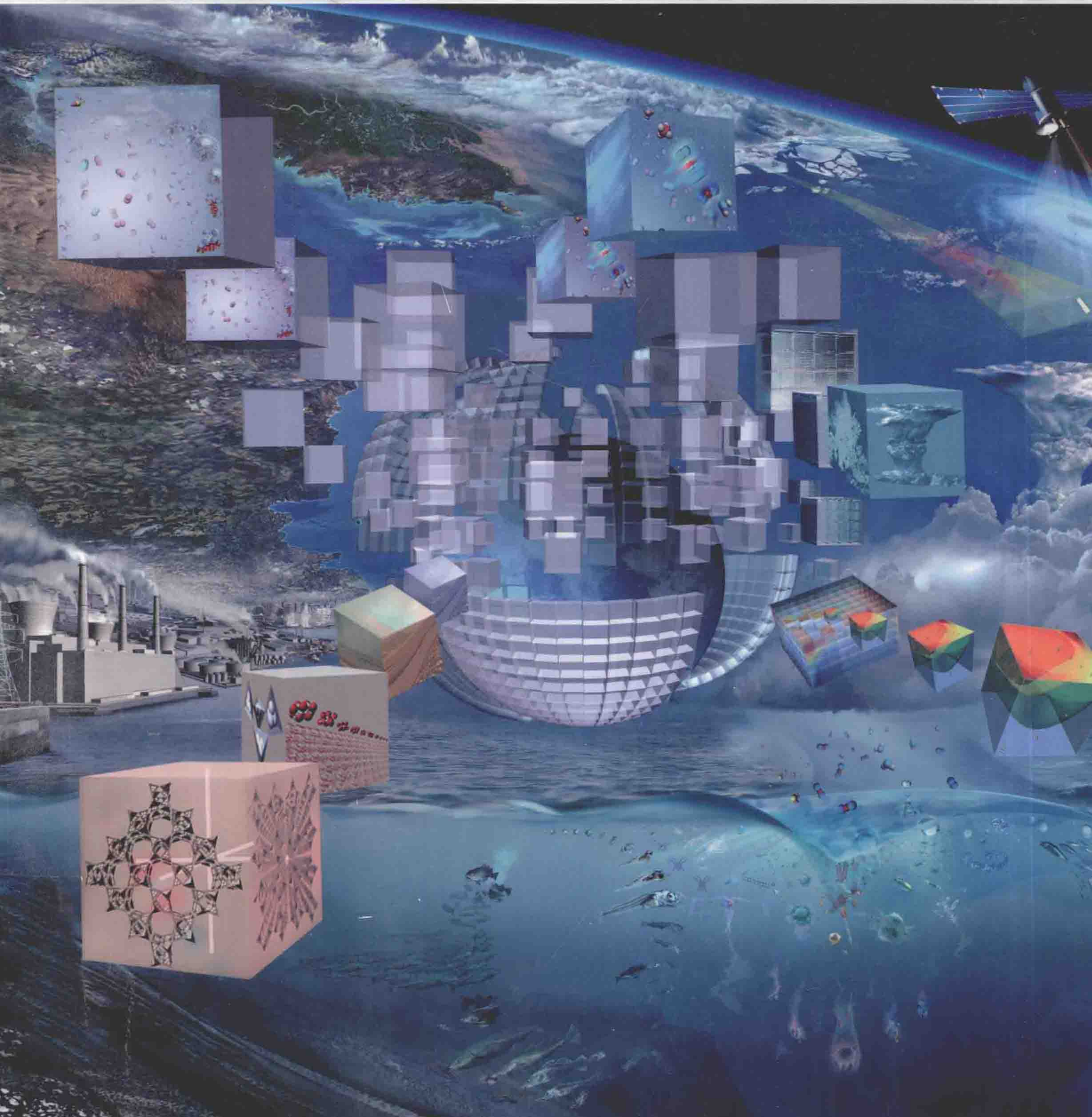
Third Edition

THE EARTH SYSTEM

Lee R. Kump • James F. Kasting • Robert G. Crane



THE EARTH SYSTEM

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Prentice Hall
San Francisco Boston New York
Cape Town Hong Kong London Madrid Mexico City
Montreal Munich Paris Singapore Sydney Tokyo Toronto

Library of Congress Cataloging-in-Publication Data
Kump, Lee R.
The earth system / Lee R. Kump, James F. Kasting, Robert G. Crane. — 3rd ed.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-321-59779-3
ISBN-10: 0-321-59779-6
1. Gaia hypothesis. I. Kasting, James F. II. Crane, Robert G. III. Title.
QH331.K798 2010
550—dc22
2009023898

Editor in Chief, Geosciences and Chemistry: Nicole Folchetti
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Composition: GGS Higher Education Resources, a division of PreMedia Global, Inc.
Operations Specialist: Alan Fischer
Project Manager, Art: Connie Long
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Cover Description: The cover shows data being collected from ocean, land, and atmosphere studies with the aim of building mathematical models of the Earth system. Detail of ocean plankton, mineral recycling, and fish biology indicate the complexity and difficulties of modelling living systems. Human impact as illustrated by industrial emissions is driving the need to provide better models for advising economic planners.

