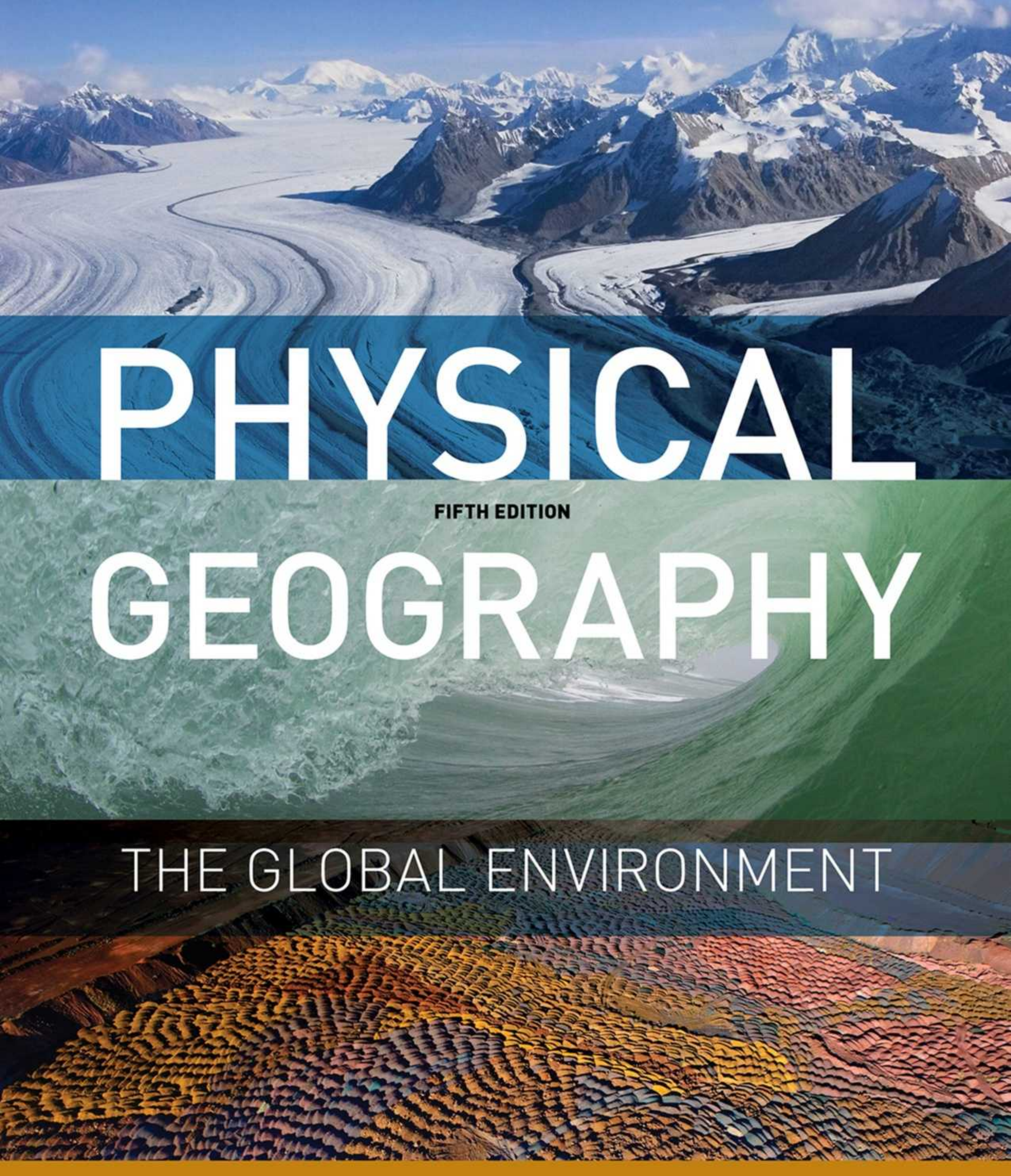

PHYSICAL

FIFTH EDITION

GEOGRAPHY

THE GLOBAL ENVIRONMENT

OXFORD
UNIVERSITY PRESS

MASON | BURT | MULLER | DE BLIJ

PHYSICAL GEOGRAPHY

THE GLOBAL ENVIRONMENT

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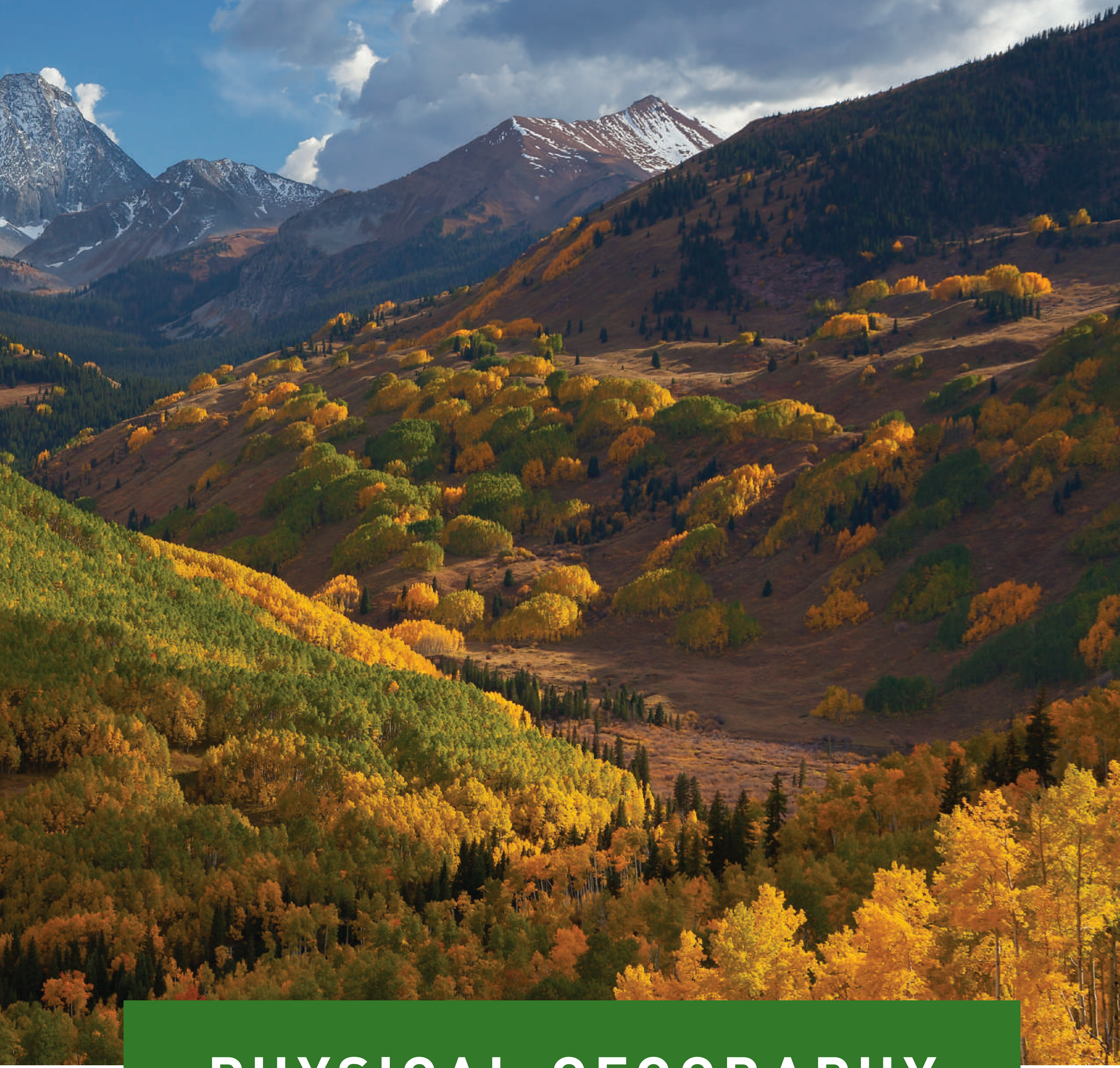

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*With great admiration for his remarkable and wide-ranging contributions to American geography,
we proudly dedicate this edition to the memory of our founding co-author*

HARM J. DE BLIJ (1935-2014)

Harm will long be remembered for his accomplishments during his highly successful career as a scholar, educator, and communicator—all of which were harnessed in his passionate, lifelong crusade to advance the cause of geography in the public arena.

