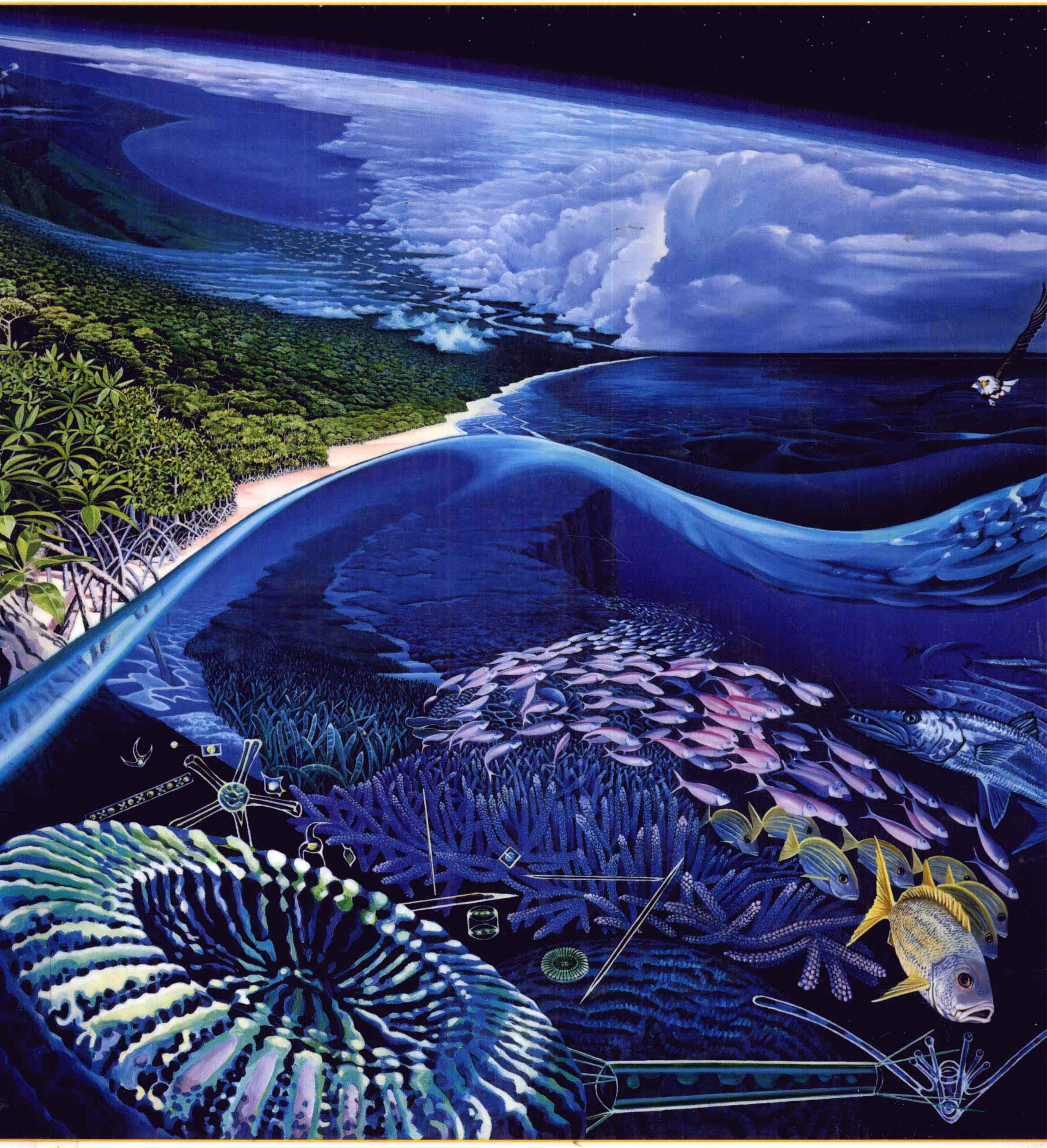
THE EARTH SYSTEM



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The Earth System

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Preface

Nearly 12 years ago, we were asked to develop an introductory course for nonscience majors that embraced the concepts and subject matter of the nascent field of Earth system science. The task was daunting, especially because there was no text available for such a class and, moreover, there was no conceptual framework available to assist us in the design of such a class. We began to offer our class in the late 1980s. From the multitude of concepts and facts taught in traditional Earth science and life science courses, we spent a couple of challenging years identifying the concepts that were essential for a basic understanding of Earth as a system. It took us several years, but we now feel that we have distilled the essence of Earth system science and captured it in the material presented in this book. We use a top-down approach to the natural sciences: The details of geology, climatology, oceanography, and ecology are foregone in favor of unifying principles applied at the global scale.