Any uncredited photos were supplied by the authors.

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

ISBN-10: 0-32-159779-6
ISBN-13: 978-0-32-159779-3

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ABOUT THE AUTHORS

Lee R. Kump received his AB degree in geophysical sciences from the University of Chicago in 1981 and his PhD in marine sciences from the University of South Florida in 1986. He has been on the faculty of the Department of Geosciences at Penn State since 1986, where he now serves as Professor of Geosciences and affiliate of the NASA Astrobiology Institute and Penn State's Earth System Science Center (ESSC), and is the Assistant Director of the *Canadian Institute for Advanced Research, Earth System Evolution Program*. Dr. Kump is a co-author with Michael Mann of *Dire Predictions: Understanding Global Warming* (DK/Pearson, 2008). He serves on the editorial board of *Geobiology* and is a reviewing editor for *Science*. He is a fellow of the Geological Society of America and the Geological Society of London, received the Distinguished Service Medal from the Geological Society of America in 2000, and is a distinguished alumnus of the University of South Florida (2009). Dr. Kump's research interests include environmental and biotic change during extreme events in Earth history (mass extinctions, supergreenhouse periods, glaciations), the evolution of ocean and atmosphere composition on geologic time scales, biogeochemical cycling in aquatic environments, and the behavior of nutrient and trace elements in natural environments.

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Robert G. Crane received his PhD in Geography from the University of Colorado, Boulder. After working as a Research Associate in the National Snow and Ice Data Center and the World Data Center-A for Glaciology in Boulder, he spent a year teaching at the University of Saskatchewan before moving to Penn State in 1985. Dr. Crane's research has been on microwave remote sensing of sea ice, ice–climate interactions, and, more recently, regional- scale climate change, climate downscaling techniques, and climate change and variability in sub-Saharan Africa. He is coeditor of a text on the applications of artificial neural networks in geography. Currently Dr. Crane holds the position of Professor in the Department of Geography and an affiliate of the ESSC. He also serves as the Director of Penn State's Alliance for Earth Science, Engineering and Development in Africa.

PREFACE

This is not a traditional Earth science textbook. Such books treat individual components of the Earth system—the solid Earth, atmosphere, and oceans—separately, with little consideration of the interplay among them or the important interactions with living organisms (the stuff of ecology texts). And, although they are the focus of this book, the modern environmental problems of global warming, ozone depletion, and loss of biodiversity are treated in a fundamentally different way here than in most texts. Here we recognize that these problems have analogues from Earth history: The geological past is the key to the present and to the future.

CONTENT

Chapter 1, on global change, is an overview of these important issues—the observational data that convince us that serious problems exist and the events in Earth's history that illuminate how the Earth system responds under stress. The rest of the book is organized into three major sections. Chapters 2 through 9 are devoted to an exploration of how Earth "works." They develop the notion that processes active on Earth's surface are functioning together to regulate climate, the circulation of the ocean and atmosphere, and the recycling of the elements. The biota plays an important role in all of these processes. Chapters 10 through 14 take the reader through the history of Earth, highlighting those events that provide lessons for the future. The final five chapters focus on the future of the Earth system, addressing the modern problems of global change and the prospect of life on other planets in the context of what was presented in the first two sections.

REVISIONS TO THE FIRST EDITION

In the 10 years since the first edition of this book came out, a lot has changed. Atmospheric CO_2 has increased by about 7 parts per million, freon-11 concentrations have decreased by 6 parts per trillion, and global surface temperatures have continued their inexorable, but ragged, rise. For this reason alone—just to keep up with the new data on global change—a book like this one needs to be regularly updated. However, it is not just the data that are changing. Ideas have been evolving as well during the past 10 years. New geologic evidence indicates that "Snowball Earth" episodes actually occurred not just once, but several times during Earth's history. The case has been made that CH_4, rather than (or in addition to) CO_2, was the main greenhouse gas that helped keep the early Earth warm despite reduced solar luminosity. The IPCC (Intergovernmental Panel on Climate Change) released a new report that for the first time states unambiguously that human activities are responsible for at least part of the observed surface temperature increase. And NASA's generous support for the new discipline of "astrobiology" has made us even more aware of the tight connections between the evolving Earth and its biota.

We have tried to reflect these and other changes in the revised edition of our book. We have added two new chapters: Chapter 6 (on global climate models) and Chapter 8 (on the biota, ecosystems, and biodiversity). We've also expanded our discussion of early Earth, now devoting two chapters to the topic: Chapter 10, on the origin of Earth and of life, and Chapter 11, on the effect life has had on the development of the atmosphere. Some of this involved simply reorganizing material that had previously been included in other chapters; however, a significant amount of new material has been added. Chapter 6 recognizes the importance of numerical modeling in the establishment of policy for a changing world. Chapter 8 highlights the role that the biota plays in the Earth system. Chapters 10 and 11 draw on the "universal" tree of life derived recently from sequencing of ribosomal RNA that places humans and fungi as closer relatives than different forms of bacteria. The order of Chapters 11 and 12 (Chapters 8 and 9 in the first edition) has been switched to reflect the increased importance of the O_2/CH_4 story for Precambrian paleoclimates.

