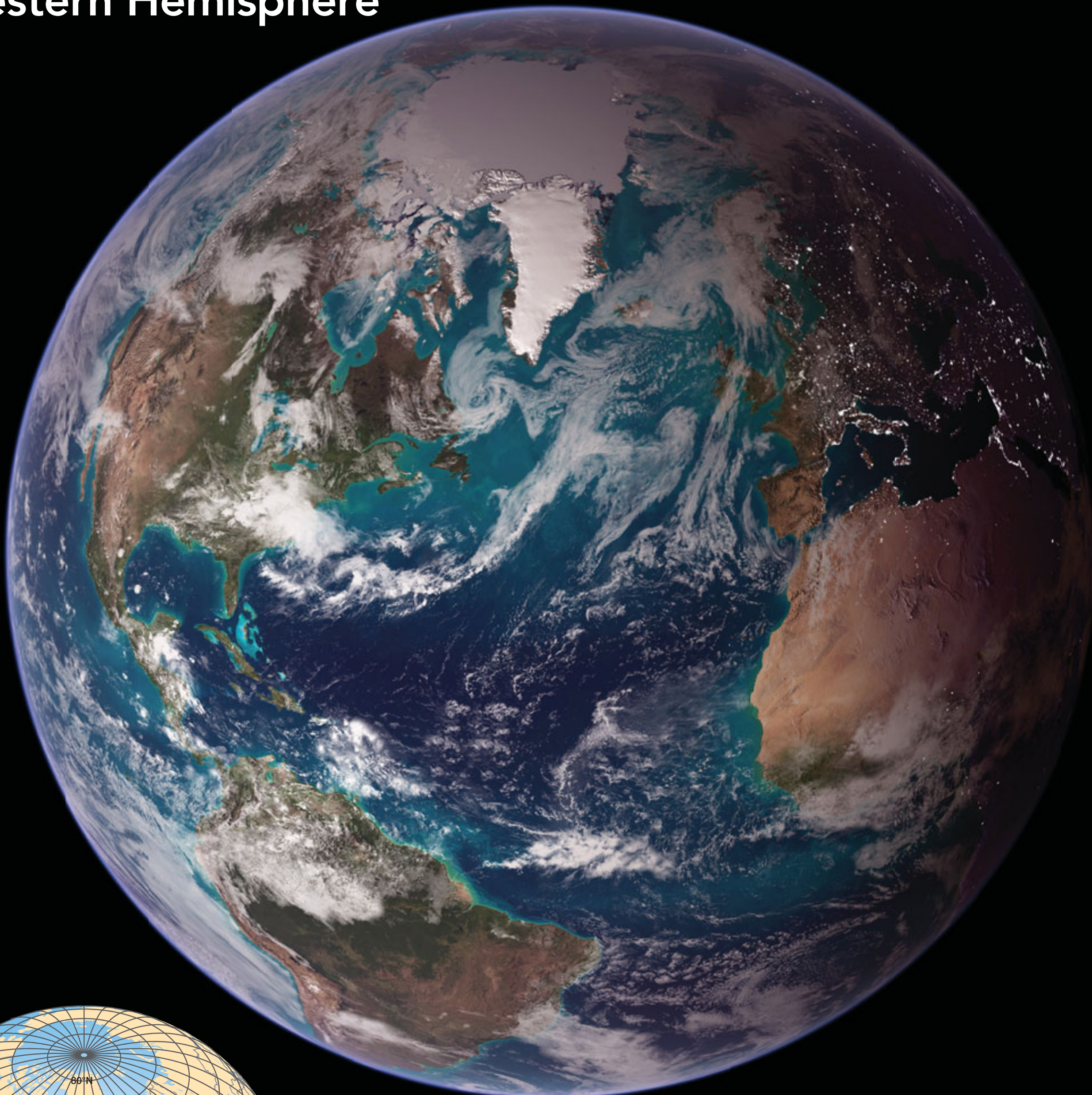
Geosystems

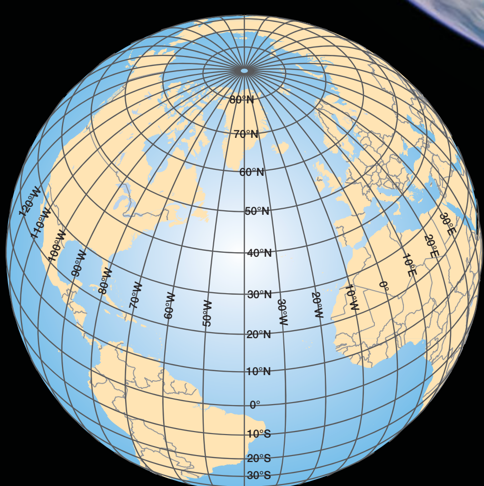
Ninth Edition

Christopherson
Birkeland



Western Hemisphere

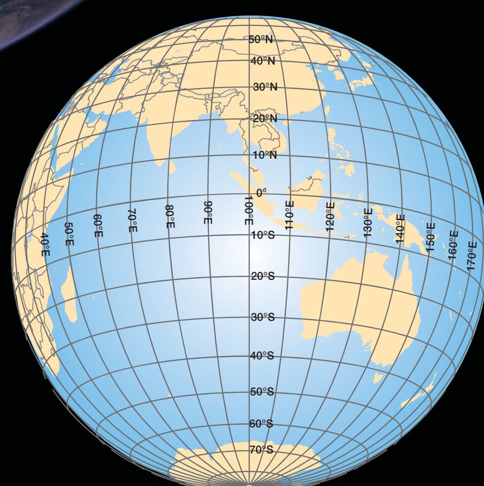




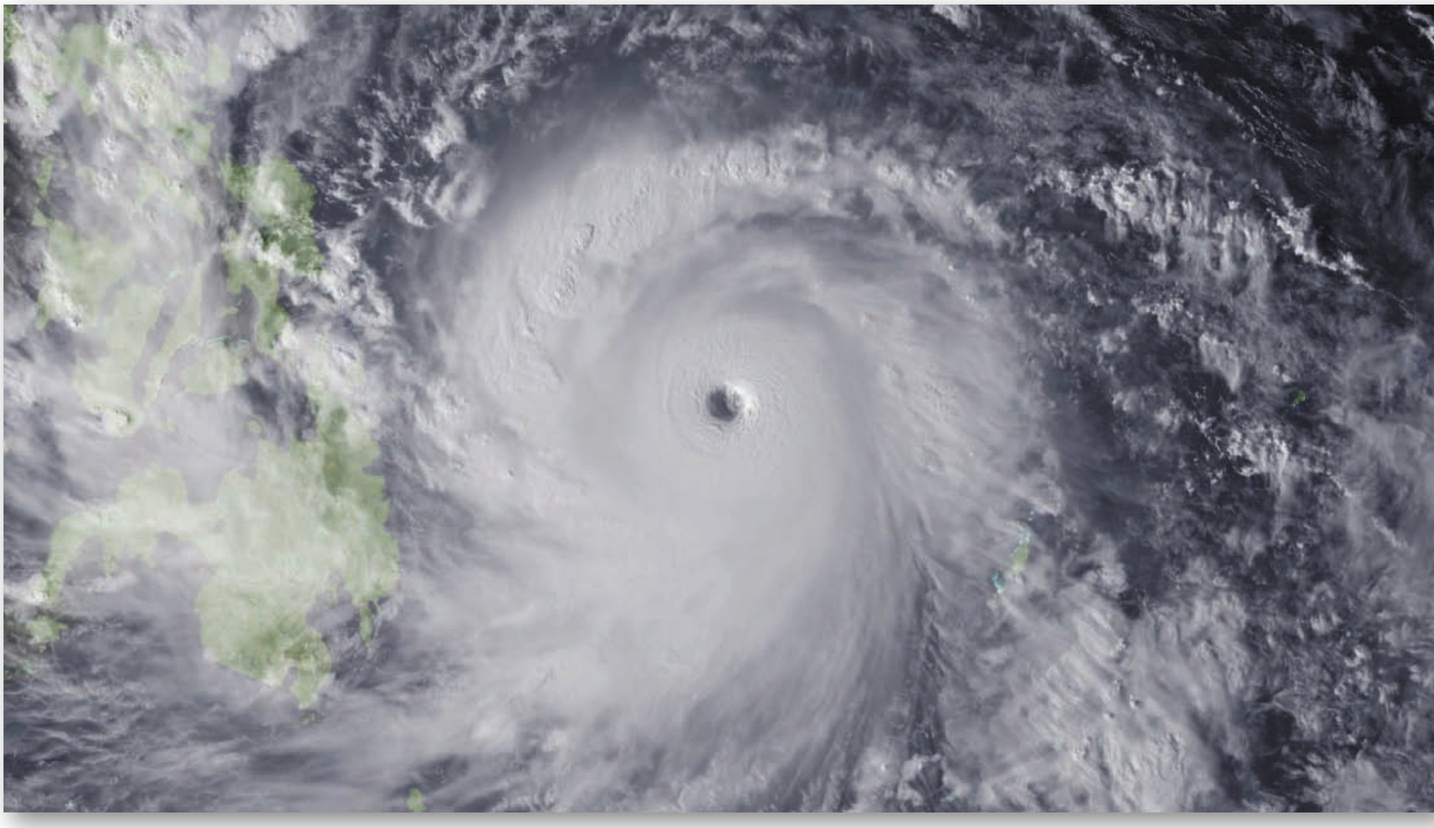
Multiple images from satellites *Terra*, *Aqua*, *Radarsat*, and *Defense Meteorological Satellite*, and from Space Shuttle *Endeavor's* radar data of topography, all merge in a dramatic composite to show the Western Hemisphere and Eastern Hemisphere of Earth. What indications do you see on these images 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.]

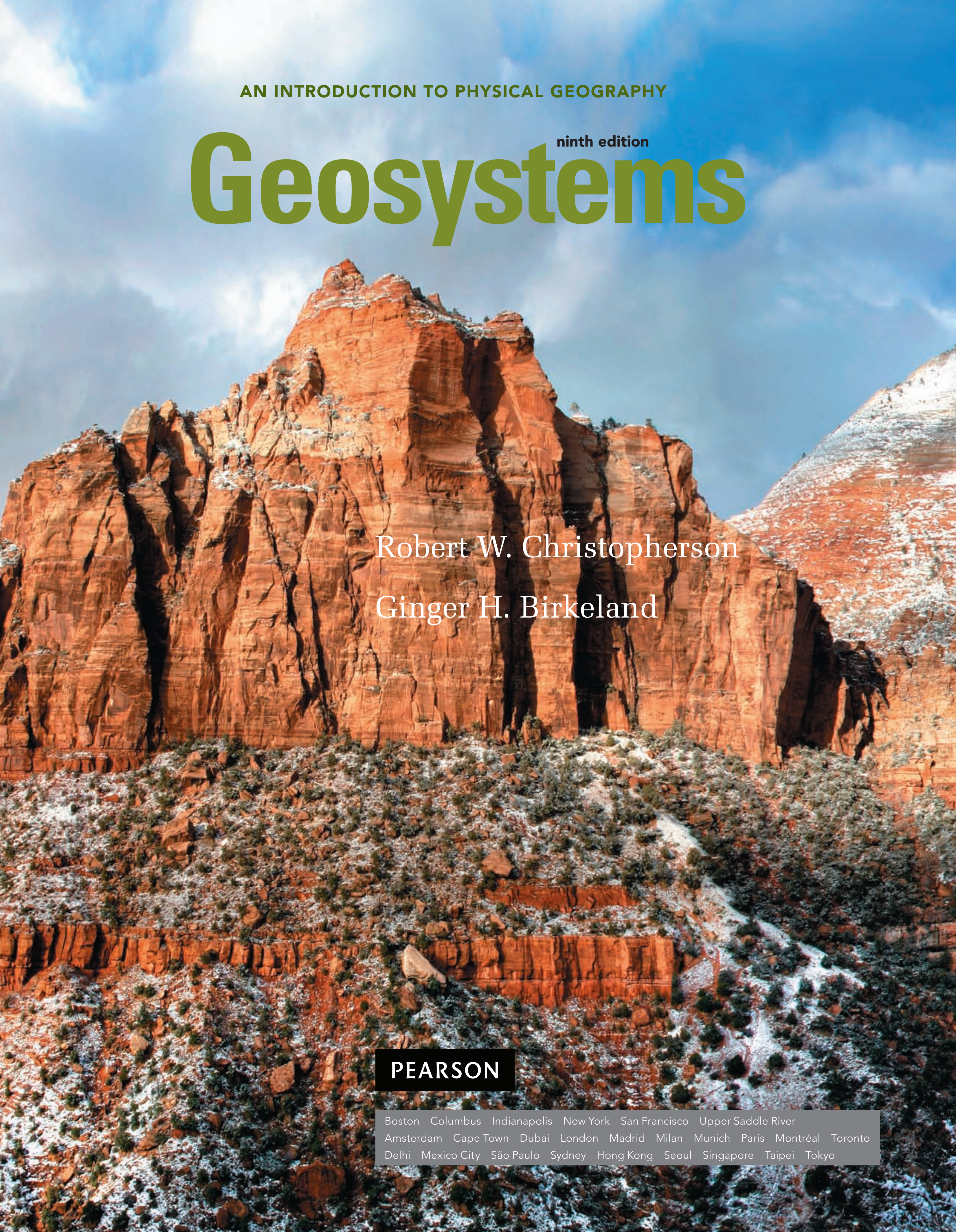
AN INTRODUCTION TO PHYSICAL GEOGRAPHY

Geosystems

ninth edition

Robert W. Christopherson

Ginger H. Birkeland



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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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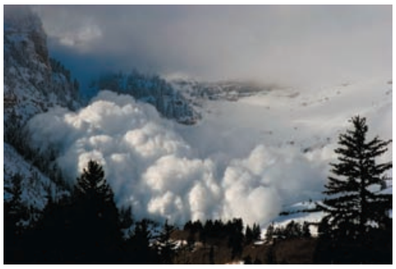

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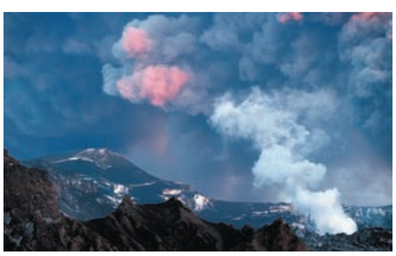

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preface

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 and links to media in *MasteringGeography*, 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.
- **Learning Catalytics**, a "bring your own device" student engagement, assessment, and classroom intelligence system, integrated with *MasteringGeography*.