Over these years we have seen enrollment in our class "Gaia—The Earth System" grow to nearly 1000 students a year. Students are attracted to the class because we cover the important problems involved in global change, including the greenhouse effect, ozone depletion, and loss of biodiversity. The systems approach tends to resonate with many students, and they find that it is used in other courses, both in the physical and social sciences.

We have been encouraged by national and international efforts to develop curricula in Earth system science. We hope that this text will serve the needs of those involved in such efforts. Most of all, we are excited to see faculty who are known internationally for their research accomplishments drawn back to the nonmajors undergraduate classroom by the challenge and appeal of teaching global change and Earth system science.

Organization

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. 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 next six chapters 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. Chapter 2 uses James Lovelock's Daisyworld to introduce important concepts from systems theory that help explain this regulation. In Chapter 3, the greenhouse effect, the most familiar regulatory process, is shown to be an essential part of Earth's natural climate system—a process that is intensified by, rather than the result of, human disturbance. Chapters 4 through 6 explain the connections between the atmosphere, oceans, and crust that cause heat, moisture, and materials to be distributed and recycled and that control global biogeochemical cycles. These cycles are in turn the subject of Chapter 7 (with a focus on the carbon cycle).

In Chapters 8 through 12 we explore the history of Earth for lessons that we can apply to the present and to the future. We discuss the causes of environmental change, especially climate change, that act on a variety of time scales. The evolution of the climate system over billions of years is the subject of Chapter 8. On this time scale, increasing luminosity of the Sun, changes in volcanic activity, the drift of the continents, and the making of mountains are primary factors influencing climate. Chapter 9 discusses the origin of life, early Earth environments, and perhaps the most significant environmental change of Earth history—the establishment of an oxygen-rich atmosphere. Changes in Earth's biota are the focus of Chapter 10. There we find that the diversity of life has, in general, increased over geologic time, but this increase has been punctuated by a number of catastrophic losses of biodiversity. Focusing in toward the present, Chapter 11 describes the climate of the last 2 million years, during which Earth has oscillated in and out of glaciation. On these time scales, climate change is driven by changes in Earth's orbit around the Sun. However, on these and longer time scales, changes in the amount of atmospheric carbon dioxide are also important. The more recent history of Earth's climate, discussed in Chapter 12, reveals smaller climate fluctuations, some of which seem to be driven by oscillations internal to the Earth system (for example, the phenomenon of El Niño).

The last four chapters draw on knowledge gained from previous sections to provide a unique perspective on current and future global change issues. Predictions of future climates, presented in Chapter 13, are based on the understanding of the climate system and carbon cycle developed in earlier chapters. In Chapter 14, ozone depletion is shown to be a serious problem, but one for which international cooperation appears to be heading toward a solution. In contrast, the loss of biodiversity, covered in Chapter 15, remains a poorly understood problem, far from resolution and with unclear but undoubtedly serious implications for the vitality of our planet. In Chapter 16 we use what we have learned about the Earth system in the past and in the present to speculate on what might happen to it in the distant future and to try to estimate the chances that other Earthlike planets and technological civilizations exist elsewhere in our galaxy.

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. *Suggested Readings* include both general readings and advanced readings for students (and instructors) interested in further information about the subject matter. 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 Questions* are thought questions or analytical exercises that require students to synthesize concepts presented in the chapter.

