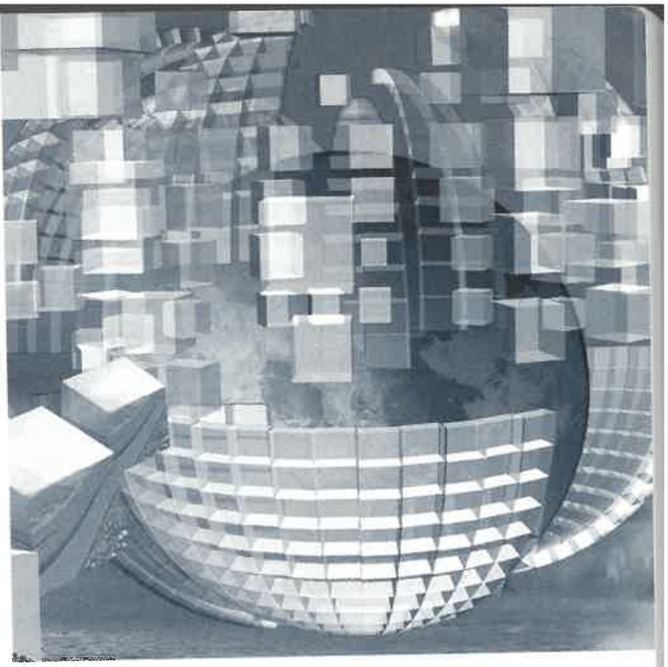
CHAPTER 1

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

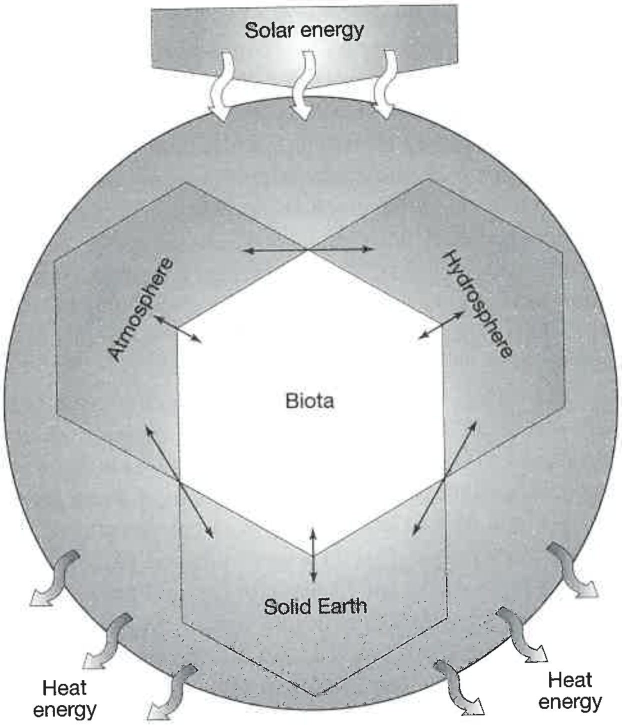


FIGURE 1-1 Schematic diagram of the Earth system, showing interactions among its four components. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography,* 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

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.)

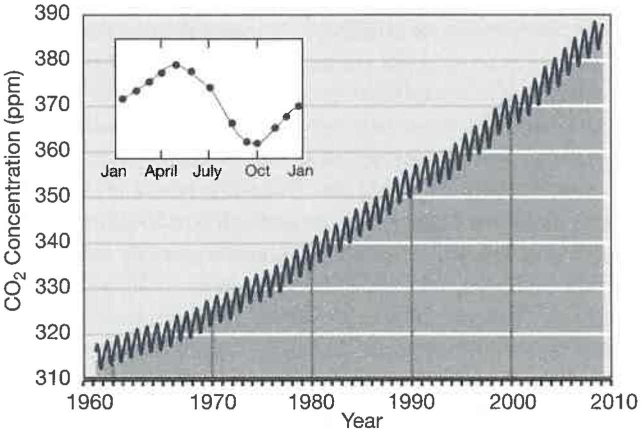


FIGURE 1-2 Measurements of atmospheric CO_2 concentrations at the top of Mauna Loa in Hawaii. These data are known as the "Keeling curve." (*Source:* C. D. Keeling and T. P. Wharf, Scripps Institute of Oceanography, La Jolla, California, http://scrippsCO2.ucsd.edu.)

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.

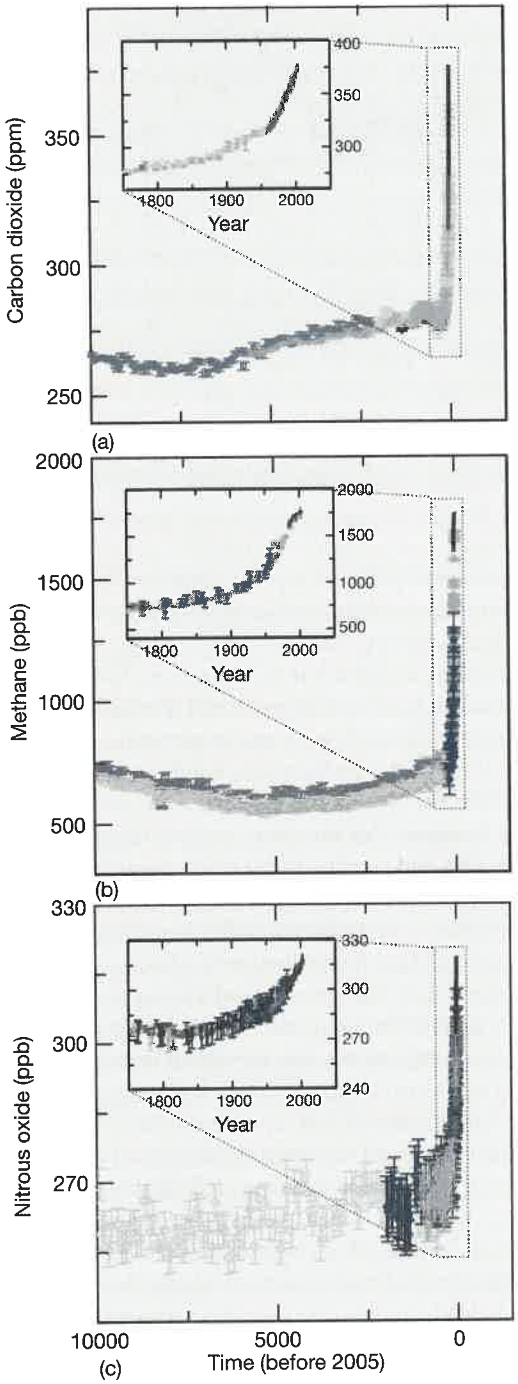


FIGURE 1-3 Atmospheric CO_2 concentrations over the past 1000 years, as determined from ice cores and from direct atmospheric measurements (The dashed line is the Keeling curve.) (*Source: After Climate Change, 1994,* Intergovernmental Panel on Climate Change, Cambridge: Cambridge University Press.)