WHAT'S NEW IN THIS EDITION

1. The discussion of the science of global warming has been updated to reflect the 2007 IPCC report (Ch. 15).
2. We added a new chapter on the cryosphere in response to the current interest in the reduction of the Arctic summer ice extent and the recent observations of greater than expected melt on the Greenland Ice Cap. The chapter follows the discussion of the atmospheric and oceanic circulations and focuses on ice sheets and sea ice as dynamic components of the Earth system. Most of the material is new, but it includes a section on sea ice and climate from Chapter 15 of the second edition.
3. All graphs showing trends in greenhouse gases, surface temperature, freons, etc., have been updated to the latest versions (Chs. 1, 15, and 17).

4. The discussion of the economic impacts of global warming (Ch. 16) has been completely revised and now includes a comparison of the different approaches taken by Nicholas Stern in "The Stern Review on the Economics of Global Warming" and by William Nordhaus in his new 2008 book "A question of balance: weighing the options on global warming policies."
5. The global cycling of nitrogen and phosphorus has been added to what was the carbon cycle chapter (Ch. 8).
6. The discussion of ozone depletion has been updated to reflect the 2006 WMO report (Ch. 17).
7. We removed the chapter on Short-Term Climate Variability. We took much of the material from this chapter and moved the relevant sections to other chapters as examples of atmosphere-ocean interactions and rapid climate change at the end of the Pleistocene, and to set the scene for the discussion of global warming in Chapters 15 and 16.

REVISIONS TO THE SECOND EDITION

Five years have passed since the second edition of this book was published. During that time, three working groups of the IPCC were busy assessing the current state of understanding of the scientific basis and impacts of climate change, and the roles of adaptation to and mitigation of future climate change in society's response to the problem. The tone of this Fourth Assessment Report is more urgent than previous reports; we need to begin taking action immediately if we are to avoid dangerous climate change. Getting society as a whole to respond to global warming is exceedingly difficult—there is tremendous inertia in both the infrastructure and economics of the present fossil fuel–based energy system. We hope that this book will help overcome some of that inertia by giving the reader a deeper appreciation of what scientists know and how they know it, and why this knowledge compels most scientists to conclude that human-induced climate change poses a serious threat both to humans and to natural ecosystems.

This third edition is prompted by the Fourth Assessment of the IPCC, released in 2006. Just as the Fourth Assessment differed considerably from the Third, this edition differs considerably from the second. Recognizing the critical role that the melting of ice sheets and sea ice plays in future projections of the effects of global warming, we have added a new chapter (Chapter 6) on the cryosphere (the ice-dominated regions of the planet). Following suggestions from geochemist colleagues, the chapter on carbon cycling has now been expanded to cover other essential elements, namely phosphorus and nitrogen. The chapters covering Earth history have been streamlined to improve readability and have also been brought up to date with our current understanding of the co-evolution of life and environment over the 3.5 billion years of Earth's habitation. The discussion of global warming has been expanded from one chapter to two. The first chapter (Chapter 15) focuses on the scientific evidence for global warming, drawing heavily on the report from IPCC Working Group 1. Impacts, adaptations to, and mitigation of climate change—the focus of Working Groups 2 and 3—form the basis of the second chapter (Chapter 16). Chapter 16 also contains an expanded discussion of the economics of climate change, a topic that is often considered separately from climate science, but which is critical in making decisions about energy and climate policy.

ORGANIZATION AND PEDAGOGY

We have employed a number of pedagogical features to assist in the learning process. Each chapter begins with *Key Questions* (objective questions students should be able to answer after they have read the chapter) and a *Chapter Overview* (a broad preview of the chapter to come). Within each chapter are *boxed essays* that provide interesting asides, more detailed or quantitative treatments of material in the text, or recent advances in scientific understanding. *Chapter Summaries* are provided in outline form at the end of each chapter to aid in reviewing the most important concepts. These are followed by *Key Terms* lists, which consist of **boldfaced** terms that are introduced in the chapter and that appear in the *Glossary* in the back of the book. *Review Questions* focus the students' review on important concepts and require only brief answers, whereas *Critical-Thinking Problems* are thought questions or analytical exercises that require students to synthesize concepts presented in the chapter. *Further Readings* include both general readings and advanced readings for students (and instructors) interested in further information about the subject matter. In designing this third edition, we have tried to organize our topics more logically, categorizing special topics into "boxes" of different types, with the following designations: **A Closer Look**, which offers a closer examination of topics discussed in the book; **Useful Concepts**, with in-depth presentations of fundamental concepts from the natural sciences essential to our understanding of the Earth system; and **Thinking Quantitatively**, which emphasizes how mathematics is used to better understand the workings of the Earth system. Instructors may choose whether to make any or all of these boxes assigned reading. We have also corrected errors pointed out to us by our students and by other faculty using the book, and we've brought the data graphs up to date. We hope that these changes will help make the book easier to use in a variety of different courses, as well as being more accessible and informative to students.