Many nonscience majors become uncomfortable when equations and chemical formulas appear in textbooks for introductory or general-education courses. However, cogent discussion of global change issues requires some quantification. For example, we need to understand the energy and carbon budgets before we can assess the impact of fossil fuel burning on future climates. Similarly, the issue of ozone depletion cannot be understood without at least a little knowledge of chemistry. Our experience has been that the effort that goes into mastering a challenging equation, such as the planetary energy-balance equation (Chapter 3), is more than compensated for by the satisfaction that comes from making the same sort of climate prediction that scientists such as Carl Sagan have made in the past.

Chapter Sequencing

We anticipate that this book will be used in a variety of ways. We teach a general education class at The Pennsylvania State University that covers approximately three-quarters of the book (12 or 13 chapters) during one semester. Several instructors teach this course, but not all of us choose to cover the same chapters. All instructors normally do go through the first seven chapters in order, but after that we pick and choose according to our own interests and needs. An instructor who is most interested in climate issues, for example, might use Chapters 8, 11, 12, 13, and 16. One who is most interested in biodiversity might choose Chapters 8, 9, 10, 11, and 13. The course can also be tailored to emphasize either Earth history (Chapters 8 through 12) or modern global environmental problems (Chapters 13 through 15). 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

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Over the years, our students have provided verbal and written comments on various drafts of the manuscript, and we have valued their input. The book also benefited from careful reviews by a number of our colleagues, including the following:

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They were a tough group to satisfy, but their input, from a wide variety of perspectives, was invaluable in defining the content and style of the book.

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The Pennsylvania State University

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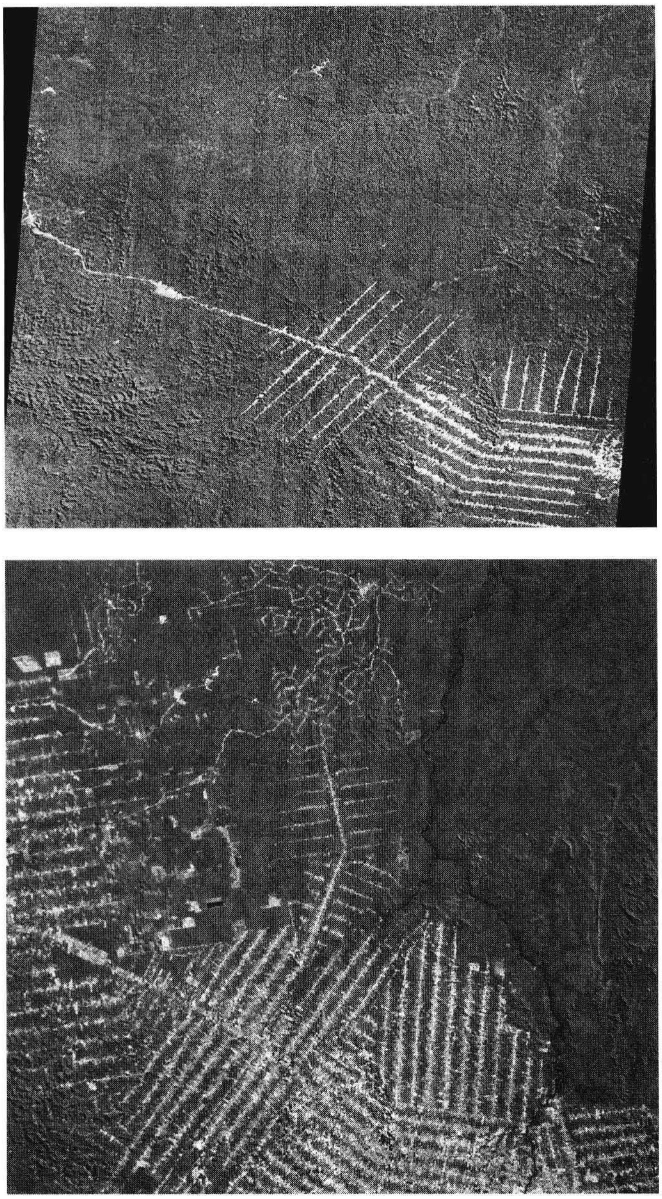
Chapter 1
Global Change



Satellite photos of Amazonia in 1972 and 1992. (Top: From Earth Satellite Corporation/Science Photo Library, Photo Researchers, Inc. Bottom: From NASA/Science Photo Library, Photo Researchers, Inc.)