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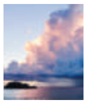
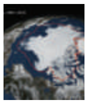


PART TWO Atmospheric and Oceanic Processes



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PART SEVEN Sculpting the Surface: Ice, Wind, and Coastal Processes

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PREFACE

On March 25, 2014, American geography lost one its most distinguished and best-known practitioners of the past half-century, Dr. Harm J. de Blij, the John A. Hannah Professor of Geography at Michigan State University. For the authors and editors of this book, the loss was far more personal: Professor de Blij was the dynamic senior author of the four previous editions, our constant inspiration, and a cherished friend of many years. His training as a professional geographer, all the way through earning his Ph.D. at Northwestern University, focused on the geomorphology of the lithosphere (both terms that readers will shortly become familiar with); more specifically, he analyzed landform patterns in the southeastern African country of Swaziland, particularly rift valleys that would shortly become defined as pieces of the gigantic jigsaw puzzle that constitute global plate tectonics—a central component of the contemporary Earth sciences.

Perhaps the most important contribution of Professor de Blij, during the six-plus decades of his hugely successful career, was to almost single-handedly advance the cause of geography in the U.S. public arena. His talents and skills as a communicator and passionate ambassador for our scholarly discipline were truly legendary—a rich legacy that survives in a range of media, from YouTube videos of his lectures to his remarkable, user-friendly writings for college-level student readers (including many that still grace the pages of this book). No wonder he was so greatly admired for his work as Geography Editor in a seven-year stint on ABC's *Good Morning America*. He subsequently parlayed that platform into several books for general readers, all beautifully written, every page sparkling with insights and boundless enthusiasm for the subject he loved and literally pursued in his travels to the ends of the Earth. His three most successful forays into this realm were proudly published by Oxford University Press: *Why Geography Matters* (2005), *The Power of Place* (2009), and *Why Geography Matters . . . More Than Ever* (2012).

It is indeed an honor for his coauthors of this book to dedicate the Fifth Edition of *Physical Geography* to the memory of Professor Harm de Blij. In fact, his contribution to this book was so fundamental and enduring, we are able to reprint the immediately following opening section of this Preface as he revised it for the previous edition in 2013. As an introductory overview of the scope, importance, and current scientific context of physical geography with respect to our changing global environment—he absolutely nailed it!

Why spend a semester (or more) studying physical geography? You will find the answer in this course, but you can also find it elsewhere: in your daily check on the weather before you set out; in news reports about natural events such as earthquakes, floods, and volcanic eruptions; in sometimes-vociferous public debates about climate change; in scientists' pleas for sustainable lifestyles. You will find that the components of nature that form our small planet's diverse environments are intricately interconnected not only with each other but also with you. A volcanic eruption on the other side of Earth can kill the crops on which people and animals depend half a world away—we know, because it happened as recently as the early 1800s. An earthquake near Indonesia can take lives thousands of kilometers away: it happened to more than a quarter of a million people in December 2004. When a combination of offshore earthquakes and resulting sea waves struck nuclear plants in northeast Japan in March 2011, radiation exposure threatened those who did not perish, and in the aftermath huge "rafts" of resulting debris, floating in the North Pacific Ocean, reached beaches in California and Oregon.

We live on a planet whose crust is still unstable, and we will show you maps that reveal where the risk is greater, and where it is less. But while the crust, after another few billion years, may finally come to rest, planetary environments are likely to continue changing. Again, these changes affect you directly: the continued thinning of the protective ozone layer makes sunburn ever more dangerous to your health, and the environmental swings associated with climatic reversals are related to severe droughts in some areas and, perversely, floods in others, resulting in crop failures and rising food prices (and hunger among the poorest of the world's poor). In August 2012 India was struck by a series of power outages called the worst in human history, the second one affecting 670 million people across the country's north. Explanations ranged from overuse of electricity to lack of maintenance of India's electrical "grid," but here is the real reason: India's annual monsoon had failed, hydroelectric dams stood silent at the outlets of nearly empty reservoirs, and the country's coal-fired power plants could not cope with demand. Thus a climatic event had consequences felt in cities, at airports, on trains, and along traffic-stalled highways.

In case you have not noticed, our society has its own shortages, and one of them relates to the way we look at the wider world. We tend to localize and specialize, focusing on detail and, as many writers have found, on the small and the familiar rather than the bigger picture and the wider world. That is not what you will find in this book. This is the story of the way the planet works, of its place in our solar system, of the amazing range of its natural environments, of the powerful forces that shape its landscapes, climates, ecologies, and—yes—geographies, because humans have become part of the planetary equation. Long before humans emerged on Earth, the planet's surface was continuously shaped and reshaped by nature's systems and cycles, whose properties we will examine in the pages that follow. It is a riveting story of ice ages and intervening warmth, of sudden death from space, of rising and falling sea levels, of shifting landmasses and shocking earthquakes, of choking eruptions and giant floods, of flowering life and devastating extinctions. Less than 200,000 years ago—a matter of minutes in your lifetime when compared to the planet's 4.6 billion—modern humans appeared in Africa, and now, more than 7 billion strong, we are transforming Earth as no creature has ever done. That is why some scientists are proposing that the current "geologic" epoch be given a human name: the *anthropocene*. Not only are we paving over entire urban regions, cropping vast expanses, and damming major rivers, we are also filling the atmosphere with pollutants that are, as we will see, affecting the course of climate change. This is why the human factor has some prominence in this book.

Interesting as these topics are, they do require careful study. Not everyone who participates loudly in the climate change debate is sufficiently well informed on the basics, nor is physical geography an easy field. But if you stay the course, you will be among the most geographically literate of citizens . . . a worthy objective, to be sure. And beyond that, what you learn will be of personal, practical value and use, not only making life more interesting but, quite possibly, giving you a new outlook on it.

Hallmarks of *Physical Geography: The Global Environment*

Studying a demanding field such as physical geography is a tall order, and the process is easier if strong educational materials aid one's efforts. This book and its ancillary materials have been specifically designed to support professors and students in this endeavor. The book employs a unique approach characterized by several important attributes.