CHAPTER SEQUENCING

We anticipate that this book will be used in a variety of ways. We teach a general education class at Pennsylvania State University that covers approximately three-quarters of the book during one semester. Several instructors teach this course, but not all of us choose to cover the same chapters. An instructor who is most interested in climate issues, for example, might use Chapters 1–6, 12, 14–16, and 19. One who is most interested in biodiversity might choose Chapters 1, 2, 8–11, 13, and 18. The course can also be tailored to emphasize either Earth history (Chapters 1, 2, 3, 9–14) or modern global environmental problems (Chapters 1–6, 9, and 16–19). By providing more material than can easily be covered in a one-semester course, we provide the flexibility to emphasize topics or topic areas that are of interest to different instructors and different groups of students.

ACKNOWLEDGMENTS

In addition to the many people who helped with the first and second editions, we are especially grateful to our editors Dru Peters, Crissy Dudonis, Shari Toron and to our production editor, Suganya Karuppasamy. The following colleagues provided reviews of the first and second editions that were invaluable in our preparation of this third:

Eric Barron,
The National Center for Atmospheric Research
Kerry H. Cook,
Cornell University
Chris Duncan,
University of Massachusetts, Amherst
Jim Evans,
Utah State University
Jonathan K. Filer,
Towson University
Woody Hickcox,
Emory University
Jean L. Hoff,
St. Cloud State University
Hobart M. King,
Mansfield University of Pennsylvania
David Liddell,
Utah State University
Michael F. Rosenmeier,
University of Pittsburgh
Cameron P. Wake,
University of New Hampshire
Dean Wilder,
University of Wisconsin–La Crosse
Andrew Wulff,
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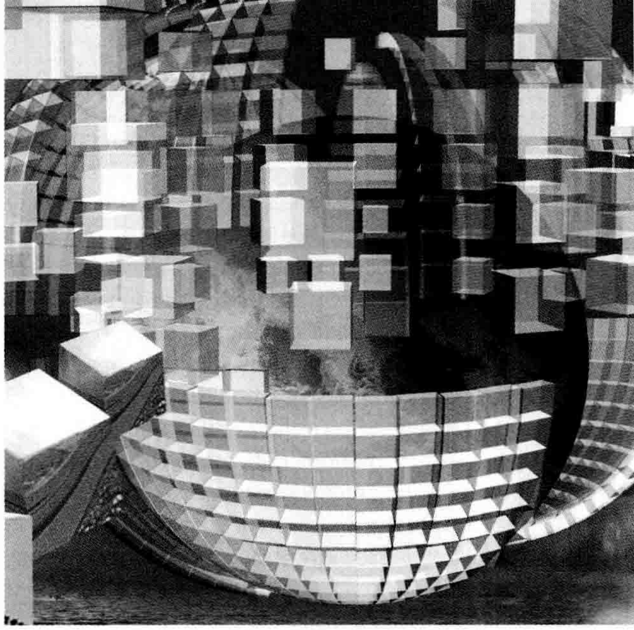
CONTENTS

CHAPTER 1

Global Change



Key Questions

- What is meant by a "systems approach" to Earth science?
- How does global warming differ from the greenhouse effect, and is global warming actually occurring today?
- What is the Antarctic ozone hole, and what is its significance?
- Should we be concerned about tropical deforestation?
- What can understanding Earth's past tell us about Earth's future?

Chapter Overview

Earth is currently being altered at an unprecedented rate by human activity. The buildup of greenhouse gases in the atmosphere has already warmed Earth's climate by a small amount, and may warm it significantly in the future unless steps are taken to reduce greenhouse gas emissions globally. The accumulation of chlorine-containing compounds in the atmosphere has damaged the ozone layer over part of the globe. Deforestation of the tropics may be causing large decreases in biodiversity. How serious are these problems, and how do they compare with past changes in the Earth system? This chapter lays out the evidence of these changes and explains why an integrated, systems approach is useful in analyzing them.

INTRODUCTION

Our world is changing. In fact, Earth has always been changing and will continue to do so for ages to come. Yet, there is a difference between the changes occurring now and those that occurred previously. Earth is changing faster today than it has throughout most of its 4.6-billion-year history. Indeed, it may be changing faster than it ever has, except perhaps in the aftermath of giant meteorite impacts. The cause of this accelerated pace of change is simple: human activity. Human populations have expanded in numbers and in their technological abilities to the point at which we are now exerting a significant influence on our planet. The effects of our actions are seen most clearly in the thin envelope of gases that supports our existence, the *atmosphere,* but they are observable elsewhere as well. Forests, mountains, lakes, rivers, and even the oceans exhibit the telltale signs of human activity.

To what extent are these **anthropogenic** (human-induced) changes a cause for concern? All of us can think of situations in which human influence has clearly been detrimental to the environment—for example, cities plagued with polluted air and water. But these are local problems, and they are hardly new. Humans have generated local pollution ever since they first developed agricultural societies around 10,000 years ago. Human inhabitants of Easter Island (which lies off the southwest coast of South America) may have set the stage for the demise of their culture about 700 years ago through **deforestation**—that is, by the clearing of all the trees—of the island. Advanced technology is not needed to damage one's immediate surroundings.