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

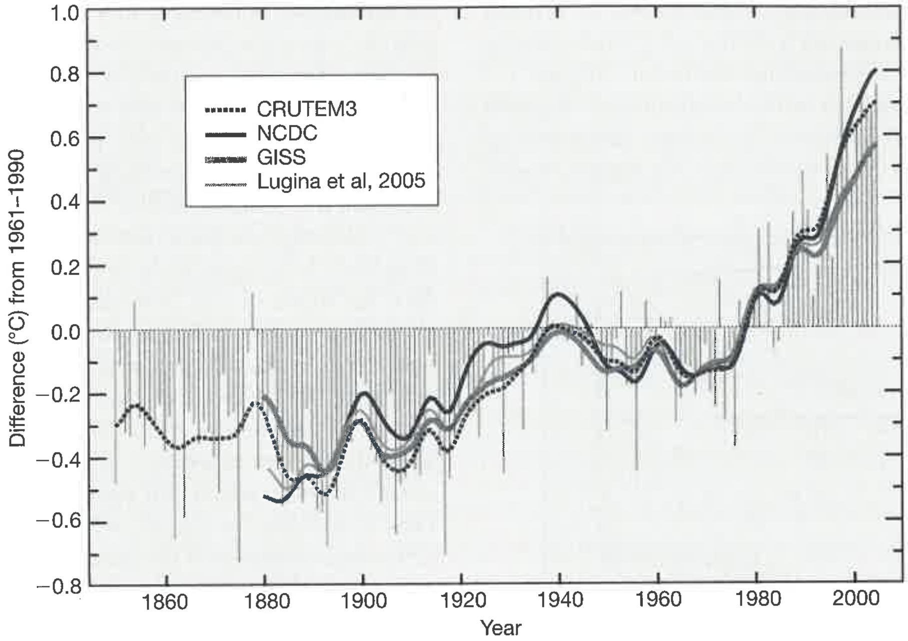


FIGURE 1-4 Change in global average surface temperature since 1861. The data are expressed as deviations from the 1961 to 1990 mean value. (*Source:* IPCC, *Climate Change 2007,* Fourth Assessment Report, Cambridge: Cambridge University Press, 2007, Chapter 3, p. 241, http://www.ipcc.ch/ipccreports/ar4-wg1.htm.)

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 1961 to 1990 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 0.5°C above this mean value today. The overall temperature increase during the 20th century was thus approximately 0.8°C (1.4°F). This increase is broadly consistent with the warming expected from a 40% rise in atmospheric CO_2. However, comparing Figure 1-4 with Figure 1-3, one can see that the surface temperature does *not* increase as uniformly or at the same rate as does atmospheric CO_2. Evidently, the climate is influenced by other factors as well. 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 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 0.8-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. 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. 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 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.

CHANGES IN THE CRYOSPHERE So far, we have focused on global average temperatures, and we have seen that they have been gradually increasing. In some parts of the globe, however, especially regions near the North Pole, the temperature appears to have been increasing much more rapidly. In central Alaska, for example, the warming over the past century has been close to 3°C, or almost four times the global average value. And this warming near the North Pole appears to be having dramatic effects on the amount of sea ice in the Arctic Ocean. Figure 1-5 shows a comparison between the minimum sea ice extent in 2005 and 2007 and that back in 1979. The images, which are actually a composite of microwave images from orbiting satellites, were taken in late September when the ice pack typically reaches its minimum size. As one can see, the ice pack in 2005 was appreciably smaller—roughly 5.3 million km^2, as compared to 7.8 million km^2 in the earlier image. So, the sea ice minimum decreased by an astounding 30% in just 26 years! And the 2007 sea ice minimum was even smaller: 4.2 million km^2, or 20% less than the 2005 value!

Based on this observed rapid decrease in sea ice, some researchers have speculated that the Arctic Ocean could be entirely ice-free in late summer by the year 2012. Already, the fabled Northwest Passage—the long-sought-after sea route between the Atlantic and Pacific oceans—is open for a few weeks each year. That in itself is a mixed blessing. It could facilitate oceangoing trade between Europe and the Far East (and the American West Coast). But it is bad news for polar bears and perhaps also for the Inuit Indians of northern Alaska and Canada who earn their subsistence from the existing polar ecosystem.

More disturbingly, large increases in north polar temperatures could potentially lead to increased melting of the Greenland ice sheet, and this, in turn, could raise sea level. The disappearance of Arctic sea ice does not affect sea level because the amount of seawater tied up as ice is precisely compensated by the downward pressure that the floating ice exerts on the ocean. (This is an application of Archimedes' principle, which states that a body immersed in a fluid is buoyed up by a force equal to the weight of the displaced fluid.) One can test this principle by placing several ice cubes in a glass and then filling it to the rim with water. As the ice cubes melt, the glass does not overflow, even though parts of the floating cubes were initially above the rim. Similarly, as Arctic sea ice melts, sea level remains the same. But the Greenland ice cap is supported by land, not by water, and so any meltwater from Greenland (or Antarctica) contributes directly to sea level rise. If the entire Greenland ice cap were to disappear, sea level would increase by approximately 6 meters, or 20 feet, and the effects

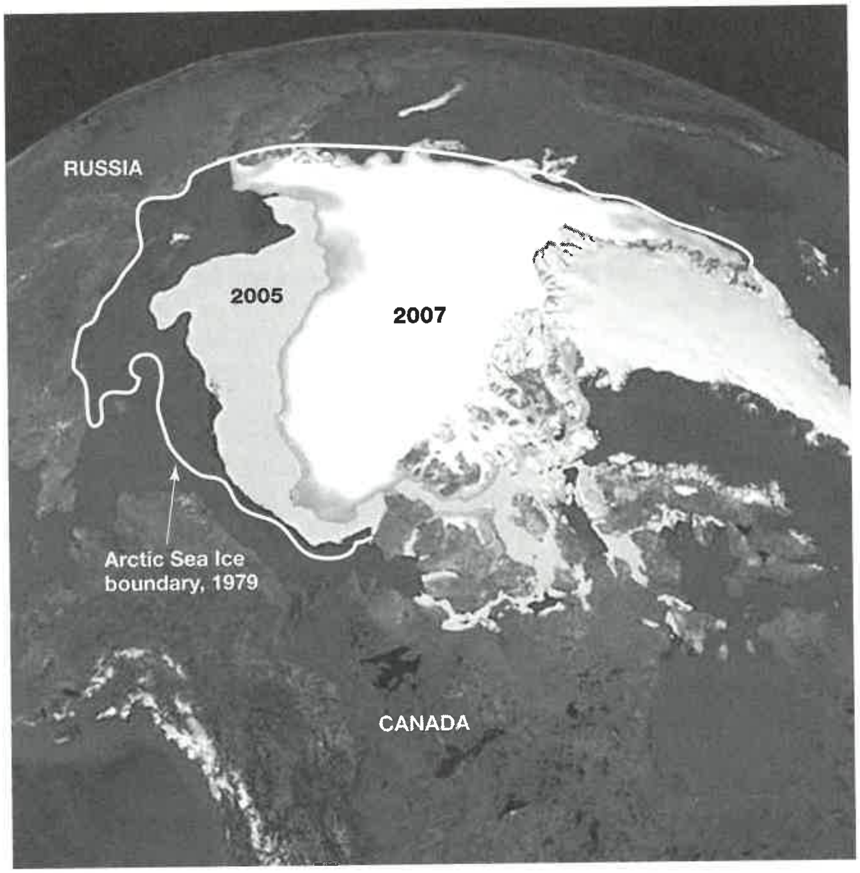


FIGURE 1-5 Arctic sea ice minimum extent in 1979, 2005, and 2007 as measured from orbit by the Special Sensor Microwave Imager (SSMI). The pictures are electronically processed composites of images obtained in late September when the Arctic ice pack is at its smallest extent. (*Source:* NASA/Goddard Space Center.)

on continental coastlines would be catastrophic. Fortunately, land ice is much thicker than sea ice, and so the rate at which the Greenland ice sheet might vanish should be much slower than that of Arctic sea ice—probably hundreds to thousands of years, as opposed to decades. But the physics of ice sheets is complex, and there are some indications that melting of the Greenland ice sheet is happening faster than expected. We shall return to this issue in Chapter 16, as it is a major cause for concern among glaciologists who study this problem.

POSSIBLE CONSEQUENCES OF GLOBAL WARMING. Although there is still some 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, associated 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. There is also some, admittedly controversial, evidence that the intensity of tropical hurricanes may be increasing as the climate warms. (See the box titled "Are Hurricanes Getting Stronger with Time?") 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.