- *Structure. Physical Geography* organizes the material into 49 short units instead of the 20 or so long chapters found in most physical geography books. These shorter and more self-contained units are a good fit for students who increasingly seem to prefer brief study periods sandwiched between other activities. (Of course, they can be read in succession and thus accommodate extended interludes.) These short units also provide instructors with much more flexibility in assigning readings or rearranging the order in which materials are taught. For those professors who wish to customize the book, the units offer an easy way to get just the right materials to the student audience.
- *Keeping humans in the picture.* Understanding the role of humans and how humans interact with Earth is critical to building a good geographic understanding. This book carefully includes the human role in the Earth system.
- *Writing with clarity and impact.* The book is known for clear, compelling prose that is free from extraneous detail and unimportant diversions.
- *Qualitative precision*. Descriptions and explanations have been methodically evaluated for accuracy, completeness, and currency. Thus, for example, there are no references to "air holding water vapor," and the classic depiction of cold fronts as snowplows is offered as a historic (and convenient) conceptual model rather than a physical process rooted in theory. Instead, the book focuses on tying fundamental physical principles to observable phenomena, such as applying a knowledge of *how* heat is converted to kinetic energy to the energetics of weather systems and discussions of how climate change is manifested in extreme events, including recent incidences of extreme heat; these discussions are supported by examples such as specific coverage of California's recent and ongoing drought.
- *Strong reliance on a systems perspective.* For us that means an emphasis on process and interaction rather than obsession over the arcane terminology of formal systems theory. Throughout the book we appeal to conservation principles presented in Unit 1 for explanation of phenomena from molecular to global scales. The book pays particular attention to feedbacks and the timescales on which they operate. For example, students reading Unit 18 will understand why the carbon cycle acts as a brake on climate change over millions of years and yet can amplify change over shorter time periods. In every unit the authors have made a conscious attempt to explain *why* things are as they are, and to point out where the knowledge gaps are when that isn't possible.
- *Meticulously chosen examples illustrate the topic at hand clearly.* Clear, illustrative examples that vividly illustrate the concept at hand are critically important to learning geography. *Physical Geography* features many such highly illustrative examples.
- *Emphasis on current* science *rather than current* events. Because current events pass quickly, this book emphasizes basic geographic science and leaves it to the professor to contextualize that material with examples from the daily newspaper. Minimizing attention to the ephemeral allows the book to stay focused on underlying concepts and on the clearest, most illustrative examples.
- *Financial discipline and nonprofit status result in lower prices to students.* Oxford University Press, a department of the University of Oxford, is a nonprofit publisher devoted to furthering the University's objective of excellence in research, scholarship, and education. Since accessible materials clearly support this mission, the Press uses a combination of nonprofit status and financial discipline to offer course materials that generally cost students significantly less money than those offered by commercial publishers.

New to the Fifth Edition

The Fifth Edition has been extensively revised, updated, and improved. Some of the most important changes include:

- *Extensive new diagrams.* New figures were developed to guide students through complex concepts like biogeochemical cycles, the rock cycle, and feedbacks in soil formation. Instead of abstract boxes and arrows, these diagrams connect cycles and systems to the real world: the rock cycle is shown as taking place in a cutaway view of the lithosphere, and feedbacks in soil development are illustrated with a series of realistic soil profiles, for example. A new figure on the mechanics of slope failure makes an important broader point by showing how an abstract view of the balance of forces on a block of soil can be related to the potential failure of a realistic hillslope. In the units on tectonics and volcanism, many of the figures have been completely revised for up-to-date scientific accuracy and to illustrate features more effectively in three dimensions. Climagraphs in all units are plotted on the same scale for easier comparison.

- New climate maps based on state-of-the-art datasets. The authors constructed new global fields of temperature, precipitation, and evaporation by merging terrestrial and satellite-derived ocean data from the University of Delaware's Center for Climatic Research and the University of Hamburg Ocean-Atmosphere project, respectively. The resulting climate maps have details not seen in traditional textbook figures (e.g., summer-dry continental climates) and are far more defensible scientifically. New figures showing the latitudinal distribution of climate types were also computed from the merged data.
- *In-depth treatment of biogeochemical cycles.* The Fourth Edition was distinguished by its comprehensive, up-to-date coverage of climate change and its environmental impacts. The new edition adds a key element to this focus: a unit devoted to biogeochemical cycles, emphasizing cycles of carbon and nitrogen. For both elements, diagrams and text illustrate the important pools and fluxes and current estimates of their magnitude, as well as recent human impacts. Major uncertainties are noted while emphasizing the rapid progress toward understanding these cycles that has been made in recent years. As in the rest of the book, the process of scientific discovery is highlighted with well-chosen examples.
- *More effective, up-to-date presentation of the science.* The Fourth Edition was also marked by an effort to move away from well-worn but often simplistic or even misleading explanations of key processes toward an approach that clearly and accurately presents up-to-date science. The Fifth Edition continues and extends this effort in a number of areas, while updating topics that are the focus of active research; for example:
    - The many connections made between ecosystems, soils, and the global carbon cycle throughout Part Four (The Biosphere) have been updated to reflect recent progress in understanding these links. For example, the "missing sink" of carbon was highlighted as an intriguing problem in the Fourth Edition; this sink is now more definitely attributed to carbon uptake by terrestrial ecosystems, especially tropical forests, in line with recent assessments. The greatly enhanced coverage of the nitrogen cycle incorporates advances in understanding the complex pathways of nitrogen (including emissions of the greenhouse gas N_2O) that have resulted from intensive study in recent years.
    - More systematic discussion of streams and glaciers as open systems, including forms of energy and work within these systems, has been included. At the same time, as in earlier editions, these somewhat-abstract discussions are balanced by vivid examples of the work of streams and glaciers, and by occasional historical background where it provides especially good illustrations of the scientific process. Explanations of other geomorphic and tectonic processes (e.g., wind erosion, mantle convection, volcanism associated with subduction) have also been carefully scrutinized and revised where needed to make them more effective, more consistent with current research, and more anchored in basic physical science
    - A substantially new discussion of evolution and its importance for biogeography has been added, including more up-to-date and effective explanations of key concepts such as natural selection, gene flow, and speciation, along with compelling examples. Here and in several other sections, the new edition retains sections on the historical background of important concepts, but in revised form, explaining how the science evolved but also leading more directly to our current understanding of it.
- Climatic time series have been updated with information through 2014, including the latest National Oceanic and Atmospheric Administration global mean temperature estimates (*Science*, June 2015) that debunked the suggestion of a warming pause or hiatus. The discussion and figures related to anthropogenic climate change have been revised based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, and there is new coverage of hydrological impacts of greenhouse gas emissions.
    - A new section on atmospheric rivers has been added in accord with the growing realization of their importance in global energy/mass transport and flood events.
- *Reorganized for better flow and clarity.* In response to reviewer feedback, Part Five, on the lithosphere, has been reorganized to place the units on minerals and rocks before those that describe the broader structure of the lithosphere. In other words, students working through the units of this part in order will proceed from mineral structures through rock types to Earth's internal structure and tectonics. The number of units has been reduced from 50 to 49.
- Presentation enlivened and economized with digitally enhanced figures. Sometimes a difficult concept or important graph comes more quickly into focus if supported by a brief explanation, or connections between landscapes and processes become more vital when motion enhances the presentation. In this edition many figures have been enhanced with live content that

runs for less than a minute per figure and can be easily played on a smartphone. These resources are designed to help users learn concepts and processes more quickly and efficiently, and thus do not burden the user with tedious re-recitations of vocabulary or foundational material already explicated in the book.

- *Digitally enhanced "Quick Review" end-of-unit materials.* In this edition students can use their smartphone to immediately check their understanding of the material by taking quizzes about the vocabulary and concepts presented in every unit.