Today, however, because technological advances abound and because there are simply more people on

Earth than ever before, human influence extends to the global environment. For example, *global climate,* the prevailing weather patterns of a planet or region over time, is being altered by the addition of greenhouse gases to the atmosphere. **Greenhouse gases** are gases that warm a planet's surface by absorbing outgoing *infrared radiation*—radiant heat—and reradiating some of it back toward the surface. This process is called the **greenhouse effect.** (The analogy is not perfect, however, because the glass walls of a greenhouse keep the air warm by inhibiting heat loss by upward air motions rather than by absorbing infrared radiation.) The greenhouse effect is a natural physical process that operates in all planetary atmospheres. For example, the greenhouse effect, and not solely proximity to the Sun, is thought to account for the high surface temperature of Venus—460°C (860°F), compared with about 15°C (59°F) at Earth's surface. On Earth, some greenhouse gases (such as water vapor) are entirely natural, but others are partly or wholly anthropogenic. The most abundant anthropogenic greenhouse gas on Earth is carbon dioxide, CO_2, which is produced by the burning of **fossil fuels** (fuels such as coal, oil, and natural gas that are composed of the fossilized remains of organisms) and by deforestation. When trees are cut down, they decay, and the carbon in their trunks, branches, and leaves is released as CO_2. Carbon dioxide is also a component of volcanic emissions, and it is cycled rapidly back and forth by living plants and animals. Thus, its abundance is controlled by a combination of natural and human-controlled processes.

Humankind is also capable of damaging Earth's fragile ozone layer. The **ozone layer** is a chemically distinct region within the *stratosphere,* part of the atmosphere. The ozone layer protects Earth's surface from the Sun's harmful *ultraviolet radiation.* Ultraviolet radiation is what gives us suntans but also sunburns. **Ozone (O_3)** is a form of oxygen that is much less abundant than, and chemically unlike, the oxygen that we breathe (O_2). As we shall see, the **ozone hole** over Antarctica, a patch of extremely low ozone concentration in the ozone layer, is almost certainly anthropogenic in origin.

We are also now deforesting parts of the planet—mainly the tropics—at a rate that was not possible until the 19th century. As we cut down the forests, we kill off many species of plants and animals that live there. Hence, we are now causing substantial decreases in **biodiversity,** or the number of species present in a given area.

The effects of these global environmental problems on humans are more difficult to assess than are the effects of local air and water pollution. Depletion of the ozone layer is a worrisome prospect, but serious losses of ozone have so far been confined to the region near the South Pole, where few people live. Small decreases in ozone have been observed at midlatitudes, but these are not yet thought to pose a serious hazard to health. Loss of biodiversity in the tropics has thus far only indirectly affected people who live at temperate latitudes. Tropical deforestation and fossil fuel burning could affect everyone by causing **global warming,** a warming of Earth's atmosphere due to an anthropogenic enhancement of the greenhouse effect. Once hotly debated in scientific as well as political circles, because it was difficult to detect, global warming has by now become quite recognizable. Some of the evidence for it is described in this chapter. There is less agreement, though, as to just how urgent the problem is and what steps might be taken to address it. Because of its importance to society, we devote two chapters (Chapters 15 and 16) to examining these difficult questions.

Three Major Themes

One major theme of ours will be global environmental issues such as these. All of us should be able to make our own decisions as to which modern environmental problems are worth worrying about and which, if any, are not. Making such decisions intelligently requires at least some knowledge of the scientific questions involved. Some of the issues, global warming in particular, are also politically contentious because the actions needed to address them are potentially very costly. In such cases, it is important that both policymakers and citizens understand the problem at a reasonably detailed level.

To understand how humankind is changing the environment today, we need also to understand how the environment was changing before humans came on the scene. Otherwise, it is difficult to distinguish short-term, anthropogenic trends from longer-term, natural trends. So, a second major theme of ours is global change in the past. Climate is a good example of the overlap of short and long time scales of global change, and one to which we will return frequently. Earth's climate is predicted to warm over the next few decades to centuries as a consequence of the buildup of CO_2 and other greenhouse gases in its atmosphere. Evidence of past climates has come from cores drilled into sediments on the ocean floor. (**Sediments** are layers of unconsolidated material that is transported by water or air.) This evidence indicates that we are in the midst of a relatively short *interglacial period* (a warm interval marked by the retreat of Northern Hemisphere ice sheets) in between *glacial periods* (cold intervals marked by the buildup of these ice sheets). Hence, in the absence of anthropogenic influence, the planet would be destined over the next few thousand years to slip slowly into the next Ice Age. Which of these tendencies—global warming or the transition to a glacial period—will win out? We will argue later that warming is likely to win out in the short term, because the rate of increase of atmospheric CO_2 and other greenhouse gases is faster than the historical rate of interglacial-to-glacial climate change. Thus, the question of time scales is important. Understanding how and why climate has changed in the past can help us understand how it may change in the future.