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 is expected to warm Earth's climate in the future—and may have done so already. The accumulation of chlorine-containing compounds in the atmosphere has damaged the ozone layer over part of the globe. Deforestation of the tropics is causing large decreases in biodiversity. How serious are these problems, and how do they compare with past changes in the Earth system? Chapter 1 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, compared with about 15°C at Earth's surface. On Earth, some greenhouse gases (such as water vapor) are natural, but others are 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 believed to be anthropogenic in origin.

We are also now deforesting parts of the planet—mainly the tropics—at a rate that was unimaginable 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. However, some people (those living in Alaska or Siberia, for instance) might see global warming as less of a threat than would others. How can we decide which global environmental problems are truly urgent and which may simply deserve careful, long-term study?

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 scientific questions surrounding them are not entirely answered and 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 disrupting 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 will be introduced to these two major themes in this chapter. A third major theme of ours is *systems*—in particular, the *Earth system.* We will examine this theme more 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. 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 comprises 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 var-

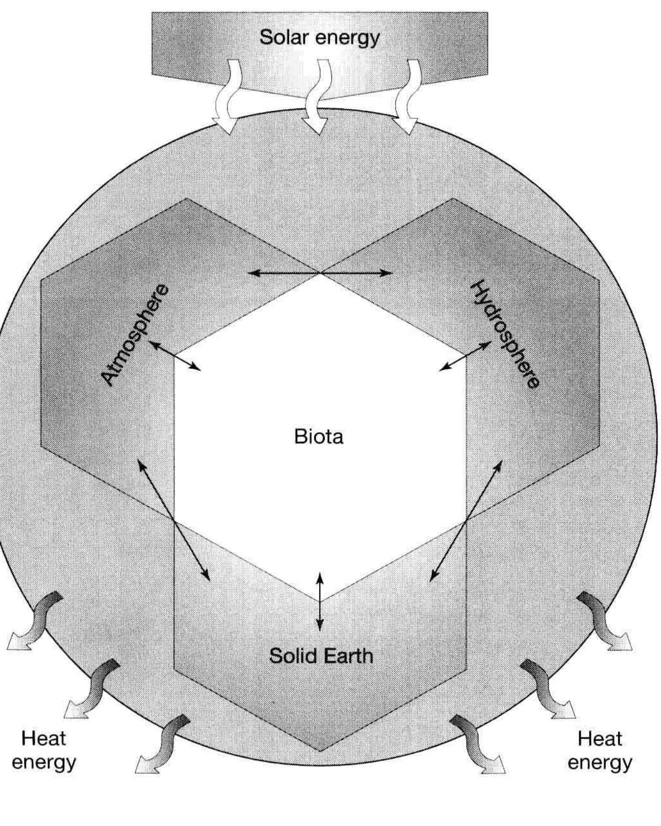


FIGURE 1-1

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

ious 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 7 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, Chapter 1 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 here 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 will 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. At present, not all scientists are convinced that global warming has begun. Most researchers agree that the climate has warmed over the past century, but not all of them believe that this warming is a result of human activities. Let us now see why many researchers do believe that humans are altering Earth's climate and why even more researchers believe that we will do so in the future.

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 a 40-year interval. 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