Teaching and Learning Package

This book is supported by an extensive and carefully developed set of ancillary materials designed to support both professors' and students' efforts in the course. The depth, breadth, and quality of these materials was dramatically expanded between the Third and Fourth editions of the book, and they have been further refined and expanded for the Fifth Edition. We have been fortunate to work with a dedicated and creative group of authors when assembling this package. Steve LaDochy and Angel Hamane of California State University, Los Angeles, have been instrumental in the creation of all of the supplements and have made great contributions to the augmented figures and end-of-chapter materials. We also continue to benefit from the efforts of Pedro Ramirez, who worked with Drs. Ladochy and Hamane on the supplements for the Fourth Edition. Much of his work has been carried forward in revised form to the Fifth Edition. The result of this combined effort is the following:

- *Oxford University Press Animation Series.* Animation and visualization are very helpful when studying physical geography. Recognizing this, our authors have worked with leading animators to produce clear, dramatic, and illustrative animations and visualizations of some of the most important concepts in physical geography. Animations are available to adopting instructors at no charge.
- *Digital files and PowerPoint presentations.* Instructors will find all the animations—the Oxford University Press Animation Series, all of the images from the text, and some animations and visualizations from other sources—available to them, pre-inserted into PowerPoint. In addition, our ancillary author team has created suggested lecture outlines, arranged by chapter, in PowerPoint. These materials are free to adopting professors.
- *Interactive animation and visualization exercises.* Our animation and visualization exercises begin with the Oxford University Press Animation Series and incorporate interesting animations and visualizations from other sources. The exercises then guide the students through a series of activities based on the visualization at hand. Responses are automatically graded by the computer.
- *Review questions for students.* Carefully crafted to highlight the most important concepts in each chapter, these computer-graded review questions accompany each chapter in the textbook. Professors can assign them for homework, or students can use them independently to check their understanding of the topics presented in the book. Responses are automatically graded by the computer.
- *Test questions and testing software.* Answerable directly from the text, these questions provide professors with a useful tool for creating and administering tests.
- *Dashboard.* A text-specific, integrated learning system designed with clear and consistent navigation, the dashboard delivers quality content and tools to track student progress in an intuitive, Web-based learning environment. This tool features a streamlined interface that connects instructors and students with the functions they perform most, simplifying the learning experience to save time and put student progress first.
- *Course cartridges.* Instructors may order selected digital supplements free of charge in ready-to-upload form for the most popular course management systems, including Blackboard, D2L, Moodle, Canvas, and Angel, by contacting their Oxford University Press representative.
- *Open-access quizzing for students.* In keeping with Oxford University Press's mission to disseminate educational materials as widely as possible at the lowest cost, we have posted free review quizzes that offer immediate feedback at www.oup.com/us/mason.
- *Lab manual.* Dalton Miller and Andrew Mercer, both of Mississippi State University, have prepared a lab manual. While this manual can be employed by anyone, it has been specifically designed to accompany the base textbook. If the professor so chooses, the lab manual can be bundled together with the text for a significant discount.

Acknowledgments

Writing a modern textbook and its ancillary package is a team effort, and during the preparation of this new edition of *Physical Geography: The Global Environment*, we received advice, guidance, and input from many quarters. First and foremost, we thank our reviewers and colleagues who supplied valuable feedback on the previous edition and valuable advice about the revised manuscript. These are:

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Several valued colleagues engaged in a technical review of some of the units. These experts combed through those units to make sure that the science was completely accurate and current. For this we thank:

Ed Aguado, San Diego State University
Michael E. Mann, Penn State University
William Monfredo, University of Oklahoma

Paul Todhunter of the University of North Dakota contributed enormously to the project by writing initial drafts of several units. We're not sure what we would have done without Paul's graceful research and writing, and appreciate his attention to detail and timeliness more than we can say here. This book is much better as a result of his efforts.

Perhaps nowhere in the textbook process is the notion of a team more apparent than in the ancillary program. We are deeply indebted to the individuals who have spent many hours crafting ancillaries for the professors and students who will ultimately use this book for their classes. Steve LaDochy, Pedro Ramirez, and Angel Hamane, all of California State University, Los Angeles, have worked together and with our authors to create a superb selection of instructor and student supplements.

Last, we are indebted to our colleagues at Oxford University Press, who superbly managed the preparation of this Fifth Edition. Executive Editor Dan Kaveney set the revision process into motion and insisted on the highest standards as he oversaw the entire project. We are grateful for his thoughtful reflection about how to improve the book, for the many concrete ideas he contributed, and for his ability to magically bring them about. Development Editor Erin Mulligan and Director of Development Thom Holmes admirably handled the developmental editing, constantly exuding high energy and infectious enthusiasm. Sarah Vogelsong provided superb copyediting and remedied many errors that had gone unnoticed by authors and editors alike. Production Editor David Bradley coordinated myriad details as he smoothed us through the production process, and the fantastic staff at the University of Wisconsin Cartography Lab, ably led by Tanya Buckingham, drafted the art program. Associate Editor Christine Mahon and Editorial Assistant John Appeldorn gracefully handled the logistics of reviewing and spent many hours providing meticulous help in preparing the manuscript for production. David Jurman, our indefatigable marketing manager, and the Oxford University Press sales staff have put forward tireless efforts on behalf of the book. Our sincerest thanks to you all.

Joseph A. Mason
James E. Burt
Peter O. Muller

UNIT 1

Introducing Physical Geography

Planet Earth and the Moon in the northern summer—clear U.S. skies, a hurricane off Mexico, snow-bearing clouds over Antarctica.

OBJECTIVES

- Identify the contemporary focus of physical geography
- Describe the relationship of physical geography to the other natural and physical sciences
- Explain the scientific method as a way of investigating the natural world
- Summarize the systems and modeling approaches of physical geography

This is a book about Earth's natural environments. Its title, *Physical Geography: The Global Environment*, suggests the unifying perspective. In this book, we survey Earth's human habitat and focus on the fragile layer of life that sustains us along with millions of other species of animals and plants. We examine features of the natural world such as erupting volcanoes, winding rivers, winter blizzards, advancing deserts, and changing climates not only as physical phenomena but also in terms of their relationships with human societies and communities.

Along the way, we will do more than study the physical world. We will learn how broad a field physical geography is, and we will discover many of the topics on which physical geographers do scientific research. To proceed, we need to view our planet from various vantage points. We will study Earth in space and from space, from mountaintops and in underground shafts. Our survey will take us from clouds and ocean waves to rocks and minerals, from fertile soils and verdant forests to arid deserts and icy wastelands.

Geography

Geographers are not the only researchers studying Earth's surface. Geologists, meteorologists, biologists, hydrologists, and scientists from many other disciplines also study aspects of the planetary surface and what lies above and below it. But only one scholarly discipline—geography—combines, integrates, and, at its best, *synthesizes* knowledge from all these other fields as it makes its own research contributions. Time and again in this book, you will become aware of connections among physical phenomena and between natural phenomena and human activities. Although you might be familiar with many of these phenomena from everyday life or perhaps have studied them in another course, you might not have encountered these connections.

Although geography is a modern discipline and its scientists increasingly use high-technology research equipment, the roots of geography extend to the very dawn of scholarly inquiry. When the ancient Greeks recognized the need to organize the knowledge they were gathering, they divided it all into two areas: geography (the study of the terrestrial world) and cosmography (the study of the skies, stars, and the universe beyond). A follower of Aristotle, a scholar named Eratosthenes (ca. 275–ca. 195 BCE), coined the term *geography* in the third century BCE. To him, geography was the accurate description of Earth (*geo*, meaning Earth; *graphia*, meaning description). During Eratosthenes's lifetime, volumes were written about rocks, soils, and plants. A magnificent library in Alexandria (in what is now Egypt) came to contain the greatest collection of existing geographical studies.

Soon the mass of information (i.e., the database) concerning terrestrial geography became so large that the rubric lost its usefulness. Scientific specialization began. Some scholars concentrated on the rocks that make up the hard surface of Earth, and geology emerged. Others studied living organisms, and biology grew into a separate discipline. Eventually, even these specializations became too comprehensive. Some biologists, for example, began to exclusively focus on plants (botany) or animals (zoology). The range of scientific disciplines expanded—and continues to expand to this day.

This, however, did not mean that geography itself lost its identity or relevance. As science became more compartmentalized, geographers realized that they could contribute in several ways, not only by conducting specialized research but also by maintaining that connective, integrative perspective that links knowledge from different disciplines. One aspect of this perspective relates to the "where" with which geography is popularly associated. The location or position of features on the surface of Earth (or above or below it) may well be one of the most significant elements about these features. Thus, geographers seek to learn not only about the features themselves but also about their spatial relationships. The word *spatial* comes from the noun *space*—not the outer space surrounding our planet, but Earthly, terrestrial space.