We are introduced to these two major themes in this chapter. A third major theme of ours is *systems*—in particular, the *Earth system.* We examine this theme more

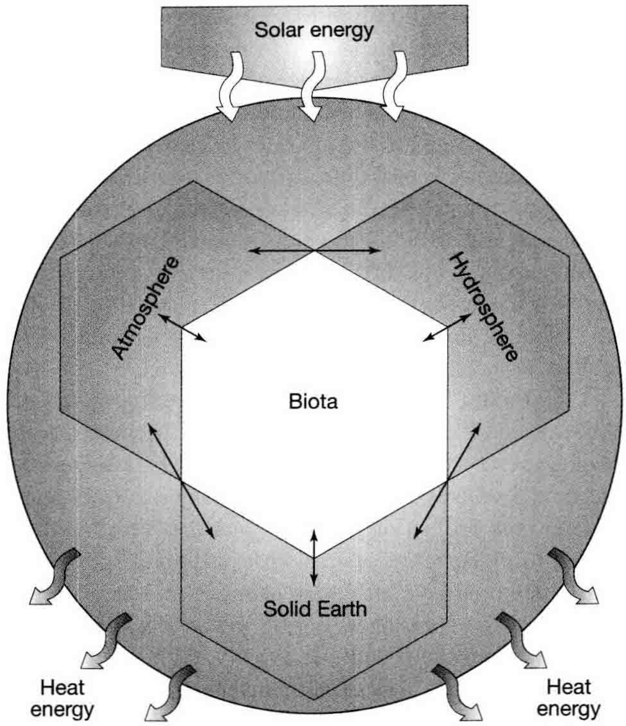


FIGURE 1-1 Schematic diagram of the Earth system, showing interactions among its four components. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography,* 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

thoroughly in Chapter 2. For now, let us say just that a **system** is a group of components that interact. The **Earth system** is composed of four parts: the atmosphere, the hydrosphere, the biota, and the solid Earth (Figure 1-1). As we have seen, the **atmosphere** is a thin envelope of gases that surrounds Earth. The **hydrosphere** is composed of the various reservoirs of water, including ice. Sometimes the ice component is separated into its own subcategory, termed the **cryosphere**. The **biota** include all living organisms. (Some ecologists define the *biosphere* as the entire region in which life exists, but we will avoid that term here, because it overlaps our other system components). The **solid Earth** includes all **rocks,** or consolidated mixtures of crystalline materials called *minerals,* and all unconsolidated rock fragments. It is divided into three parts: the core, mantle, and crust. The **core** of any planet or of the Sun is the central part. Earth's core is a dense mixture of metallic iron and nickel and is part solid, part liquid. The **mantle** is a thick, rocky layer between the core and crust that represents the largest fraction of Earth's mass. The **crust** is the thin, outer layer, which consists of light, rocky matter in contact with the atmosphere and hydrosphere.

One of our goals is to show how the different components of the Earth system interact in response to various internal and external influences, or *forcings.* A well-known example of a forcing is the variation in the amount of sunlight received in each hemisphere during the course of a year. The response to this forcing, which is governed by the interaction between the atmosphere and the hydrosphere, is the seasonal cycle of summer and winter. But there are other, more subtle forcings at work as well that may engage all four components of the Earth system. Some examples are given later in this chapter.

Chapters 3 through 8 describe the various components of the Earth system in some detail. These chapters are not particularly distinctive; many Earth science texts do much the same thing. However, this chapter and all the later chapters are devoted to problems, such as global climate history and modern global change, that cut across traditional disciplinary boundaries and that involve interactions among different parts of the Earth system. It is here that this book differs from most other introductory textbooks. The systems approach adopted in this book can lead to a more in-depth understanding of such problems by providing a convenient way of analyzing complex interactions and predicting their overall effect.

GLOBAL CHANGE ON SHORT TIME SCALES

We start our discussion of the Earth system by introducing three major, global environmental changes that are occurring today: global warming, ozone depletion, and tropical deforestation. Afterward, we will backtrack to discuss how the Earth system operated in the past and how that may help us predict what will happen to it in the future.

Evidence of Global Warming

The most pervasive, and at the same time controversial, environmental change that is occurring today is global warming. This issue is extremely complex because it involves many different parts of the Earth system. It is controversial because it is difficult to separate anthropogenic influences from natural ones and because its causes are deeply rooted in our global industrial infrastructure; hence, these causes would be difficult to eliminate. A major goal of this book, therefore, is to help the reader understand global warming and to put it in the context of past climatic change.

Although the terms "greenhouse effect" and "global warming" are sometimes used interchangeably, the two phenomena are very different. The greenhouse effect is an indisputably real, natural process that keeps the surfaces of Earth and the other terrestrial planets warmer than they would be in the absence of an atmosphere. Global warming is an increase in Earth's surface temperature brought about by a combination of industrial and agricultural activities. These activities release gases that bolster the greenhouse effect. To be fair, not all scientists are convinced that global warming has begun. Almost all researchers agree that the climate has warmed over the past century, but not all of them are convinced that this warming is a result of human activities. However, the number of global warming skeptics has dwindled over the past several years. An important milestone was reached in 2007 when the influential

Intergovernmental Panel on Climate Change (IPCC) released a new report—its fourth since 1990. Using language much stronger than in previous versions, the new report says: "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level." The importance attached to this conclusion was underscored when the Nobel Foundation awarded its 2007 Peace Prize jointly to the IPCC and to former U.S. vice president Al Gore, who has vigorously promoted understanding of this issue around the globe. We concur with the IPCC findings, and we base much of our discussion of global warming on its report.