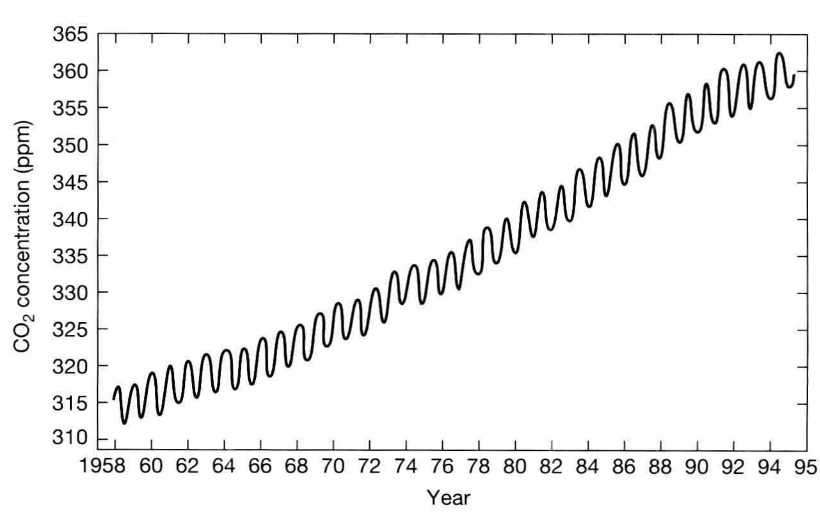


FIGURE 1-2

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://cdiac.esd.ornl.gov/ftp/maunaloa-c02/maunaloa.c02)) 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."

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.)

As Figure 1-2 shows, the CO_2 concentration in 1995 was about 358 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 43 ppm lower than today's value. The average rate of increase in CO_2 concentration since then has been 43 ppm/37 yr, or about 1.2 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 1.5 ppm/yr in the late 1980s but then dropped to less than 1 ppm/yr in the early 1990s. Scientists believe that most of the increase in atmospheric CO_2 has been caused by the combustion of coal, oil, and natural gas but that 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. This graph 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.

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 30% 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), nitrous oxide (N_2O), and certain **chlorofluorocarbon** compounds **(CFCs)** have also been increasing as a result of 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 shall 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. The extent to which we should be concerned about it remains to be determined.

Observed Changes in Surface Temperature. The observed rise in greenhouse gases is quite well documented,

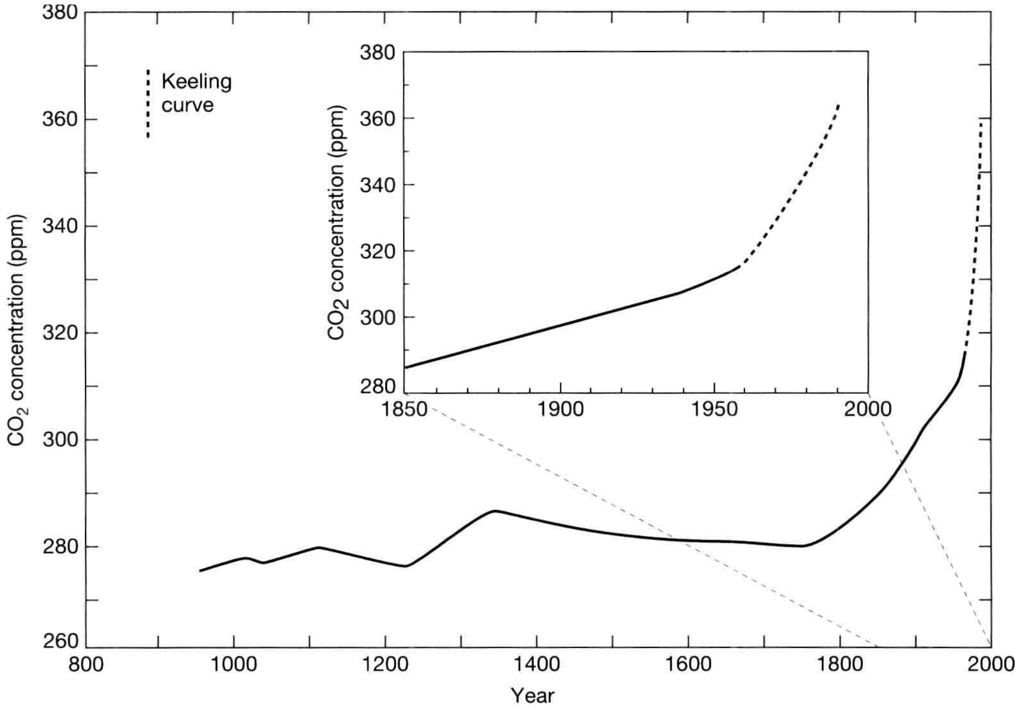


FIGURE 1-3

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.) (After *Climate Change, 1994,* Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge)