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.
- The *MasteringGeography*™ online homework and tutoring system delivers self-paced tutorials that provide individualized coaching, focus on course objectives, and are responsive to each student's progress. Instructors can assign activities built around Geoscience Animations*, Encounter* Google Earth" activities, MapMaster" interactive maps, *Thinking Spatially and Data Analysis* activities, new *GeoTutors* on the most challenging topics in physical geography, end-of-chapter questions, Test Bank questions, and more. Students now have access to new *Dynamic Study Modules* that provide each student with a customized learning experience. Students also have access to a text-specific Study Area with study resources, including a Pearson eText version of *Geosystems*, Geoscience Animations, MapMaster interactive maps, new videos, Satellite Loops, Author Notebooks, additional content to support materials for the text, photo galleries, *In the News* RSS feeds, web links, career links, physical geography case studies, flashcard glossary, quizzes, and more—all at **www.masteringgeography.com**.

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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. Please visit the photo galleries at *MasteringGeography* and learn more from her camera work. 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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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. For those who do not use *MasteringGeography*, 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

Learning Catalytics is a "bring your own device" student engagement, assessment, and classroom intelligence system. With Learning Catalytics, you can:

- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

Learning Catalytics is a technology that has grown out of twenty years of cutting-edge research, innovation, and implementation of interactive teaching and peer instruction. Available integrated with *MasteringGeography*.

***Instructor Resource Manual* (Download)** (032197249X) by Charlie Thomsen includes lecture outlines and key terms, additional source materials, teaching tips, and a complete annotation of chapter review questions. Available from www.pearsonhighered.com/irc, and in the Instructor Resources area of *MasteringGeography*.

***TestGen® Test Bank* (Download)** (032197252X) 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 www.pearsonhighered.com/irc, and in the Instructor Resources area of *MasteringGeography*.

Instructor Resource DVD (0321972538). The *Instructor Resource DVD* provides a collection of resources to help teachers make efficient and effective use of their time. All digital resources can be found in one well-organized, easy-to-access place. The IRDVD includes:

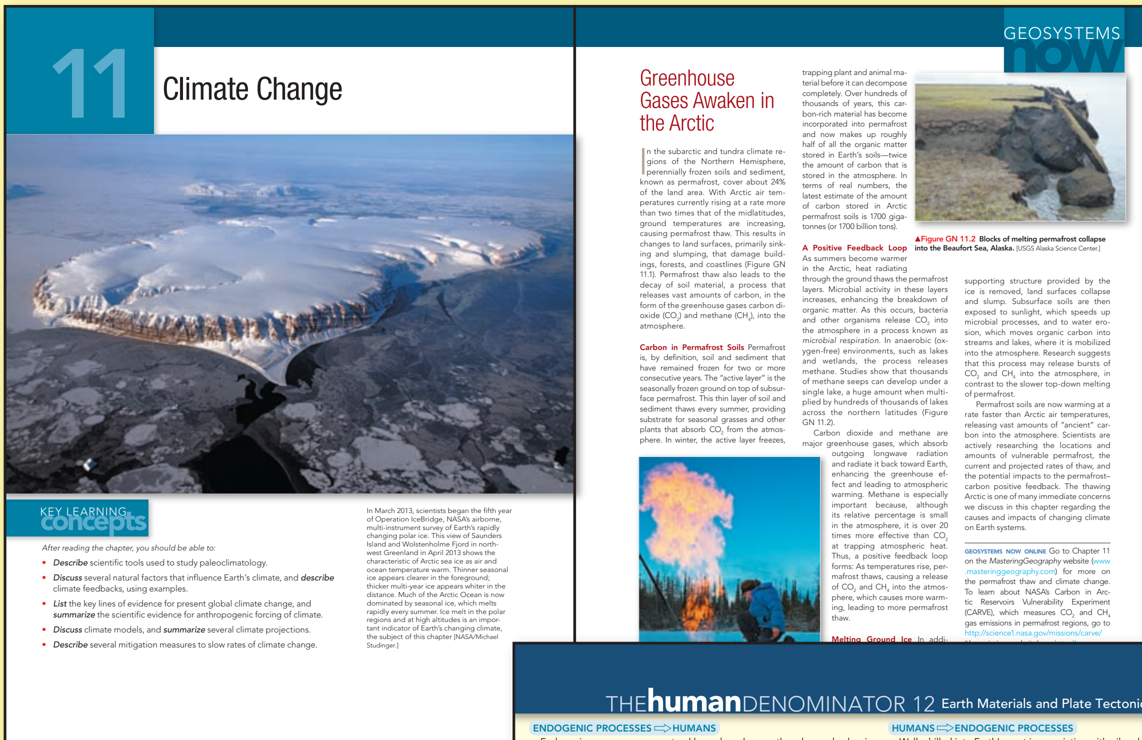
- All textbook images as JPEGs, PDFs, and PowerPoint™ Presentations
- Pre-authored Lecture Outline PowerPoint™ Presentations (by FeiFei Pan), which outline the concepts of each chapter with embedded art and can be customized to fit teachers' lecture requirements
- CRS "Clicker" Questions (by FeiFei Pan) in PowerPoint™, which correlate to the book's Learning Objectives, U.S. National Geography Standards, chapter-specific learning outcomes, and Bloom's Taxonomy
- The TestGen software, *Test Bank* questions, and answers for both MACs and PCs
- Electronic files of the *Instructor Resource Manual* and *Test Bank*

This *Instructor Resource* content is also available online via the Instructor Resources section of *MasteringGeography* and www.pearsonhighered.com/irc.

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.



11 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.]

GEOSYSTEMS now

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).

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.

Melting Ground Ice In addi-

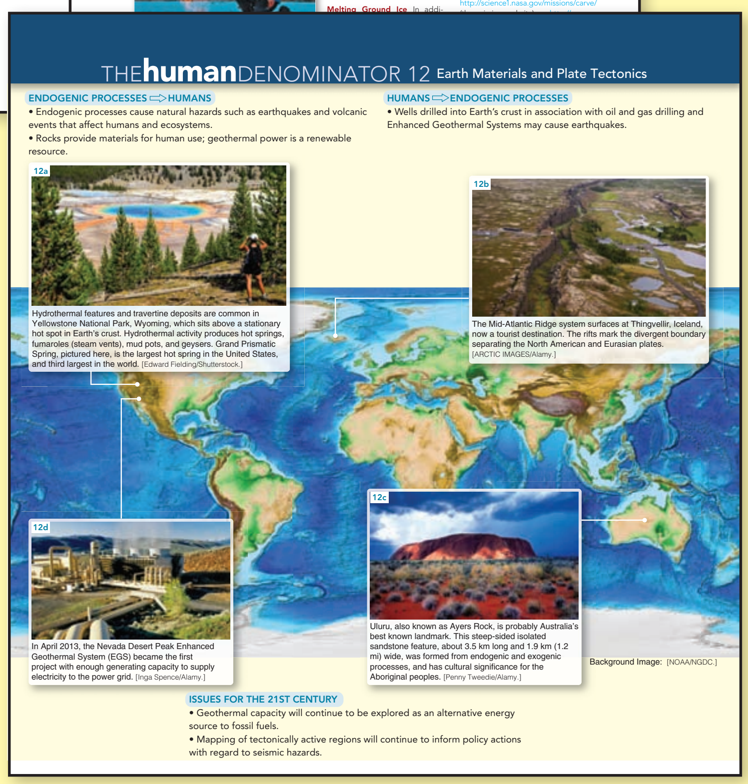
▲Figure GN 11.2 Blocks of melting permafrost collapse into the Beaufort Sea, Alaska. [USGS Alaska Science Center.]

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 Go to Chapter 11 on the *MasteringGeography* website (www.masteringgeography.com) for more on the permafrost thaw and climate change. 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/

► **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.

12a 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.]

12b 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.]