MEASUREMENTS OF ATMOSPHERIC CO_2: THE KEELING CURVE The data that have aroused much of the current concern about global warming are shown in Figure 1-2. The graph shows the atmospheric CO_2 concentrations measured at the top of Mauna Loa, a 4300-m-high volcano in Hawaii, over the last 50 years. Mauna Loa was chosen as the measurement site because the air blowing over its summit—clean air from the western Pacific Ocean—is far removed from local sources of pollution. The measurements were begun in 1958 by Charles David Keeling of the Scripps Institute of Oceanography. For this reason, the data are often referred to as the "Keeling curve." Dr. Keeling passed away in 2005, just 3 years prior to the time of this writing. His name is honored by environmentalists everywhere because his straightforward, but precise, measurements begun half a century ago are still the most powerful evidence that our atmosphere and climate are changing.

In Figure 1-2 the concentration of atmospheric gas is measured in *parts per million,* or *ppm.* A value of 1 ppm of a particular gas means that one molecule of that gas is present in every million air molecules. We shall use the abbreviation "ppm" to represent parts per million *by volume* rather than parts per million *by mass.* (In technical literature, "ppmv" is often used for parts per million by volume.) Units of mass and volume are not interchangeable, because a given gas molecule may be heavier or lighter than an average air molecule. Although one part per million may not sound like much, it represents a large number of molecules. A cubic centimeter of air at Earth's surface contains about 2.7×10^{19} molecules, so a 1-ppm concentration of a gas would have 2.7×10^{13} molecules in that same small volume. (If you are not familiar with scientific notation, refer to Appendix I for help.)

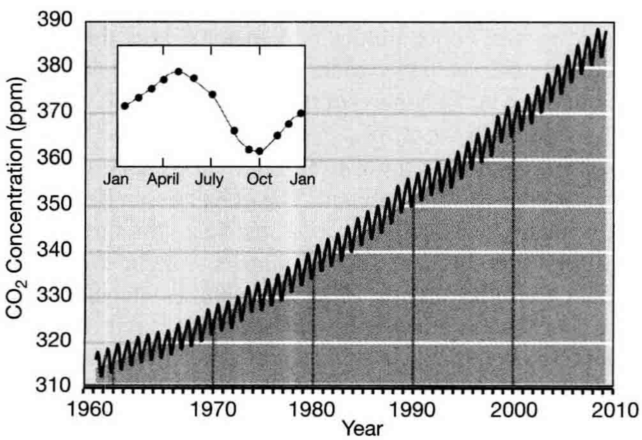


FIGURE 1-2 Measurements of atmospheric CO_2 concentrations at the top of Mauna Loa in Hawaii. These data are known as the "Keeling curve." (*Source:* C. D. Keeling and T. P. Wharf, Scripps Institute of Oceanography, La Jolla, California, http://scrippsCO2.ucsd.edu.)

As Figure 1-2 shows, the CO_2 concentration in late 2007 was about 384 ppm. We say "about" because the atmospheric CO_2 concentration varies slightly from place to place and oscillates seasonally over a range of 5 to 6 ppm. This seasonal oscillation has to do with the "breathing" of Northern Hemisphere forests. Forests take in CO_2 from the atmosphere (and give off O_2) in summer, and they release CO_2 back to the atmosphere during winter. Hawaii is in the Northern Hemisphere (latitude 19° N) and hence is influenced by this cycle. The cycle is reversed in the Southern Hemisphere, but the amount of land area is much smaller, so the magnitude of the CO_2 change is reduced.

Keeling's data show, in addition to this seasonal oscillation, that atmospheric CO_2 levels have increased significantly since 1958. The mean CO_2 concentration that year was about 315 ppm, or 71 ppm lower than the average 2008 value. The average rate of increase in CO_2 concentration since then has been 71 ppm/50 yr, or about 1.4 ppm/yr. More-detailed inspection of the curve reveals that the rate of CO_2 increase rose from 0.7 ppm/yr in the early 1960s to 1.9 ppm/yr over the last decade. Most of the increase in atmospheric CO_2 has been caused by the combustion of coal, oil, and natural gas, but tropical deforestation is also partly to blame.

The evidence that atmospheric CO_2 is increasing is indisputable. Similar measurements have been conducted at many different stations around the globe. The long-term increase in CO_2 is visible in every set of measurements and is essentially the same as that seen at Mauna Loa. (The range of the seasonal fluctuations, however, varies with the location.) For this reason, both scientists and policymakers agree that the long-term trend in atmospheric CO_2 is real rather than an artifact.

CO_2 Data from ICE Cores When did this increase in atmospheric CO_2 begin, and what was the CO_2 level before that time? If we had to rely entirely on measurements made in the modern era, we would not be able to answer these questions. This is where analysis of the record of climate in the past can help. The composition of the atmosphere in the past can be determined by analyzing the composition of air bubbles trapped in polar ice. The bubbles are formed as snow at the top of an ice sheet is compacted, and their composition is preserved as they are buried under more snow. The age of the ice can be determined by drilling deep into the ice, removing a section of it, and counting the annual layers of snow accumulation. Figure 1-3 shows results from ice cores—cylindrical sections drilled into the ice—taken at several locations on Antarctica. Figure 1-3a compares the CO_2 composition of the air bubbles in the ice with a "smoothed" version of the Keeling curve (the dashed curve, from which the seasonal oscillation has been removed). The fact that the ice-core measurements match up well with the direct atmospheric measurements in 1958 is convincing evidence that the ice-core technique for determining atmospheric CO_2 concentrations yields reliable results.