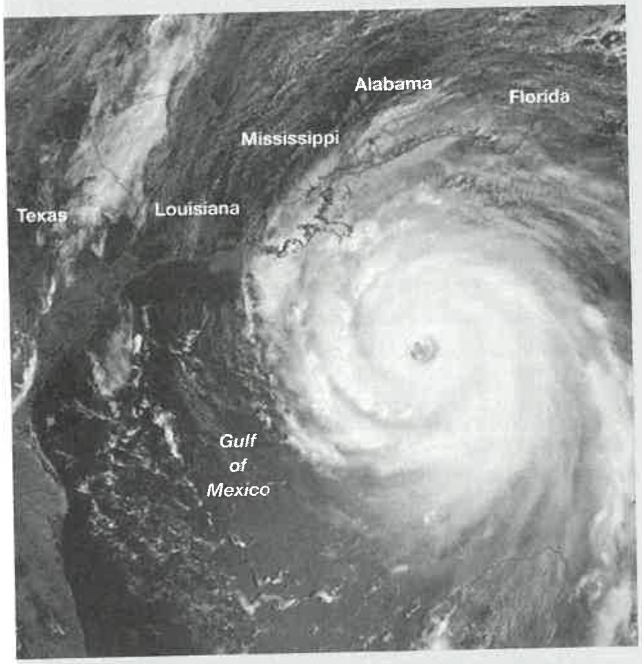
Evidence of Ozone Depletion

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

A CLOSER LOOK

Are Hurricanes Getting Stronger with Time?

Hurricane Katrina (Box Figure 1-1) formed over the Bahamas on August 23, 2005. It crossed over Florida as a weak, Category 1 storm, then grew rapidly in strength as it drew energy from the unusually warm surface waters of the Gulf of Mexico. Within a few days, it had turned into a powerful Category 5 hurricane—the highest rating given to such storms—meaning that it had sustained winds over 155 mph, or 249 km/hr. On August 29, it slammed into the U.S. Gulf Coast as a Category 3 storm (111–130 mph). But it was still enormous in extent, with hurricane-force winds extending out more than 120 miles from its center. The low pressure at its center, combined with the onshore winds on the eastern side of the hurricane, caused a powerful storm surge of as much as 14 feet that overwhelmed the levees holding back Lake Pontchartrain and the southernmost outlets of the Mississippi River. The consequences for New Orleans were devastating. Large parts of the city were flooded, over 700 people were killed in New Orleans alone, and the nearby Mississippi Gulf Coast was similarly ravaged.

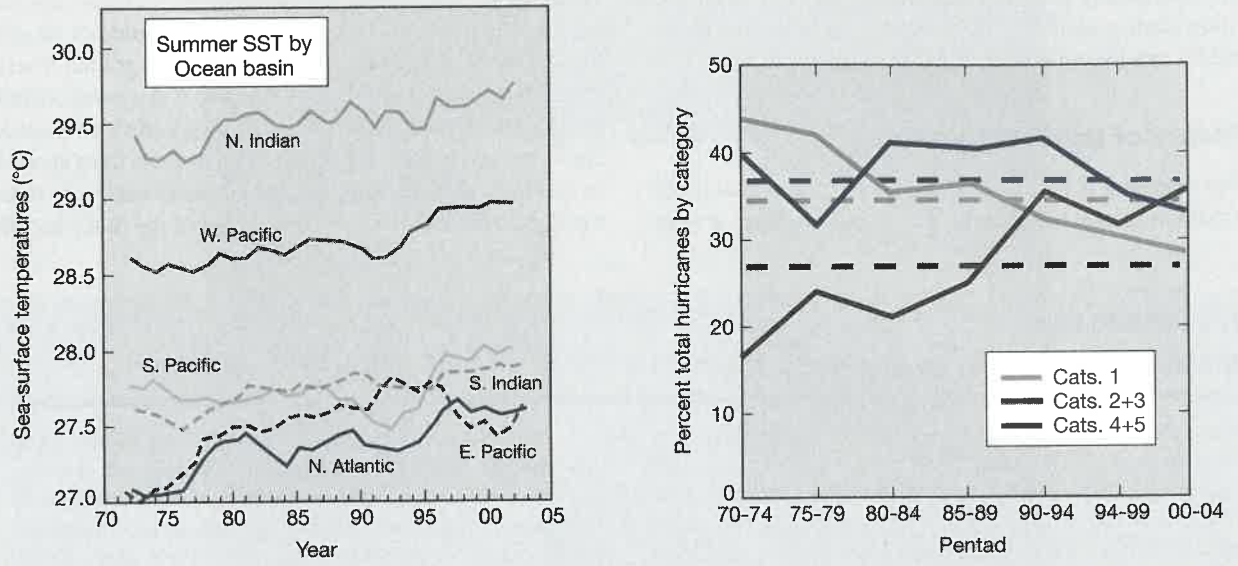


BOX FIGURE 1-1 Hurricane Katrina near peak strength, August 28, 2005. (*Source:* Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC.)

In that same year, 2005, two important papers were published in the prestigious journals *Nature* and *Science*. The first, by Kerry Emanuel of the Massachusetts Institute of Technology, suggested that warmer sea-surface temperatures induced by anthropogenic greenhouse gases might result in stronger hurricanes in the future. Hurricanes derive their tremendous power by tapping the energy present in surface water. Sunlight, combined with the strong winds generated by the hurricane, causes seawater to evaporate. When it recondenses as rain, its energy (or **latent heat**) is released, and this adds still more energy to the hurricane. Emanuel used existing meteorological datasets dating back to 1930 to show that these changes have actually been occurring, especially over the last 30 years.

The second paper, by Peter Webster of the Georgia Institute of Technology and his colleagues, provided additional evidence to support this hypothesis. Their key findings are shown in Box Figure 1-2. Many of the data for their analysis come from satellites, and so the record dates back only to 1972. Box Figure 1-2a shows sea-surface temperatures in various ocean basins. As one can see, they have all warmed by several tenths of a degree over this time period, consistent with the global average surface temperature data shown in Figure 1-4. Box Figure 1-2b shows the percentage of hurricanes of different categories over the entire globe per pentad. (A pentad is a period of 5 years.) The total number of hurricanes per pentad has remained roughly constant over this time period, so the *frequency* of hurricanes has not changed. But the percentage of the stronger Category 4 and 5 hurricanes has nearly doubled, suggesting that the *intensity* of hurricanes is increasing with time. This result is therefore consistent with Emanuel's independent analysis.

Whether or not this trend will continue into the future is unclear. The datasets used in both papers are too short to rule out the possibility that some decadal-scale natural cycle could account for the observed trend in hurricane strength. And Hurricane Katrina itself was not all that exceptional and cannot necessarily be attributed to global warming. Nevertheless, the combination of the two papers and the natural disaster really set the meteorological research community rocking. Large numbers of people live along tropical or subtropical coastlines that are affected by such storms. If stronger hurricanes are indeed to be expected in the future, many people will be concerned.



BOX FIGURE 1-2 (a) Observed change in summer sea-surface temperature (SST) of different ocean basins, 1972–2003. (b) Number of hurricanes of different categories during this same time period. The dashed lines indicate the average number of hurricanes in Categories 1, 2 and 3, and 4 and 5. The uppermost curve is the maximum recorded wind speed for all hurricanes, which has remained more or less constant with time. Legend: NIO—Northern Indian Ocean, WPAC—Western Pacific, SPAC—Southern Pacific, SIO—Southern Indian Ocean, EPAC—Eastern Pacific, NATL—North Atlantic. (*Source:* P. J. Webster et al., *Science* 309, 2005, p. 1844.)

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 1-6b shows year-to-year variations of the mean ozone *column depth* above Halley Bay in Antarctica for Octobers between 1957 and 2001. (The location of Halley Bay and other sites in Antarctica that we will discuss later is shown in Figure 1-6a.) 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 during a short period between 1975 and 1990. Since then, they have remained relatively constant. During the rest of the year, ozone levels in this region have remained close to normal throughout this time period. What has been destroying half the ozone over Antarctica during one particular month?