The question is not only *where* things are located but also *why* they are positioned where they are and *how* they came to occupy those positions. To use more technical language: What is the cause of the variations in the distribution of phenomena we observe to exist in geographic space? What are the dynamics that shape the spatial organization of each part of Earth's surface? These are among the central questions that geographers have asked for centuries and continue to pose today.

GEOGRAPHY AND PHYSICAL GEOGRAPHY

Specialization has also developed within geography. Although all geographers share an interest in spatial arrangements, distribution, and organization, some geographers focus on physical features or natural phenomena, whereas others concentrate on people and their activities. This results in two very broad divisions of the discipline, *physical* and *human* geography. Other geographers work in *geographic information science*, developing new methods for the display, analysis, and management of spatial information. Still others emphasize two-way interactions between people and their physical environment in a subarea known as *nature-society relations*. And even within these four broad areas, there are subdivisions. For example, a physical geographer may work on shorelines and beaches, on soil erosion, or on climate change. A human geographer may be interested in urban problems, in geopolitical trends, or in health issues. As a result, geography today consists of an ever-evolving cluster of fields and subfields.

Our book's concern is with just one subfield—namely, the geography of the physical world. Much of the planet remains unaffected by humans and thus

FIGURE 1.1 This view of Phoenix, Arizona, points to many questions addressed by physical geography, such as: Why are arid climates found in this corner of the United States? What plant forms and plant communities develop in such locales? In what ways and why are the landforms and soils so different than those found in more humid landscapes? How do concrete, glass, and tall buildings affect the local climate in the city core?

remains in its "natural" state. Physical geography certainly studies the natural world, but this is not to say it concerns itself only with natural landscapes. For example, a geographer examining the effects of dam removal on flood events is doing physical geography. Similarly, determining the hydrologic response to the invasion of farmland by suburbs is a topic for physical geography. As suggested by Figure 1.1, studies of how cities affect their climate are physical geography, despite the obvious human role in creating the physical environment. The distinguishing feature of physical geography is that where human activity is involved, the human element is largely a given rather than the object of study. Untangling the economic and cultural forces that produce changes in land use, for example, is not considered a physical geography topic.

SUBFIELDS OF PHYSICAL GEOGRAPHY

Over the past century, physical geography has evolved into a cluster of subfields, the most important of which are diagrammed in the inner circle of Figure 1.2. To make things easier, we have numbered the eight subfields. Notice that each is connected to a related discipline. Physical geographers specializing in a subarea typically have substantial training in the associated field.

The geography of landscape, **geomorphology** (1 in Fig. 1.2), remains one of the most productive subfields of physical geography. As the term suggests (*geo*, meaning Earth; *morph*, meaning shape or form), this area of research focuses on the structuring of Earth's surface. Geomorphologists seek to understand the evolution of slopes, the development of plains and plateaus, and the processes shaping dunes and caves and cliffs—the elements of the physical landscape. Often, geomorphology has far-reaching implications. From the study of landscape, it is possible to prove the former presence of ice sheets and mountain glaciers, rivers, and deserts. *Geology* (the study of Earth's physical structure) is geomorphology's closest ally, and there is enough overlap between the two that geomorphology is sometimes taught as a subfield in geology departments. But regardless of where it is located academically, within geomorphology the processes of running water, moving ice, surging waves, and restless air are the primary concerns because of their role in landscape genesis. Proceeding clockwise from the top of Figure 1.2, we observe that *meteorology* (the branch of physics that deals with atmospheric phenomena) and physical geography combine to form **climatology** (2), the study of climates and their spatial distribution. Climatology involves not only the classification of climates and the analysis of their distribution but also broader environmental questions, including those concerning climatic change, vegetation patterns, soil formation, and the relationships between human societies and climate.

As Figure 1.2 indicates, the next three subfields relate physical geography to aspects of *biology*. Where biology and physical geography overlap is the broad subfield of **biogeography** (3–5), and there are specializations within biogeography itself. Physical geography combined with botany is *plant geography* (also called phytogeography) (3); combined with zoology, it becomes *zoogeography* (5). Note that biogeography (4), itself linked to *ecology*, lies between these two subfields. Both zoogeography and plant geography are parts of biogeography. The next subfield of physical geography is related to soil science, or *pedology*. Pedologists' research tends to focus on the internal

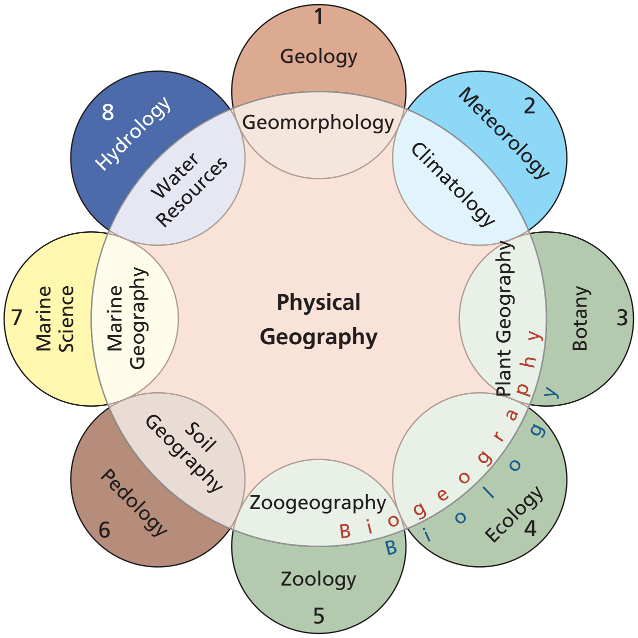

FIGURE 1.2 Important subfields of physical geography and related disciplines.

properties of soils and the processes of soil development. In **soil geography** (6), research centers on the spatial patterns of soils, their distribution, and their relationships to climate, vegetation, and humankind.

Other subfields of physical geography are **marine geography** (7) and the study of **water resources** (8). Marine geography, which is related to the discipline of *marine science*, also has human as well as physical components. The human side of marine geography has to do with maritime boundaries, the competition for marine resources, and the law of the sea; therefore, this subfield is closely allied with the geographic subdiscipline of political geography. The physical side of marine geography deals with coastlines and shores, beaches, river mouths, and other landscape features associated with the oceanic margins of the continents. The subfield of water resources (where *hydrology* and physical geography intersect) also has human as well as physical elements. The landmasses contain fresh water on their surfaces (in the form of lakes and rivers) and below (as groundwater). As we will see later in this book, the study of these waters may be approached from geomorphic as well as economic standpoints.

Figure 1.2 is a simplified view of physical geography, and the subareas themselves comprise more specialized fields. These days, when you ask a physical geographer what his or her specialty is, you frequently hear such answers as hydroclimatology, periglacial processes, paleogeography, or wetland ecosystems. All this helps explain the wide range of material you will encounter in this book, which is an overview of a broad field encompassing many topics. In the 49 units that follow, these various subfields of physical geography are examined in some detail, and the connections between physical and human geography are revealed. As you will see, we must go beyond the confines of Figure 1.2 to put our work in proper perspective. To understand the basics of physical geography, we must comprehend the general properties of our planet, not only deep below its surface but also far beyond as it orbits the Sun as part of the solar system in our tiny corner of the vast universe. Comprehending the general properties of Earth will be among our first tasks and will constitute much of the remainder of Part One.

Physical Geography and the Scientific Method

Physical geography is an Earth science, and like its related fields (and physical sciences generally), it relies on a framework called the **scientific method**. The term is a bit misleading, because the scientific method is more a way of knowing or learning about the world than a strict method or process. Humans have developed a variety of ways to "know" or claim something is one way and not another. We sometimes rely on common sense or intuition in asserting something as fact. Or we grant some persons the right to speak with certainty about some topics. This authority might be an expert with impressive scientific credentials, or it might be a religious leader who claims to have a divine source for his or her pronouncements. Of course, many oral and written traditions offer explanations for elements of the physical world, including Earth's formation. Any of these might yield a fact no reasonable person would dispute, but none is scientific.