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 and no. Historical data indicate that Earth's surface temperature is on the increase. The data are not as easy to interpret as are the greenhouse gas data discussed earlier, but they are considered to be reliable. At a number of stations around the world, scientists have made accurate atmospheric temperature measurements that date back more than a century. Ocean-crossing ships have also routinely measured sea-surface temperatures during most of this time. Figure 1-4 illustrates the combined data from both types of historical measurements for the entire globe. The mean surface temperature from 1951 to 1980 has been subtracted from the data. The global mean surface temperature has increased from about 0.3°C below this mean value prior to 1900 to about 0.2°C above this mean value today. The overall temperature increase during the 20th century was thus approximately 0.5°C (or 0.9°F). This increase is broadly consistent with the warming expected from a 30% rise in atmospheric CO_2, although some climate models predict that the surface temperature should have increased about twice that much.

Problems do exist with these historical temperature data. For example, weather stations located near cities are subject to a well-documented "heat island" effect: As a city grows and as more area becomes covered with dark surfaces such as asphalt, more sunlight is absorbed and the local air temperature can increase by as much as 3°C. This systematic error has been removed from the

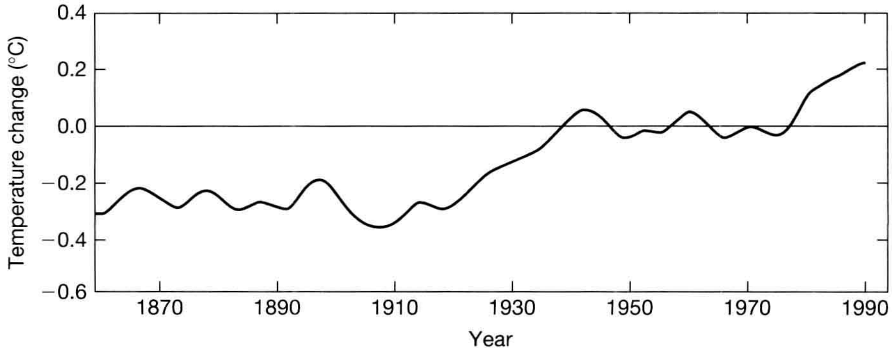


FIGURE 1-4

Change in global average surface temperature since 1861. The data are expressed as deviations from the 1951 to 1980 mean value. (After *Climate Change: The IPCC Scientific Assessment,* J.T. Houghton et al., eds., Cambridge Univ. Press, Cambridge, 1990) data shown in Figure 1-4, but it is still a source of uncertainty, because it is difficult to remove accurately. (*Systematic* errors exhibit a regular pattern. *Random* errors do not follow any pattern.) Sea-surface temperature measurements are also subject to systematic errors. Prior to the mid-1900s, water temperatures were determined by the "bucket method." A crewmember dropped a bucket over the side of the ship, then hauled it back up and measured its temperature with a thermometer. Since then, water temperatures have generally been measured with flow-through devices located on the ship's hull. The two methods do not yield exactly the same results, because the samples may be taken at different water depths and because buckets can warm or cool as they are being examined. Furthermore, the current procedure draws water up through the ship (normally near the engines) and can heat it up. These effects, too, can be corrected for, but not without creating additional uncertainties.

A second problem with the temperature data is that the coverage in time and space is much better in some parts of the world than in others. Populated areas of Europe and North America have been monitored most closely and for the longest time, so the coverage is best in these regions. Most land areas in the Southern Hemisphere have shorter and less-consistent temperature records. And the coverage over some regions of the ocean, particularly remote parts of the Southern Ocean where few ships travel regularly, is sparse indeed. Because sea-surface temperatures can now be monitored from satellites, the oceanic database should improve in the future. But it may well require several decades of such measurements to establish reliable trends.

Despite such difficulties, climatologists who collect and analyze these surface temperature data are confident that the observed half-degree warming trend over the past century is real. This does not mean, though, that it has been caused by human activities. Evidence shows that the climate was unusually cool between about 1500 and 1850. This period has been termed the "Little Ice Age." At least part of the warming since that time may represent a recovery from that naturally cool period rather than warming produced by anthropogenic greenhouse gases. This is another illustration of why it is necessary to understand the past if we want to predict the future.