As soon as the ozone hole was discovered, atmospheric scientists guessed that chlorine compounds were to blame. By 1974, scientists had confirmed that chlorine is capable of destroying stratospheric ozone, and stratospheric chlorine levels have been increasing for the past few decades. Scientists are now fairly certain that the ozone hole is caused by chlorine compounds released from the breakdown of anthropogenic CFCs. The definitive evidence was provided in 1987, when a NASA research plane flew directly into the hole. One of the plane's instruments measured chlorine monoxide, ClO, which was thought to be a main culprit in ozone destruction; another instrument measured ozone (Figure 1-7). Outside the hole, ozone concentrations were at their normal stratospheric level, and ClO concentrations were very low. Inside the hole, ozone values were more than a factor of two lower, and ClO values were about 15 times higher, than the respective values outside the hole. Faced with such a strong inverse relationship, even scientists who had been skeptical about the connection between stratospheric chlorine and ozone depletion were driven to conclude that the chlorine was directly responsible for destroying the ozone.

The real concern about ozone depletion is not whether it is occurring over Antarctica in October but whether it might occur at hazardous levels over populated regions of the globe. (The few people living down in the far southern portions of Chile and New Zealand are already concerned, because they are so close to Antarctica.) So far, nothing as dramatic as the Antarctic ozone hole has been seen elsewhere. However, during the 1990s ozone did decrease gradually at midlatitudes in both hemispheres, perhaps because CFC concentrations in the upper stratosphere were still going up at that time. The good news is that the midlatitude ozone decrease appears to have slowed or stopped in recent years, and the ground-level concentrations of most CFCs are now decreasing because production of these gases has been reduced or eliminated. Hopefully, the world has acted in time to prevent ozone depletion from becoming a catastrophic problem.

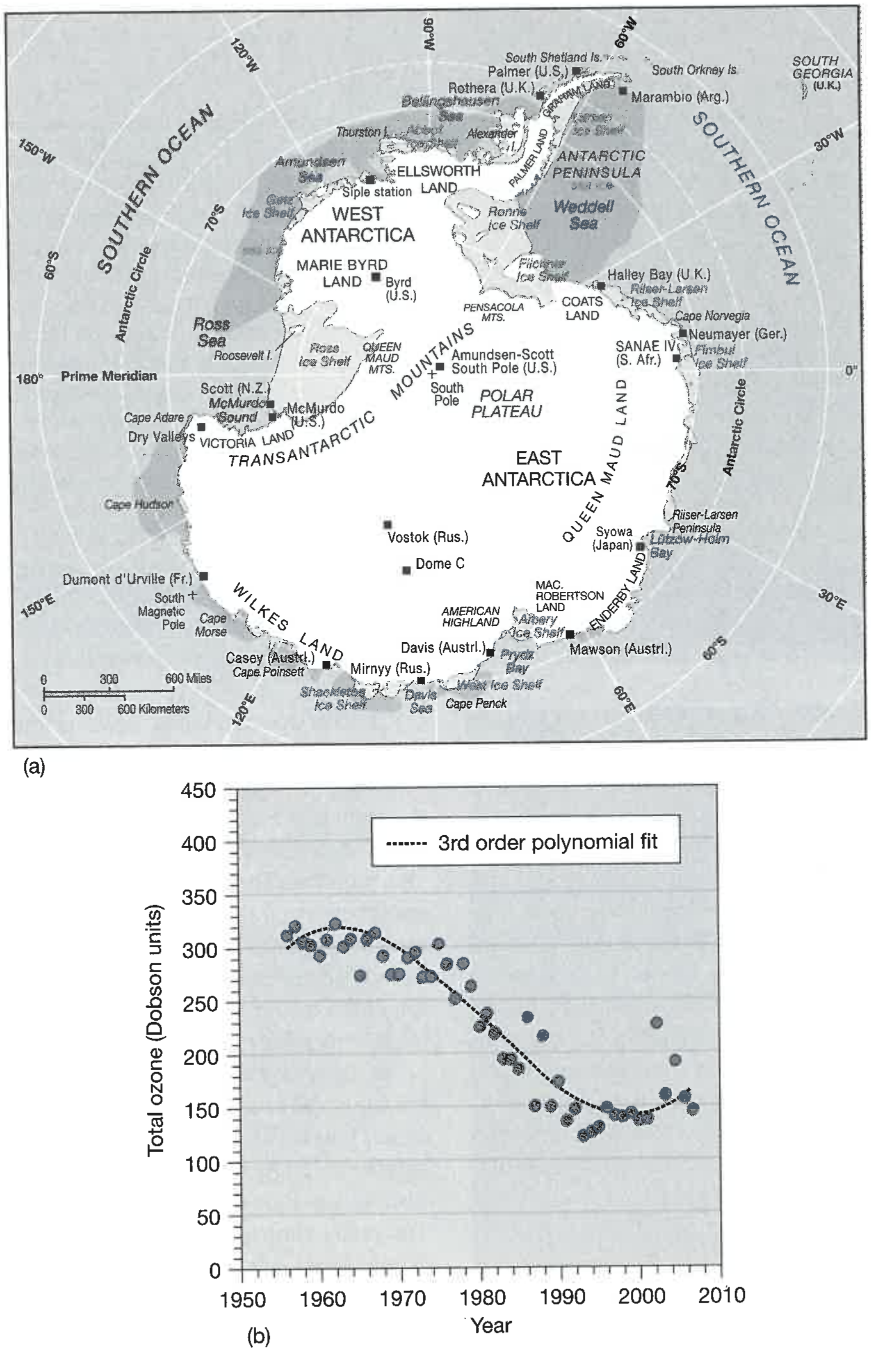


FIGURE 1-6 (a) Map of Antarctica showing the location of Halley Bay and other research sites. (b) Mean total ozone over Antarctica during the month of October. The units, called Dobson units, measure the gas per unit area between Earth's surface and the top of the atmosphere (a measurement known as the column depth). One Dobson unit (DU) is equivalent to a 0.001-cm-thick layer of pure ozone at the surface. (*Source:* http://www.antarctica.ac.uk/met/jds/ozone/images/zmeanoct.jpg.)

Deforestation and Loss of Biodiversity

Ever since a substantial portion of the human population switched from being hunters and gatherers to being farmers some 10,000 years ago, humans have been altering the land surface. More and more of Earth's land is being "managed" in one way or another—to the extent that it is now fairly difficult to find land areas that are pristine.

Most of these changes have tended to reduce the complexity of the landscape, such as when forested areas (or grasslands) have been cleared and replaced with a single crop species. When the natural vegetation cover is removed, it is not simply the plant species that are lost. With the plants go all the animals (mammals, birds, insects, and so on) and microorganisms that depended on that vegetation in order to live. New species may replace them, but normally the number of species decreases; that is, biodiversity is reduced. When a species is unable to move away or adapt, the change in land use can result in extinction of the species.

A CLOSER LOOK

The Discovery of the Antarctic Ozone Hole

The story of the discovery of the ozone hole above Antarctica is one of the classic misadventures of modern science. Measurements of Antarctic ozone made from Earth's surface date back to 1956 and represent by far the longest continuous record of atmospheric ozone levels. But these measurements were made at only one site, Halley Bay, where a research station happened to be located. Continuous measurement of ozone levels above the entire Antarctic continent (and the rest of Earth) began in 1979 with the launching of the Total Ozone Mapping Spectrometer (TOMS) instrument on the Nimbus 7 satellite.

TOMS was a sophisticated and expensive instrument that should have been fully capable of detecting significant Antarctic ozone depletion within the first few years of going into orbit. It did not do so, however. The ozone hole was first reported at Halley Bay in 1985 by the British scientist Joseph Farman and his colleagues, who had relied on their "old-fashioned" ground-based instruments. TOMS failed to detect the hole, it was later discovered, because the computer that processed the raw satellite data had been programmed to reject as "noise" any ozone measurements below a particular cutoff value. Values as low as those observed over Antarctica in October were considered too low to be real!