12c 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.]

12d 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.]

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 and MasteringGeography, 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 (Figure 15.1). Through these "scour-and-fill" processes, a meandering stream moves position laterally across its valley and creates a distinctive landscape (Figure 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.

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

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

Animation Meanders

MasteringGeography™
Visit the Study Area in MasteringGeography™ to explore meander and oxbow lake formation.
Visualize: Study a geosciences animation of meander and oxbow lake formation.
Assess: Demonstrate understanding of meander and oxbow lake formation (if assigned by instructor).

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15.2 AN ACTIVE STREAM MEANDERING
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**

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.

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

MG 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 photograph GIA15.2a.

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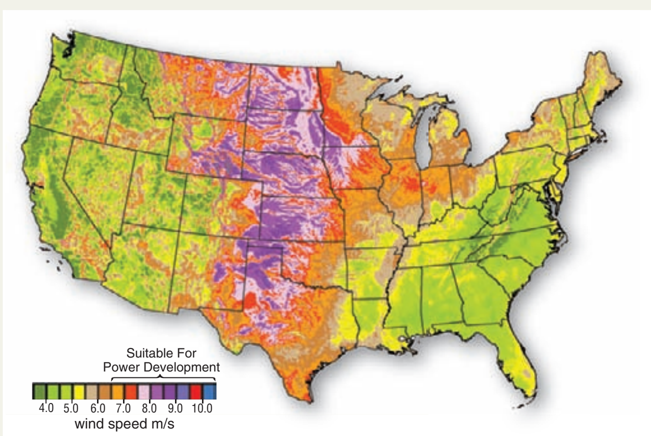
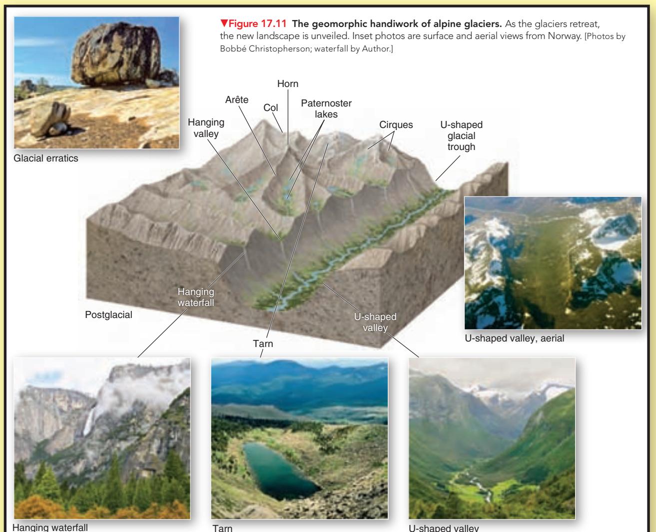
geosystems in action 15 MEANDERING STREAMS

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 are considered suitable for power development. Map has a spatial resolution of 2.5 km. [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: Go to Chapter 16 on the *MasteringGeography* website for resources and activities. 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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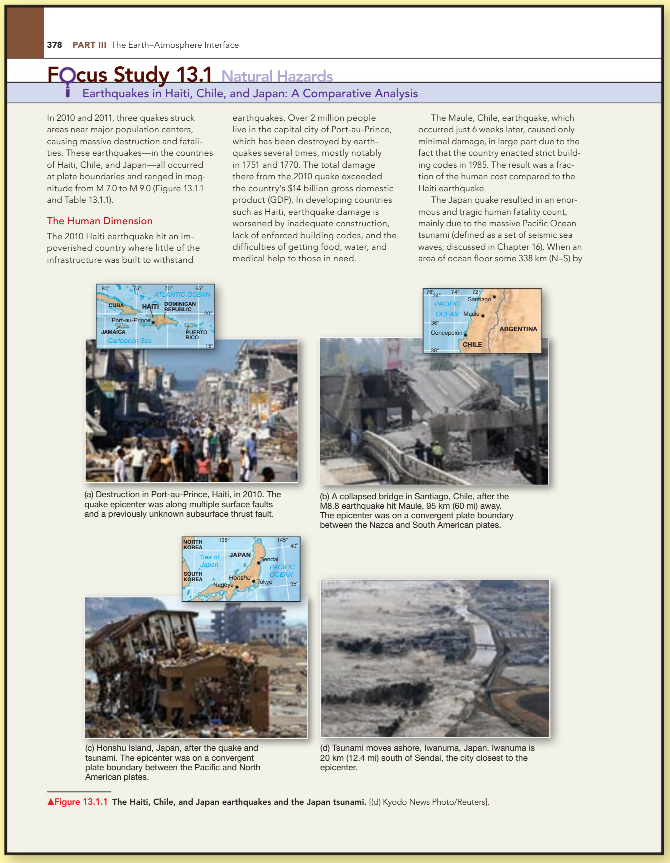
▼ ***Focus Studies*** present detailed discussions of critical physical geography topics, emphasizing the applied relevance of physical geography today.



378 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.** [(d) Kyodo News Photo/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. The average annual precipitation there is 1143 cm (450 in., 37.5 ft), placing it second only to Mount Waialeale.

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. 444)
estuary (p. 444)
flood (p. 446)
artificial levee (p. 447)

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. What is meant by the statement, "The Nile River delta is disappearing"?
23. Specifically, what is a flood? How are such flows measured and tracked, and how are they used in floodplain management?
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.

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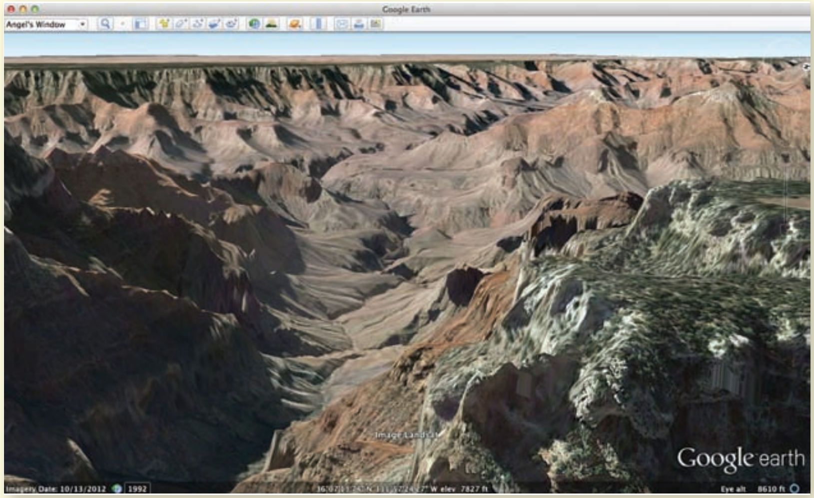
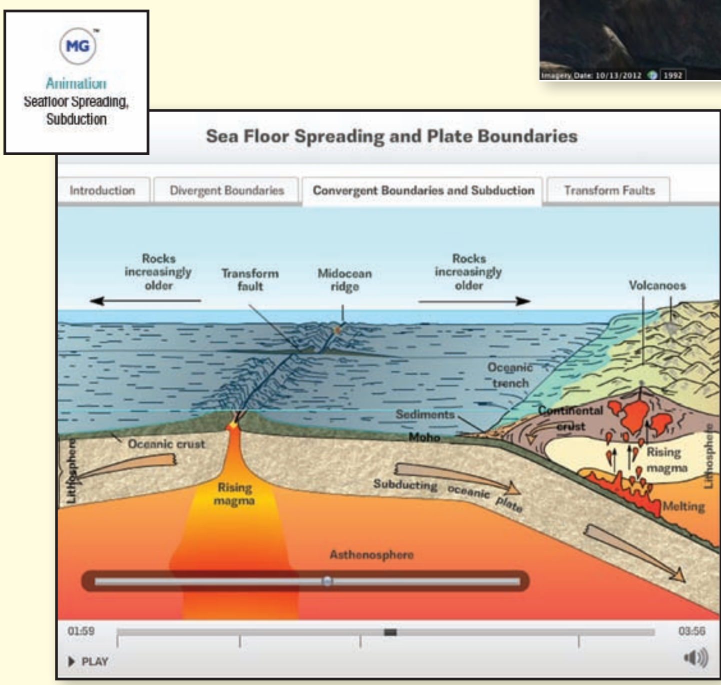
MasteringGeography delivers engaging, dynamic learning opportunities—focusing on course objectives and responsive to each student's progress—that are proven to help students absorb geography course material and understand difficult physical processes and geographic concepts.