An additional puzzle in the data shown in Figure 1-4 is that the warming trend seemed to slow, or stop entirely, between about 1940 and 1970. In the Northern Hemisphere, temperatures actually declined by a few tenths of a degree during this period (Figure 1-5). The decrease over Northern Hemisphere land areas is so pronounced that, by 1970, some climatologists were concerned that Earth might be entering a new glacial period. This worry was heightened by the historical data mentioned earlier that indicated that the present interglacial period might be nearing its end.

One possible explanation for the 1940 to 1970 cooling trend is that it was caused by increased reflection (and thus decreased absorption) of sunlight by *sulfate aerosol particles.* These tiny airborne particles are formed from sulfur dioxide (SO_2) emitted by the burning of coal. Most of the coal burning has taken place in the Northern Hemisphere, so this hypothesis could also explain why that hemisphere cooled more than did the Southern Hemisphere (see Fig. 1-5). Recent climate model simulations show that the magnitude of the aerosol effect is sufficient to account for the observed trend. But coal burning also releases CO_2 and hence should contribute to global warming—just the opposite of the observed effect during this 30-year period. This situation is a good example of why it is necessary to understand the whole Earth system in some detail if we are to interpret properly the changes that are occurring.

We cannot assume, however, that even though coal burning may have cooled Earth from 1940 to 1970, it will continue to do so in the future. In the United States, SO_2 is now being removed, or "scrubbed," from smokestack emissions in order to reduce its contribution to acid rain. **Acid rain** is produced when various acids, including sulfuric acid formed from the oxidation of SO_2, dissolve in rainwater. Acid rain can kill fish and damage plants in regions downwind from strong sources of pollution. It has been a problem in parts of the northeastern United States and in eastern Canada because there are many coal-fired

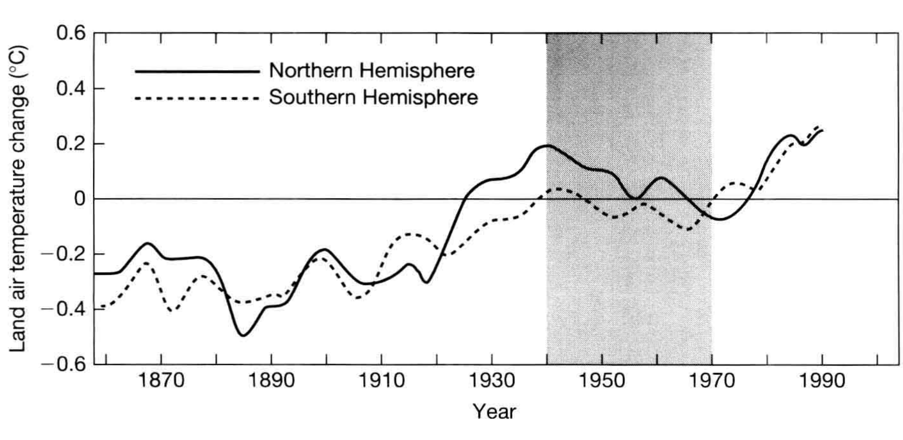


FIGURE 1-5

Change in temperature recorded over land surfaces in the Northern and Southern Hemispheres since 1861. (After *Climate Change: The IPCC Scientific Assessment,* J.T. Houghton et al., eds., Cambridge Univ. Press, Cambridge, 1990.)

power plants along and northward of the Ohio River valley. Other parts of the world, notably Europe, have problems with acid rain as well. Paradoxically, cleaning up smokestack emissions to cut down on acid rain may exacerbate the problem of global warming by reducing sulfate aerosol concentrations in the atmosphere.

Even if we were to quit scrubbing SO_2 out of smokestack gases, the ultimate effect of coal burning would be to warm Earth's atmosphere. Sulfate aerosols are removed from the lower atmosphere by precipitation in a matter of weeks, whereas CO_2 lingers in the atmosphere for decades to centuries. Thus, the CO_2 effect on climate is cumulative, whereas the aerosol effect is not. This example points out the importance of being aware of the time scale on which a global change occurs.