On learning about the Halley Bay measurement, the TOMS scientific investigators reanalyzed their original data using a technique that retained the anomalously low values. The ozone hole was there, all right! Had it not been for the ground-based measurements, however, the hole might have gone undetected for years. Besides providing a wonderful illustration of the perils of having rigid preconceptions, the story of the discovery of the ozone hole shows that dedicated individuals working with relatively simple equipment can still make important contributions to modern science.

The genetic information that is shared by—and only by—all the members of that species is thus lost permanently.

Some of the best-known examples of animal species that have gone extinct are the woolly mammoth, the saber-toothed tiger, the dodo bird, and the dinosaurs. Many species that exist today, such as the mountain gorilla and the giant panda, are faced with the threat of extinction. The potential loss of these large mammals represents only the most visible of many similar threats.

The largest, and potentially the most significant, species loss occurring today is taking place in tropical rainforests. These warm, moist forests are centered around the equator. Marked by lush vegetation, they are the most biodiverse habitat on Earth. But they are rapidly disappearing due to deforestation: The trees have been cleared for grazing, farming, timber, and fuel. By 1990, the total area of tropical rainforests had been reduced to less than half the estimated prehistoric cover. The rapidity of deforestation of the Amazon rainforest is illustrated in Figure 1-8. Exactly how fast the tropical forests are disappearing is difficult to determine, but the loss rate is thought to approach 1.8% per year. If deforestation continues at such a rate, by the first quarter of the 21st century almost half the remaining rainforests will be lost, along with 5 to 10% of all the species on Earth.

Which Changes Should Concern Us the Most?

The concerns about the loss of tropical species are, in some ways, less immediate than the concerns about ozone depletion or global warming. One worry is that the tropical plants are a potential source of medicines for fighting cancer and other diseases. This concern is valid, but it does not have the urgency of the prospect of instantaneous sunburn on exposure to the Sun or of entire states or even entire nations being submerged by a rising sea level.

This does not mean, however, that species loss is not a serious problem. Indeed, in some ways it may be the most serious problem of all. One way of judging the severity of a problem is to estimate how long it would take Earth to recover. If we take this approach, ozone depletion is the least serious problem. The lifetime of chlorofluorocarbons in the atmosphere is on the order of 50 to 150 years, when they are eventually destroyed by solar ultraviolet radiation. This range is long enough to raise serious concerns, but the ozone level should be restored within a few human generations if the preventive measures now in place are continued or strengthened.

By this measure, global warming is a more serious problem, because the time scale for recovery could be much longer than 150 years. If we actually do consume an appreciable amount of the fossil fuels that are still available to us, atmospheric CO_2 levels could remain elevated for many thousands of years. Most of the excess CO_2 would be absorbed by the oceans during this time, but even then it would not be completely gone. As we will see in later chapters, it would likely take more than a million years for the excess CO_2 to be removed from the oceans and for atmospheric CO_2 to return to its preindustrial level.

Although this time scale sounds long, it is short in comparison with the time required to restore global biodiversity. Analysis of the fossil record shows that the time scale for recovery of biodiversity after a **mass extinction** (the dying out of many species within a geologically short time interval) is on the order of tens of millions of years. In fact, the system never does recover completely: Although many new species appear and flourish after a mass extinction, they are *different* from the ones that went extinct. That is why humans, instead of dinosaurs, now rule Earth! So, if we do induce a mass extinction of tropical species by deforestation, things will never again be the same.

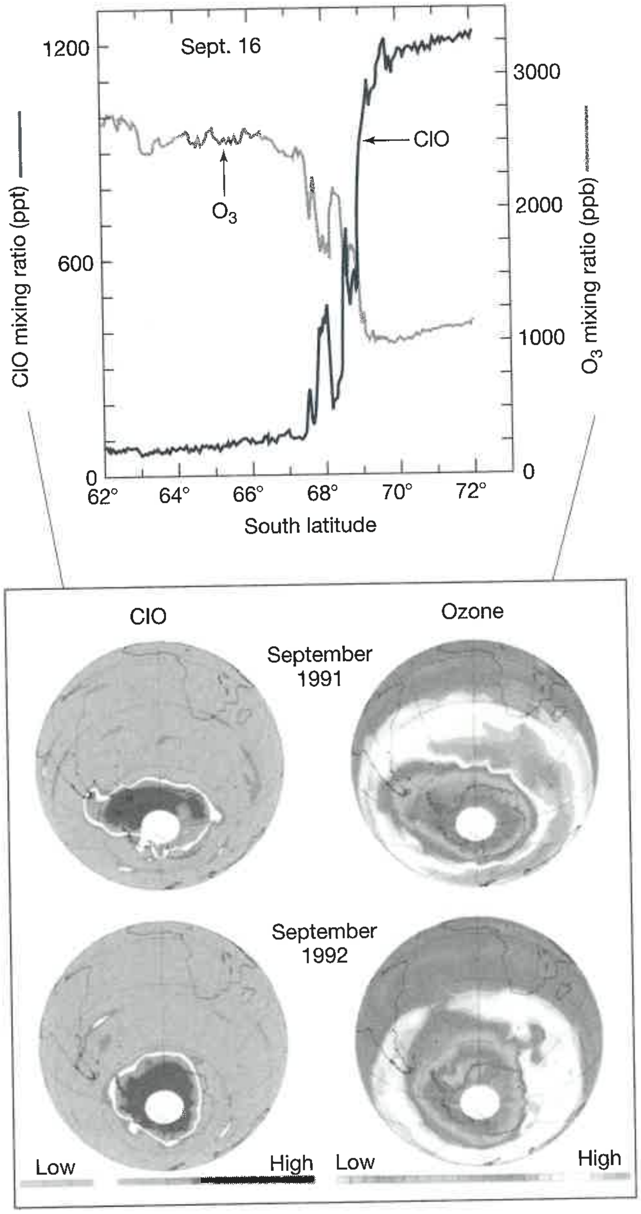


FIGURE 1-7 [See color section] (a) Simultaneous measurements of ozone (O_3) and chlorine monoxide (ClO) made from a NASA aircraft as it flew into the Antarctic ozone hole in September 1987. The hole was entered at a latitude of about 68° S. The units ppt and ppb stand for "parts per trillion" and "parts per billion," respectively. (b) Contour plots of ClO and O_3 concentrations obtained from spacecraft measurements. These data also show that ozone is low where ClO is high. (*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.)