Unlike other ways of knowing, science places demands on statements of fact. For example, intuition fails as a scientific approach because it is not reproducible. Studying the same phenomenon, two people might come up with completely different explanations. Likewise, there is no way to be sure a particular scholarly prophet has truly heard the voice of an all-knowing deity, and therefore science grants no speaker a special position. The scientific method consists of certain elements that together constitute a convention for obtaining facts or learning the "truth" about phenomena of interest. Although obviously not the only approach, this convention has been in use for centuries, and there is no denying its remarkable success in a multitude of areas. For example, we depend on vaccines to protect us from horrific diseases, we travel without qualms in metal contraptions miles above the ground, and we talk to friends on other continents using devices no larger than a child's hand. None of these would be possible or even imaginable without discoveries achieved through the scientific method.

The scientific method is typically presented as a series of steps, as shown in Figure 1.3, several of which deserve comment. First, *information gathering* is not just measurement but also includes subjective observation and the precise definition of terms. **Hypotheses** are tentative explanations of observations and measurements. For example, we might have observed stunted growth in a forest, defined as more than 50 percent of tree stems being smaller than 2 inches in diameter. As a hypothesis, we propose that unfavorable chemical conditions in the soil prevent the trees from obtaining essential nutrients. Like people, plants need calcium, iron, and other "nutrient" chemicals to grow. For a plant these must be present in the soil, and in addition, the soil must have the right level of acidity. If soil acidity is too low, nutrient uptake is hampered and plants suffer. For this example, we hypothesize that the soil acidity is too low for nutrient uptake.

A hypothesis helps us to generate *predictions*, which are not typically or even mainly forecasts. Rather, they are deductions that follow from the hypothesis. In our tree example, a prediction might be that although a certain soil contains abundant nutrients, the acidity is too low to permit nutrient uptake. The prediction leads to an **experiment**, which is a very general term. Growing plants in a greenhouse is an experiment, but so are performing calculations using a computer program or collecting soil samples and measuring acidity and nutrient content. Data resulting from the experiment are analyzed and compared with the predictions to rule on the hypothesis.

There is an important subtlety of the scientific method not always appreciated by the general public: the process can only disprove hypotheses. To see this, consider the

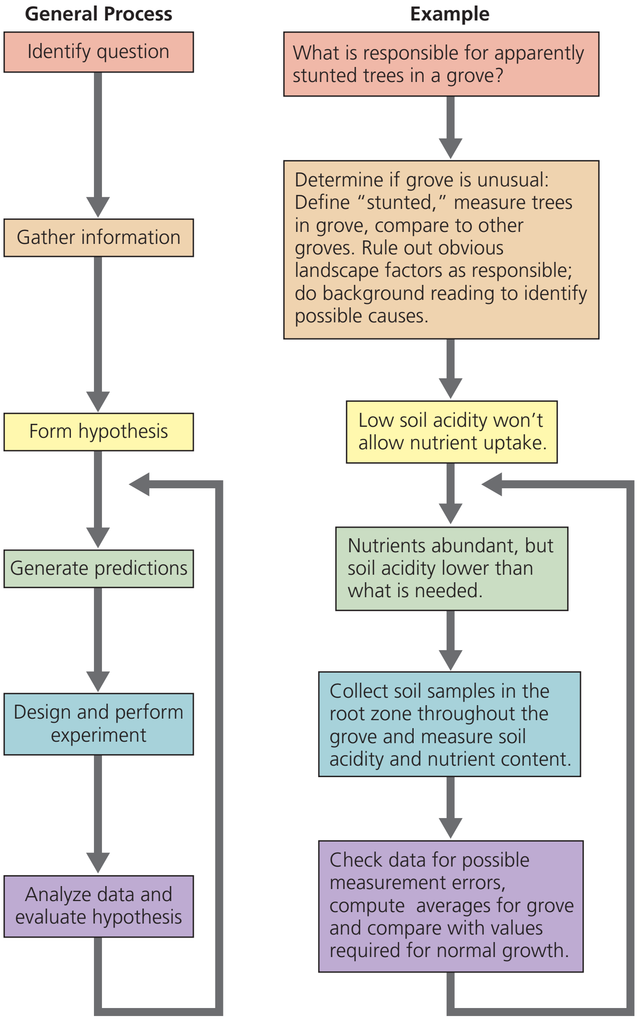

FIGURE 1.3 The scientific method in general terms (left) and by example (right).

possible outcomes of the example experiment, keeping in mind the hypothesis in Figure 1.3 (i.e., Low soil acidity won't allow nutrient uptake):

1. Soil acidity is suitable for growth. Whether nutrients are present or not, the hypothesized explanation is false because acidity can't be the explanation for the poor growth.
2. Soil acidity is unsuitable for growth, and soil nutrients are insufficient. We can't tell which (if either) aspect of the soil is responsible for low growth, and the hypothesis is neither confirmed nor rejected.
3. Soil acidity is unsuitable for growth, and soil nutrients are abundant. This is consistent with the hypothesis, but it does not prove the hypothesis. Possibly other, even more critical, resources for normal plant growth are lacking, such as water or sufficiently warm temperatures.

Notice that only outcome (1) leads to a firm decision about the hypothesis, and that outcome is rejection rather than proof of the hypothesis. In both of the other cases, more research is needed. That is, new predictions and experiments are required. This example illustrates a very important point about scientific hypotheses: only after a hypothesis survives repeated attempts to be proven false can it be accepted as correct.

Notice also that if a hypothesis is to be useful scientifically, it must be possible to prove it false. Hypotheses for which there is no conceivable disproving experiment are unhelpful and in that sense not scientific. For example, one might hypothesize that all of life is an illusion contained in the dream of a sleeping turtle. Whether this hypothesis is true or not, there is no way to prove it false, and thus, this hypothesis about a dreaming turtle has no place in the scientific method. As a less fanciful example, in the last few decades theoretical physicists, in proposing ideas about the universe, have put forth predictions that are impossible to verify experimentally. Some scientists within the discipline have labeled such theories as unscientific.

Finally, we should say a word about what is meant by **theory** in science. Rather than mere speculation or conjecture, the term is reserved for a comprehensive body of explanatory knowledge that is both widely supported by experiment and generally accepted among scientists. For example, heat-transfer theory is used to design air conditioners, and gravitational theory underlies the calculation of satellite orbits. The scientific method cannot prove a theory is true, and theories are not considered immutable truth. Indeed, established theories are constantly refined as new evidence accumulates.

Scientists often speak of **scientific laws** in connection with theories. Laws are fundamental principles believed to hold without exception. One famous example is Newton's law, which states that the velocity of an object is constant unless acted on by an outside force. Like good hypotheses and theories, laws cannot be proven true, but there is so much confirming evidence for them that they are taken as absolute within the limits of their application. For instance, Newton's law applies to objects moving much slower than the speed of light. At higher speeds, the law needs modification, but for everyday phenomena like water plunging down a mountain stream, landslides, erupting volcanoes, and even tornado winds, we can be sure Newton's laws are unfailing. Theories are often constructed by combining and applying fundamental laws to particular problems.

Systems and Models in Physical Geography

Physical geography is a multifaceted science that seeks to understand major elements of our complex world. To deal with this complexity, physical geographers employ numerous concepts and specialized methods. We will discuss many of these in the units that follow. This section provides an introduction to that analysis by considering two general approaches to the subject: systems and models.