Visualize the Processes and Landscapes that form Earth's Physical Environment

▶ **Encounter Activities** provide rich, interactive explorations of geography concepts using the dynamic features of Google Earth™ to visualize and explore Earth's physical landscape. Available with multiple-choice and short answer questions. All Explorations include corresponding Google Earth KMZ media files, and questions include hints and specific wrong-answer feedback to help coach students towards mastery of the concepts.





◀ **Geoscience Animations** illuminate the most difficult-to-visualize topics from across the physical geosciences, such as solar system formation, hydrologic cycle, plate tectonics, glacial advance and retreat, global warming, etc. Animations include audio narration, a text transcript, and assignable multiple-choice quizzes with specific wrong-answer feedback to help guide students towards mastery of these core physical process concepts. Icons integrated throughout the text indicate to students when they can login to the Study Area of **MasteringGeography** to access the animations.

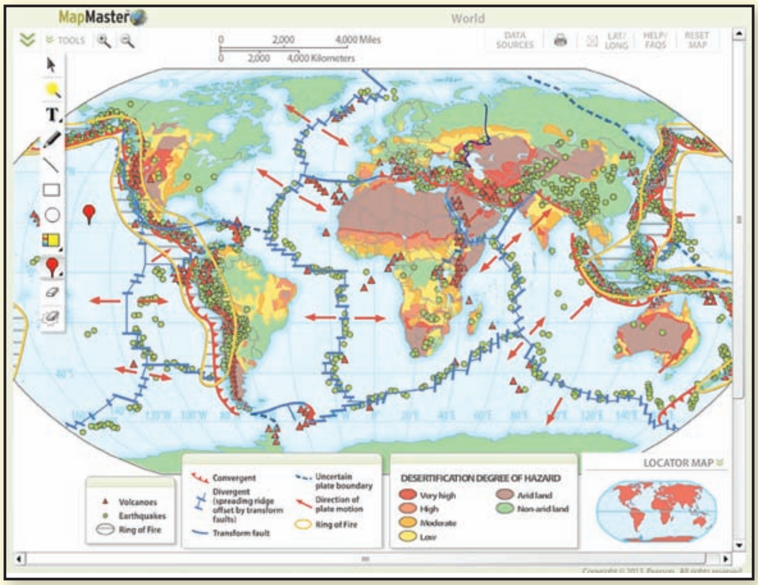
▶ **NEW! Quick Response Codes** in the ***Geosystems in Action*** features link to select videos,t animations, and web sites, providing students with just-in-time access to visualization and data resources from their mobile devices.

Tour of the Cryosphere

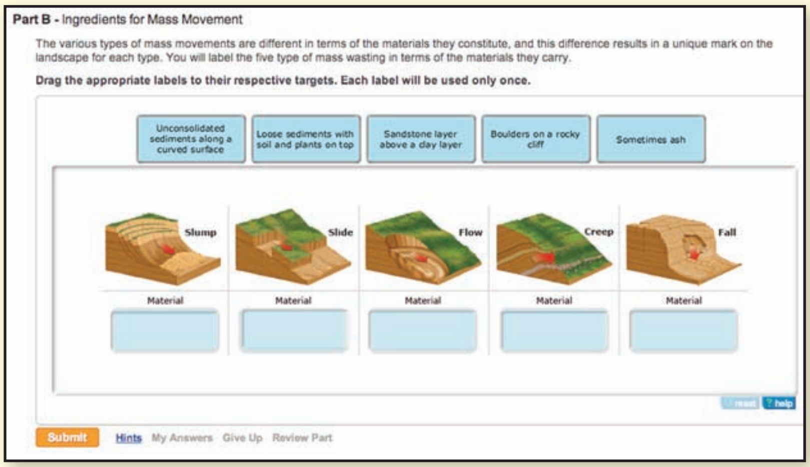
Engage in Map Reading, Data Analysis, and Critical Thinking

MapMaster™ is a powerful tool that presents assignable layered thematic and place name interactive maps at world and regional scales for students to test their geographic literacy, map reading, data analysis, and spatial reasoning skills.

▶ **MapMaster** Layered Thematic Interactive Map Activities allow students to layer various thematic maps to analyze spatial patterns and data at regional and global scales. Available with assignable and customizable multiple-choice and short-answer questions organized around the textbook topics and concepts. This GIS-like tool includes zoom and annotation functionality, with hundreds of map layers leveraging recent data from sources such as NOAA, NASA, USGS, U.S. Census Bureau, United Nations, CIA, World Bank, and the Population Reference Bureau.



▼ **Thinking Spatially & Data Analysis and NEW GeoTutor Activities** help students master the toughest geographic concepts and develop both spatial reasoning and critical thinking skills. Students identify and label features from maps, illustrations, graphs, and charts, examine related data sets, and answer higher-order conceptual questions, which include hints and specific wrong-answer feedback.



▼ **Videos** provide students with a sense of place and allow them to explore a range of locations and topics. Covering physical processes and critical issues such as climate and climate change, renewable energy resources, economy and development, culture, and globalization, these video activities include assignable questions, with many including hints and specific wrong-answer feedback.

Student Study Area Resources in MasteringGeography:

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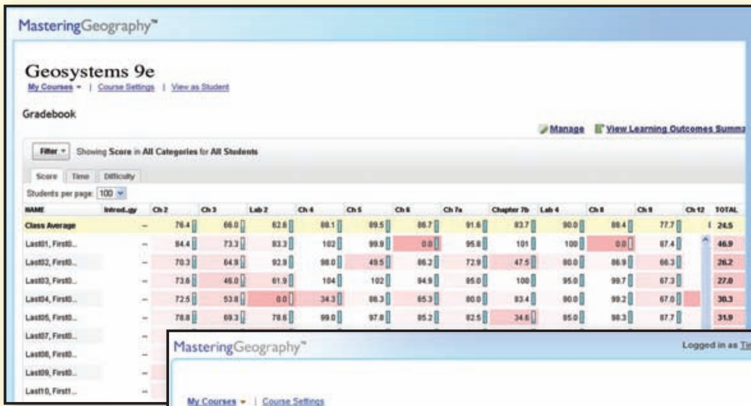
▶ The **Gradebook** records all scores for automatically graded assignments. Shades of red highlight struggling students and challenging **assignments.**