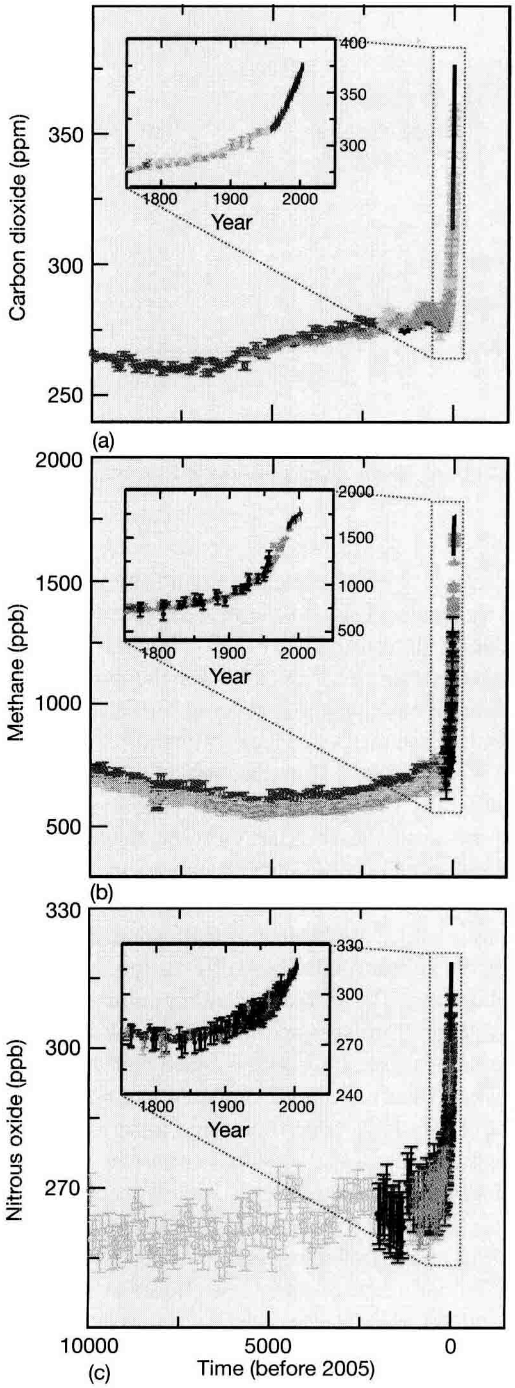


FIGURE 1-3 Atmospheric CO_2 concentrations over the past 1000 years, as determined from ice cores and from direct atmospheric measurements (The dashed line is the Keeling curve.) (*Source: After Climate Change, 1994,* Intergovernmental Panel on Climate Change, Cambridge: Cambridge University Press.)

According to these measurements, the buildup of atmospheric CO_2 began early in the 19th century—well before the dawn of the Industrial Age, which started in earnest around 1850. The rise in CO_2 levels between 1800 and 1850 has been attributed to the deforestation of North America by westward-expanding settlers and is thus known as the *pioneer effect.* The ice-core measurements show that the *preindustrial CO_2 concentration* (the value circa 1800) was about 280 ppm. Evidently, humans have been responsible for almost a 40% increase in atmospheric CO_2 concentration over the past two centuries.

OTHER GREENHOUSE GASES Carbon dioxide is not the only greenhouse gas whose concentration is currently on the rise. Methane (CH_4) and nitrous oxide (N_2O) have also been increasing as a result of human activities, primarily agriculture. Their concentrations have also been measured in ice cores (Figures 1-3b and 1-3c), along with CO_2. The methane concentration has more than doubled from a preindustrial concentration of about 700 ppb (parts per billion) to approximately 1800 ppb (or 1.8 ppm) today. Nitrous oxide has been less strongly influenced by human activities because it has large natural sources. Certain **chlorofluorocarbon** compounds **(CFCs)** are also produced by human activities. Also called *freons,* CFCs are synthetic compounds containing chlorine, fluorine, and carbon. Collectively, such gases that are present in the atmosphere in very low concentrations, called **trace gases,** are thought to have contributed almost as much additional greenhouse effect over the past few decades as has CO_2. (Because CO_2 is much less abundant than N_2 or O_2 it is also classified as a trace gas, but it is more than 200 times as plentiful as any of the other gases mentioned here and hence deserves to be in a class by itself.) The CFCs have also been implicated in the destruction of stratospheric ozone, as we discuss later in this chapter. For now, we simply note that the evidence for an increase in anthropogenic greenhouse gases is unequivocal: Humans are indeed modifying the composition of Earth's atmosphere. This has been recognized for at least 40 years.

OBSERVED CHANGES IN SURFACE TEMPERATURE The observed rise in greenhouse gases is quite well documented, but what about the effects of this rise? Is there any direct evidence that climate is changing as a result?

The answer to this question is yes, according to the IPCC, but agreement on this answer has been reached only within the last few years, and as noted previously, a few scientists still remain skeptical. Historical data indicate