SYSTEMS AND FEEDBACKS

For the past few decades, many physical geographers have found it convenient to organize their approach to the field within a systems framework of thinking. For our purposes here, we define a **system** as any set of related events or objects and their interactions. For example, a city could be described as a large and elaborate system. Each day, the system receives an inflow of energy, food, water, and vast quantities of consumer goods. The various populations that reside in the urban center consume this energy and matter and change its form. At the same time, huge amounts of energy, manufactured goods, and services, along with sewage and other waste products, are produced in and exported from the city. As a physical geography example, consider the reservoir depicted in Figure 1.4. To explain even basic aspects of the reservoir, such as changes in water level, variations in water temperature, or why fish are near the bottom in winter but not summer, a systems approach is extremely helpful.

A system consists of interacting components, but what does "interacting" mean? In the physical world, it means there is an exchange of energy, mass (i.e., matter), or momentum. A precise definition of these terms isn't needed here; simply think of some familiar examples, such as the heat energy given off by hot coils in a hair drier, the transfer of paint (matter) from a paintbrush to a wall, or the momentum of a bowling ball rolling down an alley. If two physical systems are connected to each other or if there is interaction between parts of a system, there must be a transfer of one or more of energy, mass, or momentum. In the reservoir example, solar energy enters the system at the water surface, and most of it is absorbed in the upper part of the water. Some of that heat is carried downward by swirling eddies and other motions. Matter (water) enters the reservoir as rainfall and a stream inflow at the upper end, and there are losses as a result of evaporation, overflow through the spillway outlet, and downward percolation to deeper groundwater. Finally, winds blowing across the reservoir transfer momentum from the atmosphere to the water, creating small waves on the surface.

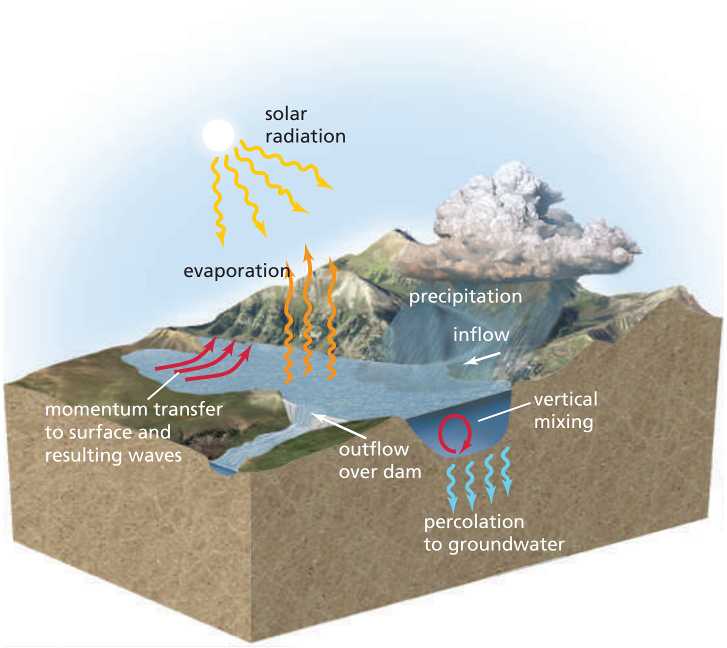

FIGURE 1.4 A reservoir can be considered as a system. This diagram shows some of the energy, mass, and momentum exchanges within the system and between the system and its surroundings.

The power of the systems approach comes in large part because nature obeys certain broad principles known as the **conservation laws**. These laws are nothing more than accounting rules stating that energy, mass, and momentum cannot be created or destroyed. In other words, these do not simply appear and disappear.* Just as an accountant can track the flow of money through a corporation, a scientist can track the flow of energy, mass, and momentum through a system, knowing that ultimately everything must add up. For example, if the reservoir water inflow increases, those additional water molecules do not disappear into nothingness. Either they are stored and the reservoir level rises or the water outflow increases or perhaps both. The point is that all of the additional water can be accounted for because mass is conserved. Similarly, if the water level were to change, mass conservation demands that there be some reason for that change.

The conservation laws provide explanations for phenomena discussed throughout the book, and you will see them applied over a huge range of scales, from the molecular to the global. Energy conservation helps explain why air temperature in a parking lot often peaks after the Sun has reached its highest point in the sky and why continents get so much colder in winter than the surrounding ocean. Momentum conservation explains not only wave action in a small cove but also wind belts on the grandest scale.

Notice that nothing in the definition of a system says exactly what constitutes a system. Is a city a system and a neighborhood within a city not a system? Or are both systems? Or is the neighborhood a **subsystem** (a system within a system) of a city? These decisions are up to the researcher. For some purposes, neighborhood differences might not matter, whereas for others they might. The researcher also decides what components of the system need to be included. For example, a water supply specialist might be willing to ignore wave action, whereas someone interested in beach erosion would find wave action essential to the phenomenon. There are also no set rules about the boundaries of a system. Does the reservoir stop at the water's edge? Is it necessary to consider the movement of water through the muck and rock below as part of the reservoir

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* As with all laws, there are limits to the application of these conservation principles. In nuclear reactions, mass is converted into energy, and it becomes necessary to talk in terms of mass-energy conservation as captured by Einstein's law.

system? Again, it depends on the goal of the analysis, and decisions like these are made by the analyst.

In the reservoir system, energy, mass, and momentum move freely across its boundaries, making it an **open system** and underscoring its relationships with surrounding systems (the atmosphere and landscape within which it is embedded). There are many examples of open systems throughout this book, such as a weather system or a river drainage basin. In terms of energy flows, Earth itself is an enormous open system that comprises several interconnected lesser systems. Although it is difficult to find one on Earth's surface, we should also know what is meant by the term **closed system**: a self-contained system exhibiting no exchange of energy or matter across its boundaries.

System boundaries are called **interfaces**. The transfer or exchange of energy and matter takes place at these interfaces. Sometimes interfaces are visible: we can see where sunlight strikes the roof of a building. But often they are not visible: we cannot see the movement of groundwater, a part of the global water system, as it flows through the subterranean rocks of the geologic system. Many geographers focus their attention on these interfaces, visible or invisible, particularly when they coincide with Earth's surface. It is here that the greatest activity of our dynamic world occurs.

FROM THE FIELD NOTES

FIGURE 1.5 "South Florida's Atlantic coast, looking northward beyond Miami Beach. At present the beach seen in this photograph represents a system in dynamic equilibrium, with currents flowing parallel to the coast, continuously removing sand and at the same time depositing a replacement supply."

Two other ideas commonly referred to in systems approaches are **equilibrium** and **feedback**. A system is in equilibrium with respect to some property if that property is unchanging over time. Thermal equilibrium means temperature is constant through time; mass equilibrium means there is no change in the number of molecules; charge equilibrium means the electric charge is unvarying; and so forth. True stasis, meaning no movement of energy, matter, or momentum, is very rare in the natural world. Most of the time, there is continuous transfer; thus, if an equilibrium exists, any gains must be balanced by losses. There may be a continuous movement of something through the system, but as long as supply and removal are equal, the conservation laws state that the amount stored is unchanging. When supply and removal are equal, the system is in **dynamic equilibrium**. On a global scale, water falls from the atmosphere continuously as rain and snow, yet the atmosphere never dries out thanks to constant replenishment from the planet's surface. We might take this grand example of dynamic equilibrium for granted, but our very existence depends on it.

Feedbacks are important in understanding how a system responds to some disturbing force or impetus for change. A feedback process is a chain of connections that affects (that is, feeds back on) some initial disturbance. This is best explained by an example. Siberian winters are murderously cold. Meager amounts of solar radiation are the ultimate cause for this cold, but two important feedbacks affect the temperature response. The first of these is a **positive feedback**, which acts to accentuate the change. Thus, as temperatures fall, there is a feedback that makes temperatures colder than they would be otherwise. The sequence can be traced out by following Figure 1.6A. As incoming sunlight declines, less heat is supplied to the ground, and temperatures fall accordingly. This means more snow on the ground and trees. As alpine skiers know, snow is highly reflective, and therefore snow cover reduces the amount of sunlight absorbed. With less energy supplied, still lower temperatures result. The feedback is positive because the feedback process amplifies the initial change.