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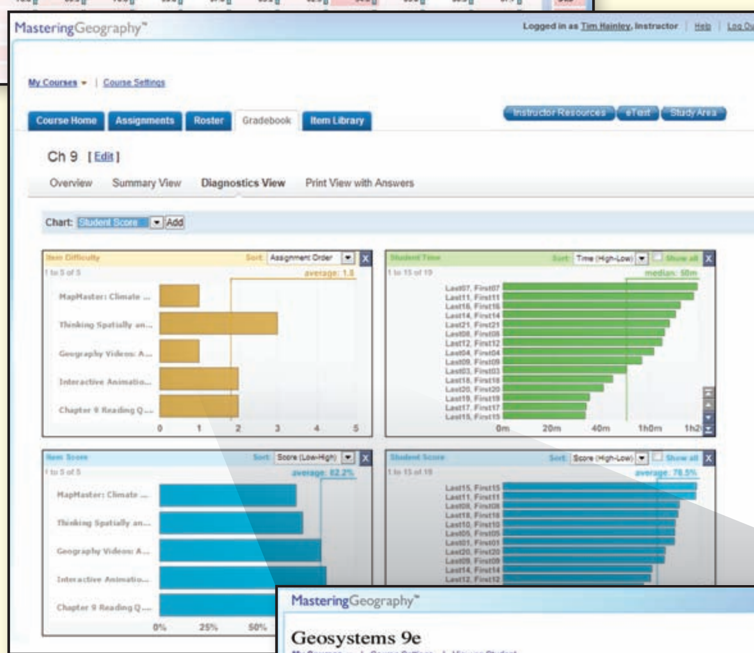
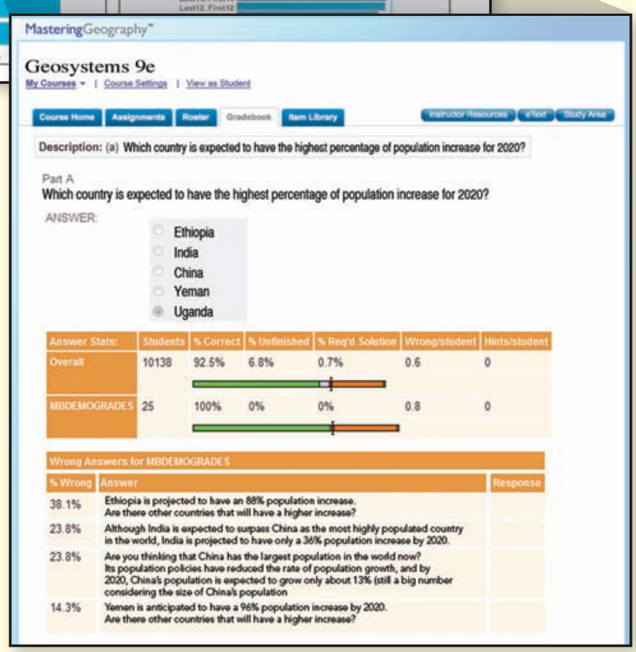


▶ With a single click, Individual Student Performance Data provide at-a-glance statistics into each individual student's performance, including time spent on the question, number of hints opened, and number of wrong and correct answers submitted.



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MasteringGeography provides quick and easy access to information on student performance against your learning outcomes and makes it easy to share those results.

• Quickly add your own learning outcomes, or use publisher provided ones, to track student performance and report it to your administration.

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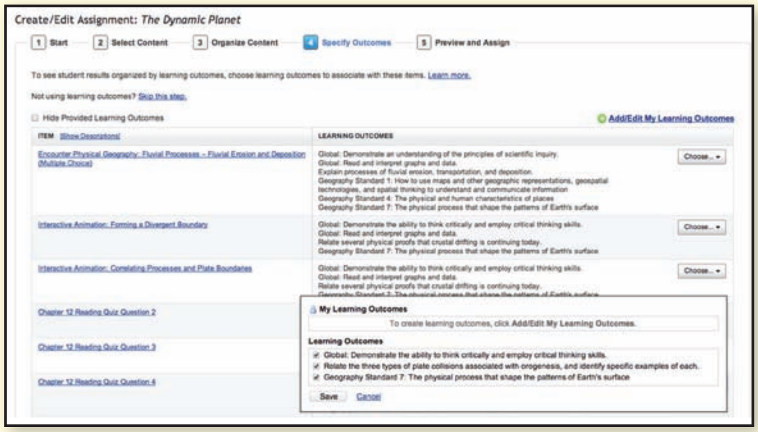
• Effortlessly export results to a spreadsheett that you can further customize and/or share with your chair, dean, administrator, and/or accreditation board.



Easy to customize

Customize publisher-provided items or quickly add your own. MasteringGeography makes it easy to edit any questions or answers, import your own questions, and quickly add images, links, and files to further enhance the student experience.

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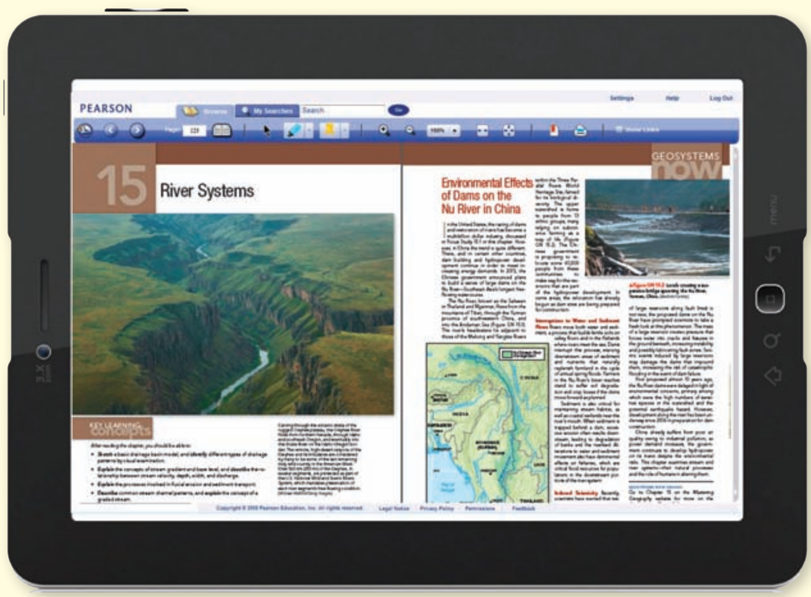
- Assess students in real time, using open-ended tasks to probe student understanding.
- Understand immediately where students are and adjust your lecture accordingly.
- Improve your students' critical-thinking skills.
- Access rich analytics to understand student performance.
- Add your own questions to make Learning Catalytics fit your course exactly.
- Manage student interactions with intelligent grouping and timing.

Learning Catalytics is a technology that has grown out of twenty years of cutting edge research, innovation, and implementation of interactive teaching and peer instruction. Available integrated with MasteringGeography or standalone.



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1

Essentials of Geography

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.

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.]

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).

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.

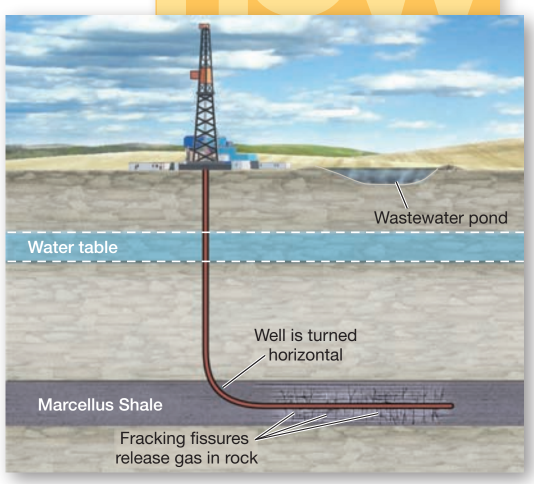
Fracking uses massive quantities of water: approximately 15 million liters (4 million gallons) for each well system, flowing at a rate of 16,000 L (4200 gal) per minute—far more than could be provided by a public water system. In southwestern Pennsylvania, storage ponds hold the water pumped to well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

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

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.