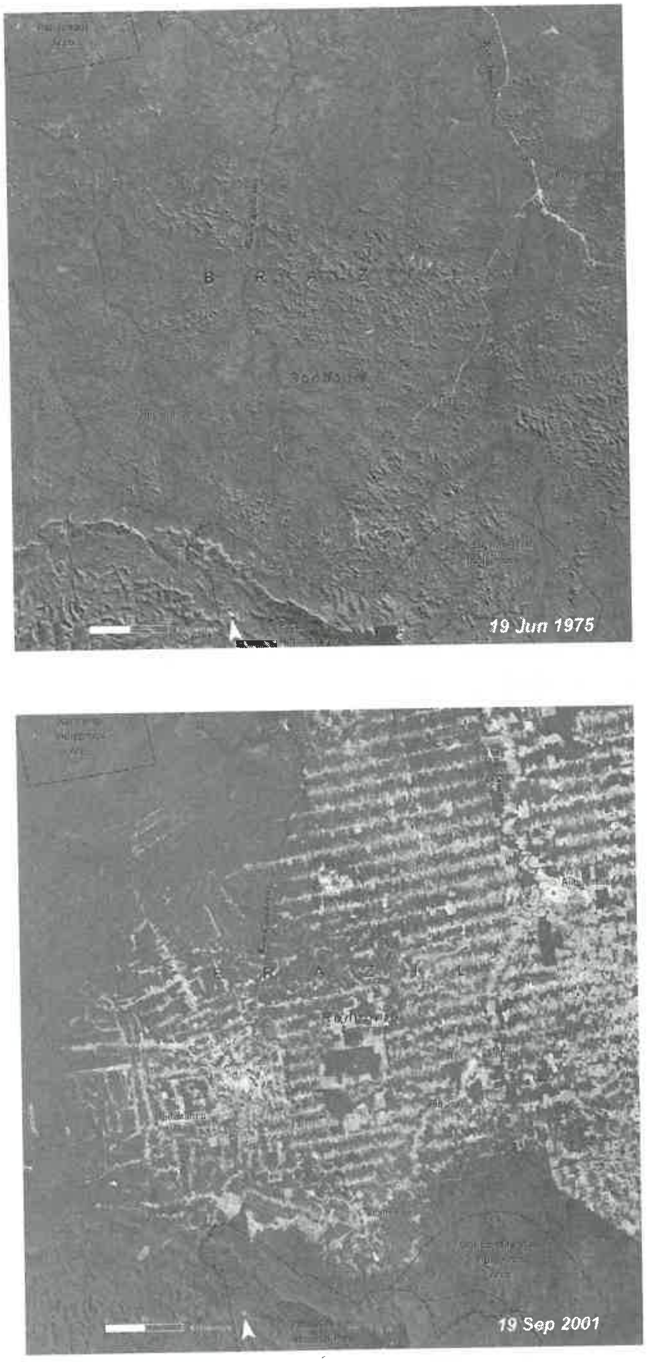


FIGURE 1-8 Satellite photos of Amazonia in 1975 and 2001. (*Source:* USGS.)

GLOBAL CHANGE ON LONG TIME SCALES

We have touched on three major global environmental changes that are occurring in the Earth system today: global warming, ozone depletion, and tropical deforestation. To understand fully the significance of these changes, however, we must understand how the Earth system operated prior to human intervention. Here, we preview three examples of past global change—glacial–interglacial cycles, mass extinction, and changes in solar luminosity—and show how the geologic record provides evidence that allows us to study such changes.

Before we look at these examples of past global change, let us see where they occur on the *geologic time scale* (Figure 1-9). Geologic time is divided into various intervals at several different levels. *Eons,* at the broadest level, are subdivided into *eras;* in turn, eras are broken

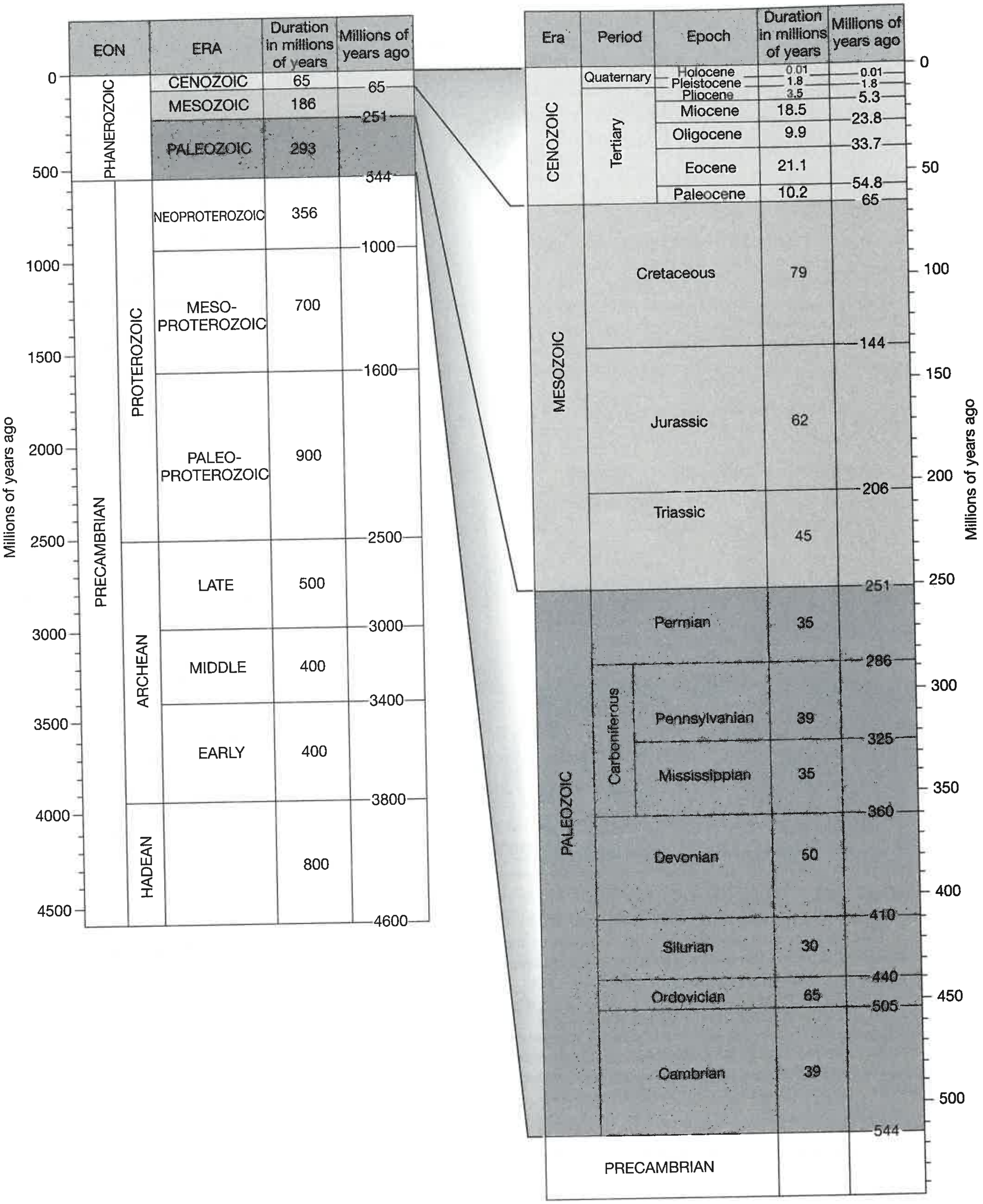


FIGURE 1-9 The geologic time scale. (*Source:* From W. K. Hamblin and E. H. Christiansen, *Earth's Dynamic Systems,* 8/e, 1998. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

down into *periods,* which may be further split into *epochs.* The glacial–interglacial cycles that we will discuss, which lasted from about 2.5 million years ago until approximately 10,000 years ago, occurred during the Pliocene and Pleistocene epochs. The mass extinction that we shall talk about occurred at the boundary between the Cretaceous and Tertiary periods, approximately 65 million years ago. A *period,* typically lasting tens of millions of years, is generally a longer unit of geologic time than an *epoch.* Finally, the solar luminosity changes that we will discuss have occurred throughout the entire 4.5 billion years of Earth history.

Glacial–Interglacial Cycles: The Ice-Core Temperature Record from Vostok and Dome C

A set of ice cores drilled between the mid-1980s and the early 1990s at Vostok, Antarctica, near 80° S latitude, has provided a wealth of information about the Pleistocene glaciations. More recently, a new core drilled in 2003 at Dome C, about 560 km from Vostok (see Figure 1-6a), has provided an even longer and more detailed record. The most important results from the Dome C ice core are shown in Figure 1-10. The bottom curve shows the measured range of CO_2 concentrations; the top curve shows the estimated change in local temperature, as determined from the deuterium content of the ice. **Deuterium,** D, is an **isotope** of hydrogen that has both a proton and a neutron in its nucleus. (Normal hydrogen, H, has only a proton.) It is used as a proxy for temperature: higher (less negative) δD values indicate warmer temperatures over the Antarctic continent and the surrounding polar oceans. We talk more about how isotopes are used to estimate temperatures in Chapter 14.