Possible Consequences of Global Warming. Although there is still a great deal of debate about whether humans have already altered the global climate, most climatologists agree that we will do so in the future if we continue to consume large amounts of fossil fuel. Should this be a cause for concern? In terms of the change in mean global temperature, we might expect people living in hot places such as India to be worried whereas those living in Siberia would look forward to the change. But the problem is not quite so simple: A change in temperature might cause other changes as well. A rise in sea level is one frequently mentioned concern. Sea level has already risen by at least 10 cm over the past century. The likely cause is *thermal expansion* of a gradually warming ocean; like most forms of matter, water expands when it is heated (except between 0 and 4°C when, paradoxically, it contracts). But warmer temperatures could also induce melting of mountain glaciers and ice caps. Increases in sea level on the order of several meters are possible within the next few centuries, and even larger changes are possible in the very long term. Such changes could have serious consequences for people in coastal areas and would be catastrophic for those in small island states. Other climatic changes may also have a broad-scale impact on agriculture, including decreases in soil moisture in certain areas and the spread of tropical insect pests. We will return to these possible side effects of global warming later; for now, note simply that the issues are complex and that there are very few simple answers. We also note that this is another reason to study past climate: Earth has been significantly warmer at various times in its past, and we may learn something about what it could be like in the future by examining those past time periods.

Evidence of Ozone Depletion

Global warming is not the only global environmental problem that has caught the attention of the public. Since at least 1985, the potential depletion of stratospheric ozone has also been in the news. (Stratospheric ozone should not be confused with *tropospheric* ozone—ozone near ground level—which is also often in the news because it is a component of *smog.*) The **stratosphere,** where most of Earth's ozone is located, is a layer of the atmosphere that extends from about 10 to 50 km in altitude. Stratospheric ozone is important to living organisms, because it absorbs many of the Sun's harmful ultraviolet rays. Ultraviolet radiation causes skin cancer and other health problems in humans. It adversely affects other organisms as well—notably, microscopic algae that are the base of the food chain in aquatic environments.

The year 1985 was a key one in stratospheric ozone research, because it marked the discovery of the ozone hole above Antarctica. Each year since about 1976, stratospheric ozone levels near the South Pole have fallen by large amounts during October, which is springtime in the Southern Hemisphere. Figure 1-6 shows year-to-year variations of the mean ozone *column depth* above Halley Bay in Antarctica for Octobers between 1957 and 1991. The ozone column depth is the total amount of ozone per unit area above a certain location. The decrease in ozone near the South Pole during October is striking: Ozone levels during October dropped by about half between 1975 and 1991. During the rest of the year, ozone levels have remained close to normal in this region. What has been destroying half the ozone over Antarctica during one particular month?

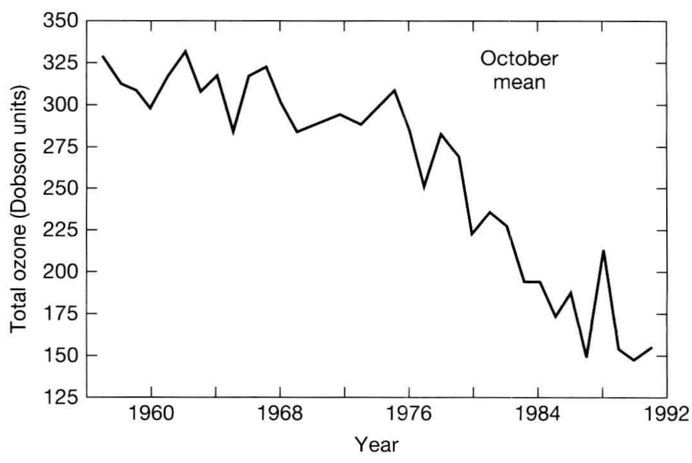


FIGURE 1-6
Mean total ozone over Antarctica during the month of October. The units, called *Dobson units,* measure the gas per unit area between Earth's surface and the top of the atmosphere (a measurement known as the *column depth*). One Dobson unit (DU) is equivalent to a 0.001-cm-thick layer of pure ozone at the surface. (After *Scientific Assessment of Ozone Depletion: 1994,* World Meteorological Organization, 1994.)