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

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 Go to Chapter 1 on the *MasteringGeography* website (www.masteringgeography.com) for resources and activities regarding shale gas as an energy resource. 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?

MG

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

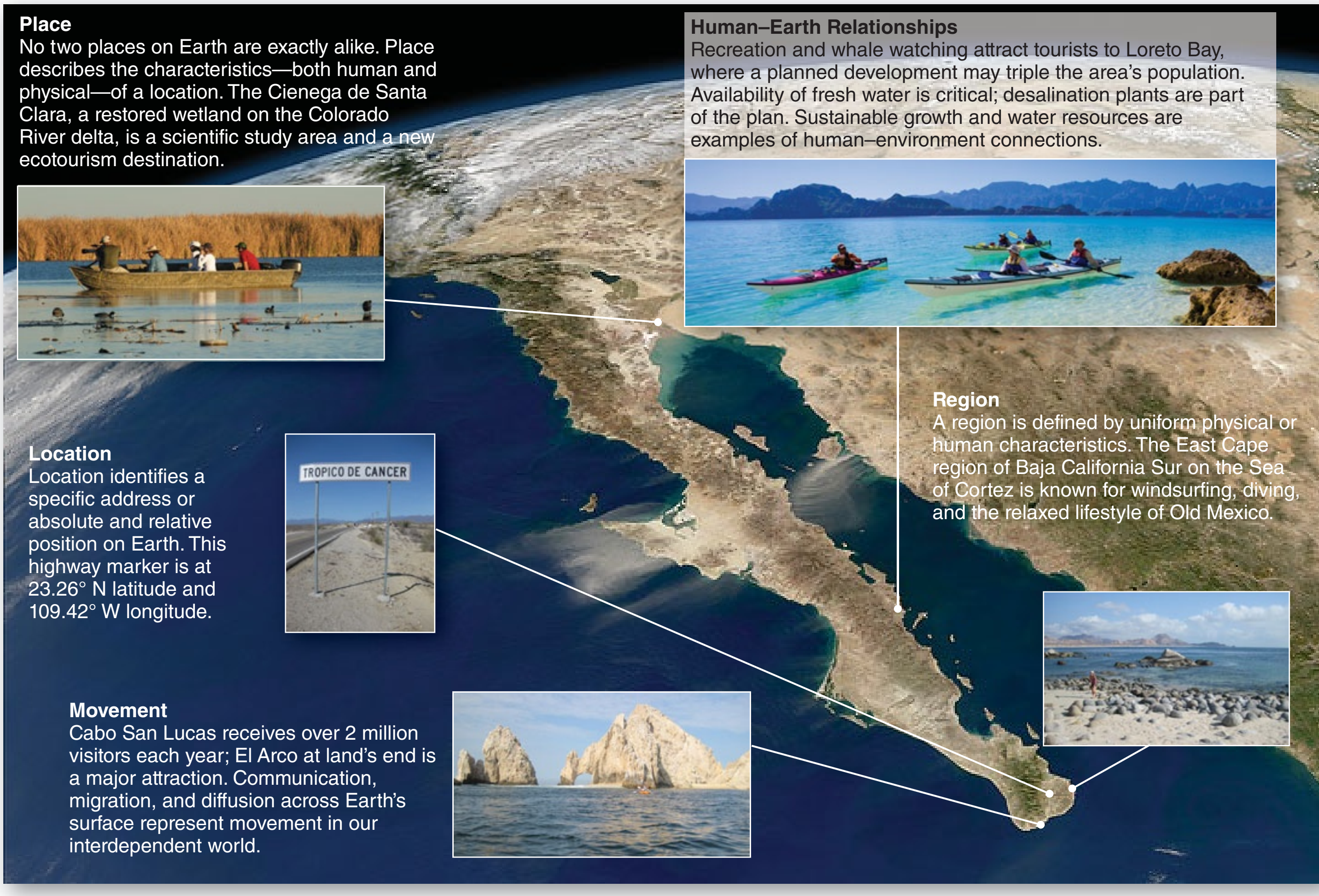
Because many subjects can be examined geographically, geography is an eclectic science that integrates subject matter from a wide range of disciplines. Even so, it splits broadly into two primary fields: *physical geography*, comprising specialty areas that draw largely on the physical and life sciences; 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.

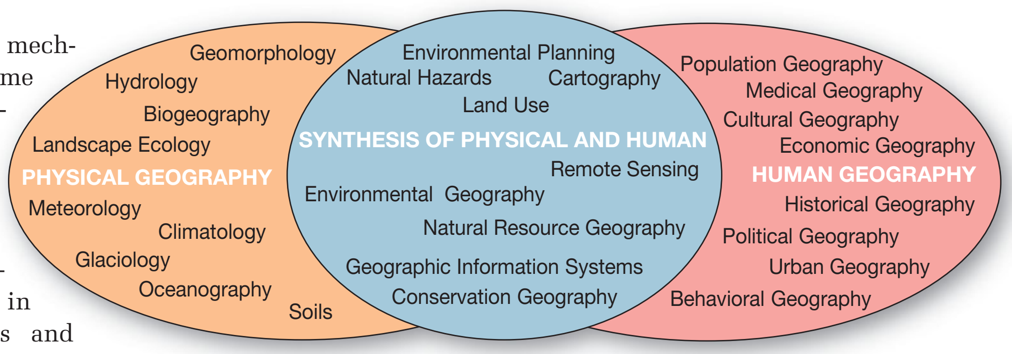


▲Figure 1.2 **Five themes of geographic science.** Drawing from your own experience, can you think of examples of each theme? This 2011 satellite image shows the entire length of Mexico's Baja peninsula, including Earth's curvature. [Photos by Karl Birkeland, except Place by Cheryl Zook/National Geographic 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.

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



▲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.

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.