The section of the Dome C ice core that has been fully analyzed is about 3.3 km deep and it extends back for an extraordinarily long time, some 800,000 years. The reason that both the Vostok and Dome C records extend so far back in time is that snow accumulates very slowly at these sites—the equivalent of only about 2.5 cm of water per year. This value is comparable to the mean annual precipitation over the Sahara Desert. Other parts of the polar ice sheets are approximately as thick, just under 4 km, but have faster accumulation rates. The short-term CO_2 record shown in Figure 1-3 comes from Siple Station, near the coast of Antarctica; there the snow accumulation rate is equivalent to about 50 cm of water per year. Cores from such locales cover much shorter periods of time than does the Dome C core, even if they are just as deep.

The time interval spanned by the Dome C core extends well beyond the last Ice Age. For the past 2.5 million

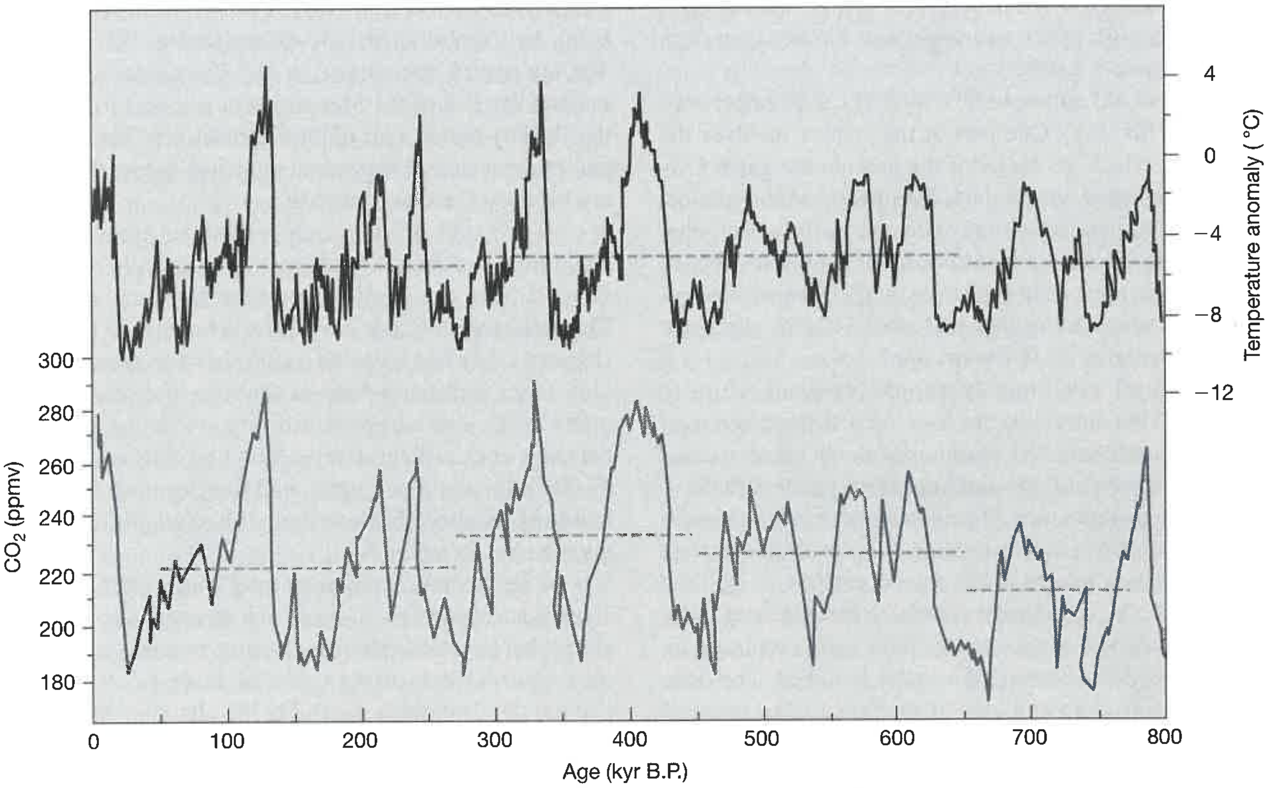


FIGURE 1-10 Measurements of atmospheric CO_2 and temperature for the Dome C ice core. The temperature is determined from the deuterium content of the ice. (*Source:* IPCC, *Climate Change 2007,* Technical Summary, Fourth Assessment Report, Cambridge: Cambridge University Press, 2007, p. 24, http://www.ipcc.ch/ipccreports/ar4-wg1.htm.)

years, Earth's climate has fluctuated between intensely cold **glacial periods,** in which ice sheets advanced across North America and Europe, and relatively warm **interglacial periods** such as the present, in which the ice sheets retreated. The present interglacial period began—and thus the last Ice Age ended—about 11,000 years ago, as an upward surge in temperature in Figure 1-10 indicates. At 21,000 years ago, Earth was in full-glacial conditions. Around 130,000 years ago, the planet was in the midst of another warm, interglacial period.

Much of the story about the advance and retreat of the glaciers was already known from other sources of data prior to the drilling of the Vostok ice core. (We shall henceforth use the terms "Vostok" and "Dome C" interchangeably, as the ice cores from both locations tell us essentially the same thing. Most of the original groundbreaking discoveries actually came from Vostok.) What was new and surprising about the Vostok results was that they showed that atmospheric CO_2 and CH_4 concentrations had varied in concert with surface temperature. The Vostok data show that between 21,000 and 11,000 years ago, atmospheric CO_2 levels rose from about 200 ppm to close to its preindustrial value of 280 ppm, whereas CH_4 increased from about 350 to 650 ppb. The current CH_4 concentration is about 1700 ppb, or 1.7 ppm. The same abrupt increase in CO_2 and CH_4 concentrations occurred after the previous interglacial period ended, between 140,000 and 130,000 years ago. Indeed, at a finer level, many of the smaller peaks and valleys in the temperature-change curve correspond to specific peaks and valleys in the concentration records of the two gases.

Why would atmospheric CO_2, CH_4, and temperature co-vary in this way? One part of the answer involves the greenhouse effect: As levels of the greenhouse gases CO_2 and CH_4 increased, the magnitude of the greenhouse effect also increased, and the climate became warmer. But what caused atmospheric concentrations of CO_2 and CH_4 to vary in the first place? In particular, why did those concentrations increase so abruptly just after 140,000 years ago and again just after 21,000 years ago?

These are tough questions, and we shall return to them later. Humans could not have caused these changes. Our ancestors were still making tools out of stone and tending small wood fires—and not burning fossil fuels—when these changes took place. One possible mechanism for driving changes in atmospheric CO_2 levels is a change in the circulation pattern of the deep ocean. As we will see in Chapter 5, the deep ocean circulates because cold, salty (and hence, dense) surface water sinks and is replaced by warmer, less dense water from lower latitudes. The deep ocean contains large amounts of dissolved CO_2, some of which is released to the atmosphere when deep water flows upward to the surface. So, the rate at which the deep ocean overturns can affect the concentration of atmospheric CO_2. But the circulation pattern of the deep ocean depends on climate, which is driven by changes in temperature and in evaporation rates at the sea surface. Thus, it would appear that atmospheric CO_2 levels affect climate and that climate, in turn, affects atmospheric CO_2 levels. What we have is a system in which the various components are tightly and intricately coupled. That is why a systems approach is the best way to understand global change.

MASS EXTINCTION: IRIDIUM AND THE K-T BOUNDARY AT GUBBIO Ever since dinosaur bones were first discovered, people have wondered why the dinosaurs disappeared. Dinosaurs flourished for more than 150 million years during an interval called the Mesozoic era, which ended 65 million years ago. At about the same time the dinosaurs disappeared, many other species went extinct as well. Some 60 to 80% of marine species died, as did numerous species of terrestrial plants and animals. Many possible reasons have been offered for their demise, including changes in climate, changes in vegetation, disease, destruction of the ozone layer by a nearby supernova (an exploding star), volcanic activity, and impact of an extraterrestrial body. No single hypothesis had attracted widespread support, however, until 1980.