A **negative feedback** also operates in the Siberian example (Fig. 1.6B). Negative feedbacks act to resist, or counteract, change. In this case, cold Siberian temperatures contribute to a large temperature difference between the warm tropics and the much-colder middle latitudes. As we will see in later units, storms and other atmospheric disturbances are for the most part driven by this temperature imbalance, and these atmospheric disturbances are more vigorous in the winter when the temperature gradient is large. The net effect of these enhanced atmospheric motions is to move additional heat out of lower latitudes

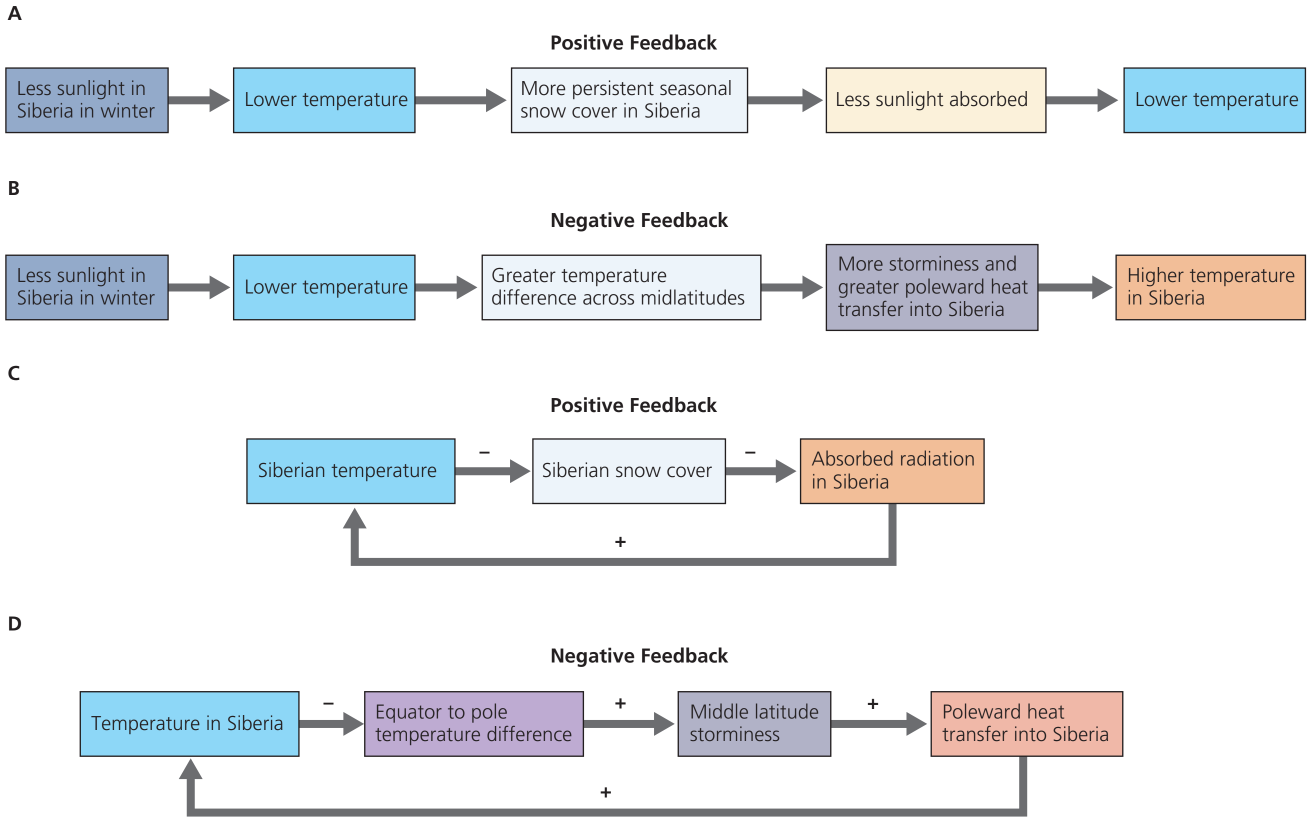

FIGURE 1.6 Examples of positive and negative feedbacks. Diagrams (C) and (D) represent the same feedback processes as (A) and (B), but as loops rather than as linear sequences. The two negative links in (C) combine to form a positive overall relationship. The single negative link in (D) means the overall loop comprises a negative feedback.

toward the poles, which benefits Siberians (human and otherwise) struggling against the cold. Nobody would say Siberia is warm in winter, but it would surely be colder without this feedback.

The two Siberian feedbacks are more usefully illustrated in parts C and D of Figure 1.6. As in parts A and B, arrows again indicate linkages, but in C and D, the arrows are labeled with plus and minus signs. A plus sign means that as one variable increases, the linked variable also increases. For example, as absorbed radiation in Siberia increases, there is a corresponding increase in Siberian temperature. Negative signs denote just the reverse. As Siberian temperature rises, the amount of snow cover falls. The negative feedback loop in Figure 1.6D has just one negative link. Thus, overall, the feedback loop is negative. In contrast, the positive loop in Figure 1.6C has two negative signs, yet the loop overall is positive. In effect, the two negative links cancel each other out, resulting in a positive relationship across them. If a loop has zero or an even number of negative links, the overall loop is a positive feedback. If a loop has an odd number of negative links, it constitutes a negative feedback. The somewhat abstract way of presenting feedbacks illustrated in Figures 1.6C and 1.6D is succinct and has other advantages. For example, we can see that the two lower diagrams work for summer as well as winter. If we wanted to draw something similar to Figures 1.6A and 1.6B for summer, the box contents would need to change ("less sunlight" would become "more sunlight," etc.). We use this more abstract presentation where feedbacks are discussed in the book.

Positive and negative feedbacks are present throughout the Earth system, operating at many spatial and temporal scales. The Siberian example has a fast-acting, molecular-scale positive feedback (individual snow crystals reflecting sunlight) and a slower large-scale feedback (atmospheric circulation changes). With multiple feedbacks, some amplifying change and others being restorative, many Earth systems can exhibit spontaneous change over time without the involvement of any external agent. That is, feedbacks give rise to changes in the system that are driven internally rather than by some outside process. This might seem strange, but pouring milk from a jug held at a steep angle (Fig. 1.7) provides an everyday example. The milk gurgles out in what is obviously highly variable flow, yet there are no changes in external forces. Instead, internal processes are to blame for the erratic flow. A little thought explains why. As milk flows out a partial vacuum forms in the jug that is able to temporarily hold the remaining milk against the force of gravity. Very quickly enough air enters the jug to destroy the vacuum, and milk again begins to flow, starting another cycle of a developing vacuum and another gurgle. In later units, you will encounter Earth-system examples of this type of behavior. For now, it is sufficient to know that in addition to external processes, internal feedbacks can generate variability in a system.

FIGURE 1.7 If a jug of milk is held at a high angle, the flow starts and stops in fits of gurgling motion. This is an example of system variation arising internally rather than in response to changes in external factors.

MODELS

Another way that physical geographers approach the study of Earth's phenomena is to make models of them. **Models** are simplified representations containing processes and features that are of interest. A wall map is one example of a model. Obviously, only certain phenomena are represented in the map, and the map departs greatly from the reality it represents. This is not a defect, provided the excluded phenomena are not important to the map's purpose.

Physical geographers today rely heavily on mathematical models in which equations represent processes and properties of the physical world. These equations can be developed from observations, or they may follow directly from physical theory. In either case, they provide a way for geographers to simulate real-world processes and understand relationships among variables of interest. Model building is complementary to systems analysis as a way of thinking about the world. It entails the controlled simplification of a complex reality, filtering out the essential forces and patterns from the myriad details in a complicated world. Such abstractions,