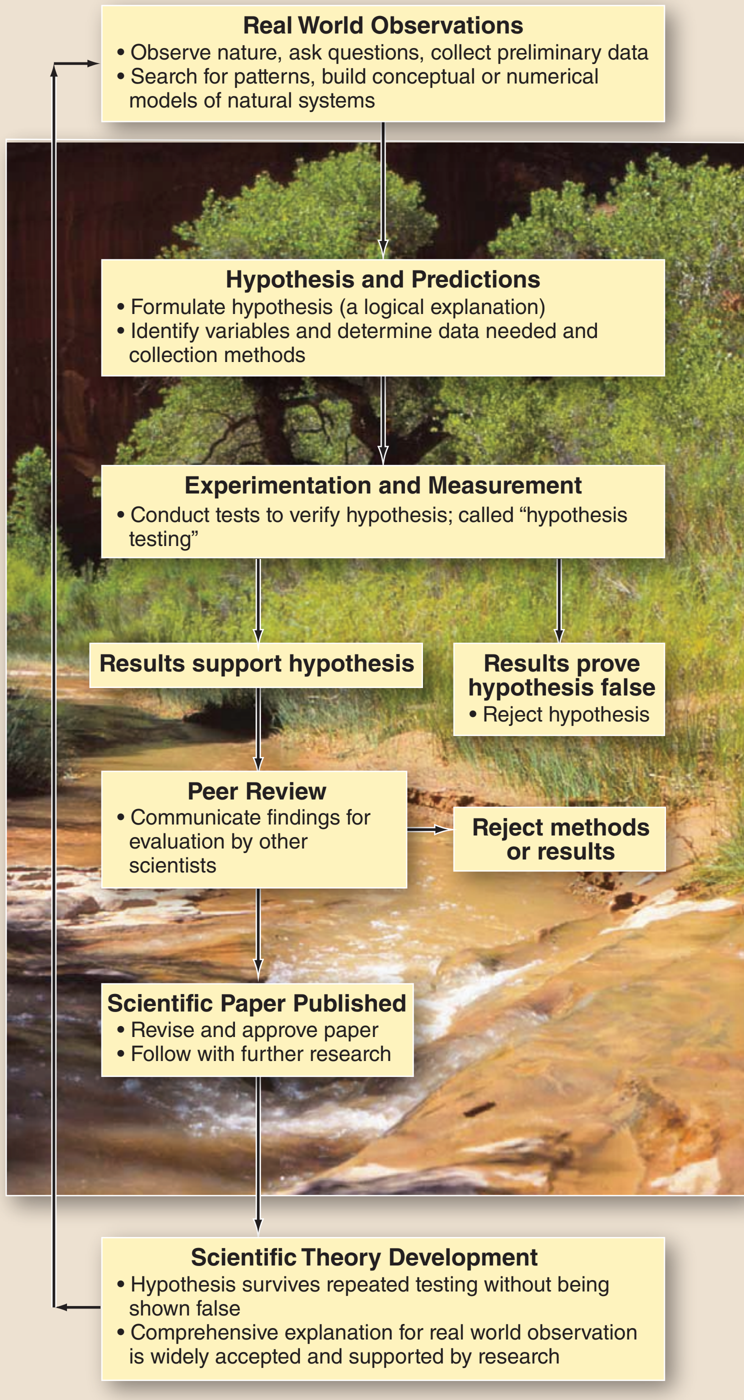
The word *theory* can be confusing as used by the media and general public. A scientific theory is constructed on the basis of several extensively tested hypotheses and can be reevaluated or expanded according to new evidence. Thus, a scientific theory is not absolute truth; the possibility always exists 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)



(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.

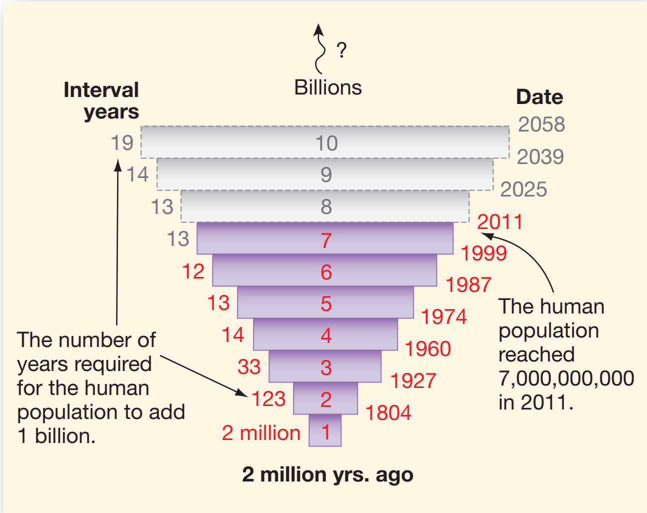
5. Results
A natural experiment often reveals a *correlation*, or a statistical relationship. If a correlation shows that the number of cottonwoods decreases away from the stream channel, then the hypothesis is supported. Continued investigation might repeat the same procedure in a different environment 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

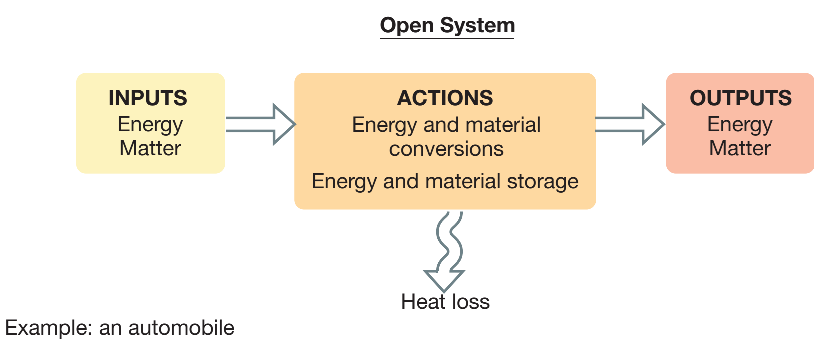
The word *system* is in our lives daily: "Check the car's cooling system"; "How does the grading system work?"; "A weather system is approaching." *Systems analysis* techniques in science began with studies of energy and temperature (thermodynamics) in the 19th century and were further developed in engineering 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.

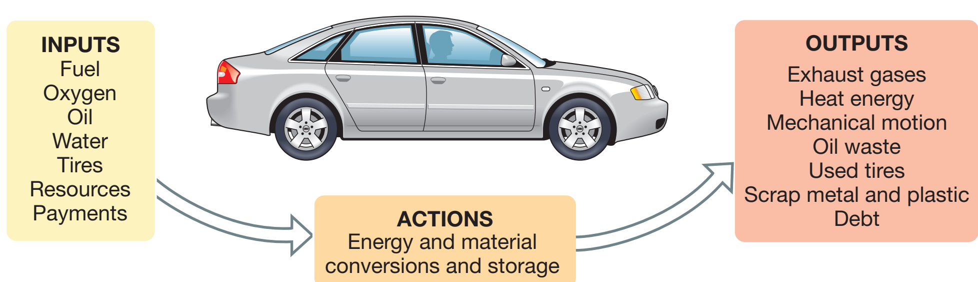
Systems Theory

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?

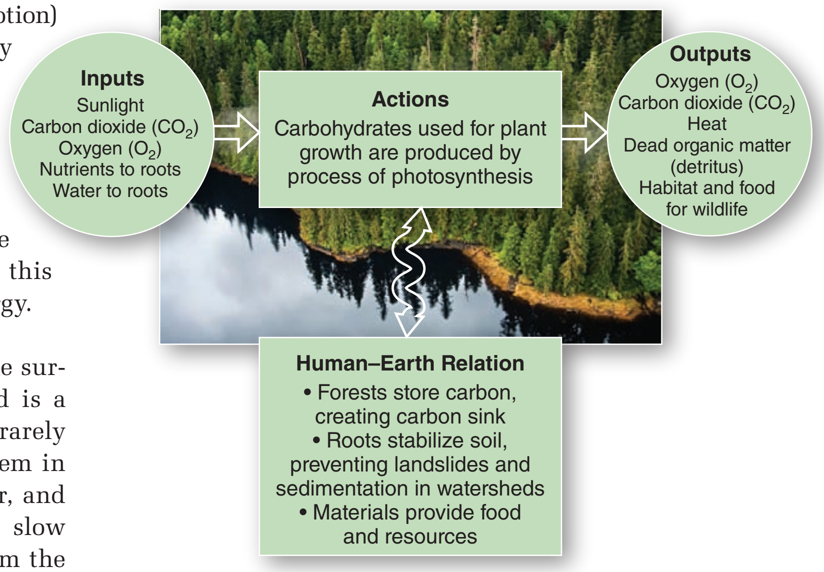
Earth systems are dynamic (energetic, in motion) because of the tremendous infusion of radiant energy from the Sun. As this energy passes through the outermost edge of Earth's atmosphere, it is transformed into various kinds of energy that power terrestrial systems, such as kinetic energy (of motion), 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.