That year, Luis and Walter Alvarez, of the University of California at Berkeley, and their colleagues published a paper about a clay layer they had studied in rocks from the mountains near Gubbio, Italy. The clay dated back 65 million years to the K-T boundary. **"K-T boundary"** stands for the transition between two time intervals: the Cretaceous period, abbreviated as "K" (to distinguish it from the Cambrian period, abbreviated as "C"), and the Tertiary period, abbreviated as "T." The Cretaceous period marked the end of the Mesozoic era and was followed by the Tertiary period, part of the Cenozoic era. The dinosaurs and other species disappeared at or just below the boundary between these two periods.

The layer of clay, only a few centimeters thick, was found between thick layers of *carbonate rock* (rock formed from the shells of certain marine organisms). The existence of this clay layer at the K-T boundary (Figure 1-11) had puzzled geologists for decades. This clay layer had been seen at Gubbio and at numerous other spots around the world, always at the boundary between rocks of the Cretaceous and Tertiary periods. Walter Alvarez, a geologist, had journeyed to Gubbio in an effort to determine how long it had taken for the clay layer to be deposited.

Luis Alvarez, a physicist (and Walter's father), had a clever idea about how to make that determination. He reasoned that he could calculate the time required to form the clay layer by measuring the abundance of the element *iridium* (Ir). Iridium is a metal in the platinum group of elements, which are very scarce in rocks of Earth's crust, because they are mostly dissolved in its molten iron core. These elements are always raining down on Earth as small particles of debris from asteroids or comets. The rate at which such debris hits Earth is known fairly accurately

FIGURE 1-11 The clay layer at the K-T boundary in sediments at Gubbio, Italy. (*Source:* Prof. W. Alvarez/ SPL/Photo researchers.)

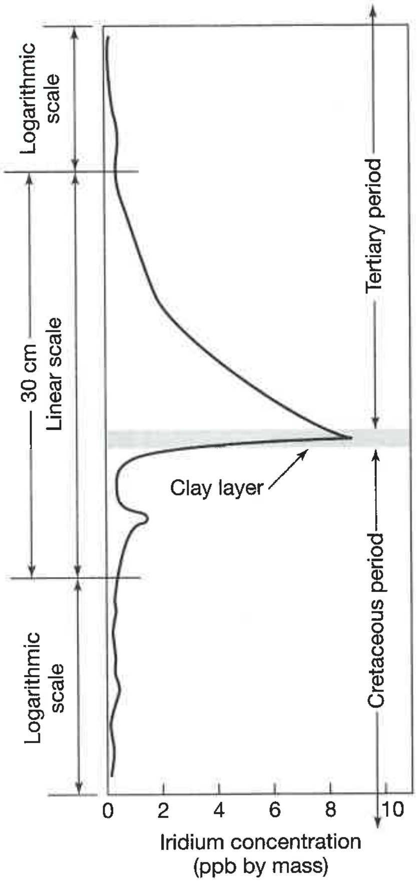


FIGURE 1-12 Iridium concentration versus depth at Gubbio. The middle portion of the depth axis is a linear scale; the upper and lower portions are logarithmic. (*Source:* L. Alvarez, *Physics Today,* July 1987.)

from measurements of its abundance in cores drilled into the ocean floor. Hence, Luis Alvarez reasoned that he could use the measured iridium abundance in the Gubbio clay layer as a kind of "cosmic clock" to determine the time needed for the clay to have been deposited.

The experiment failed, but it did so for a reason that turned out to be very informative. When the Alvarez team measured the iridium levels at Gubbio, they found the results shown in Figure 1-12. The iridium abundance in the clay layer was up to 10 ppb by mass—more than 100 times higher than what the group expected to find. The amount of iridium in the clay layer was much too large to have been supplied by debris from asteroids or comets. The time required to accumulate that much iridium would have been so long that the signal would have been swamped by the normal deposition of Earth-bound sediments. (Clay accumulates on the ocean floor at a rate of about 1 cm per thousand years as a result of wind-blown dust that falls on the ocean surface. If the clay layer at the K-T boundary had taken more than a few thousand years to form, it should have contained a large proportion of terrestrial dust and, hence, a relatively small concentration of iridium.) The Alvarez team reasoned that the iridium must have come instead from the impact of some large, extraterrestrial object, such as an asteroid or a comet. Indeed, by calculating the amount of iridium deposited worldwide, the team estimated the mass of such an incoming body—on the order of 10^{15} kg, which corresponds to a diameter of about 10 km for a rocky asteroid. If the impacting object was a comet, it would have to have been even larger because comets are thought to contain less iridium than do asteroids.

We shall see later on (Chapter 13) that the energy released by an impacting object of this size is enormous—equivalent to about 70 million, 1-megaton hydrogen bombs. Thus, it is plausible that such an event could have triggered extinctions on a mass scale. Since the Alvarez's did their work, additional evidence corroborating a large impact 65 million years ago has been identified, including a deeply buried crater 200 km in diameter underlying the region around Chicxulub, Mexico, on the Yucatan Peninsula. Even this "smoking gun" does not prove that this impact was the cause of the mass extinction. It does demonstrate convincingly, though, that in the past the Earth system has experienced large shocks from which it has recovered, albeit slowly and in a modified form.

The changes that humans are causing in the Earth system today are less abrupt than those that occurred at the K-T boundary (assuming that the impact theory is correct), but they are still fast compared to most natural changes, and the results could still be catastrophic for certain elements of the biota. We have already noted that large land mammals such as gorillas and pandas are at risk. And with the vast majority of terrestrial species concentrated in the imperiled tropical rainforests, the potential for more-widespread mass extinctions is very high. A lesson learned from the K-T boundary crisis, that biodiversity can decrease dramatically over a relatively short time interval, may therefore hold value today.

Changes in Solar Luminosity

All the examples of global change discussed thus far have been based on observational data. Observations, after all, are the cornerstone of science. Not everything of importance is observable, however. For example, we cannot see inside the Sun. Yet we are confident that the Sun produces its energy through **nuclear fusion,** the joining of two or more light atomic nuclei to form one heavier nucleus. Specifically, four hydrogen nuclei (^{1}H) fuse to form one helium nucleus (^{4}He). This process, which is thought to occur continuously within the Sun, releases large amounts of energy. Even though we cannot observe this phenomenon directly, we are reasonably sure that the fundamental concept is correct.

The fact that the Sun produces energy in this way has important consequences for its long-term evolution. Four hydrogen nuclei take up more space, and therefore exert more pressure, than does one helium nucleus. The pressure in the Sun's core (where nuclear fusion occurs) would therefore be decreasing with time if the fusion of hydrogen into helium were the only process taking place. But what actually happens, models predict, is that the core contracts and heats up slightly as its helium content increases. The temperature rise increases the core's pressure and keeps the core from contracting further, so the Sun remains stable. As the core's temperature increases, so does the rate of nuclear fusion, just as the rates of most chemical reactions increase with increasing temperature. As a result, energy production within the Sun's core rises, and this rise is balanced by an increase in the amount of energy emitted at the surface. The more energy is emitted, the brighter the Sun appears. So, contrary to what we might intuitively expect, the Sun's **luminosity** (brightness) should gradually increase as it depletes its hydrogen fuel.

By how much has solar luminosity changed over the Sun's history? Model calculations performed by a number of different astronomers have reached essentially the same conclusion. Figure 1-13 shows a typical result, in which the unit of age on the horizontal axis is *byr B.P.,* or billions of years before the present. When the Sun first formed 4.6 billion years ago, it should have been about 30% less luminous than it is today. The Sun's luminosity increased slowly at first and then more rapidly as the buildup of helium in its core continued. At present, the Sun is thought to be brightening by about 1% every hundred million years. By the time the Sun ends its lifetime as a normal star, about 5 billion years from now, it is expected to have brightened by a factor of 2 to 3 as compared with today.

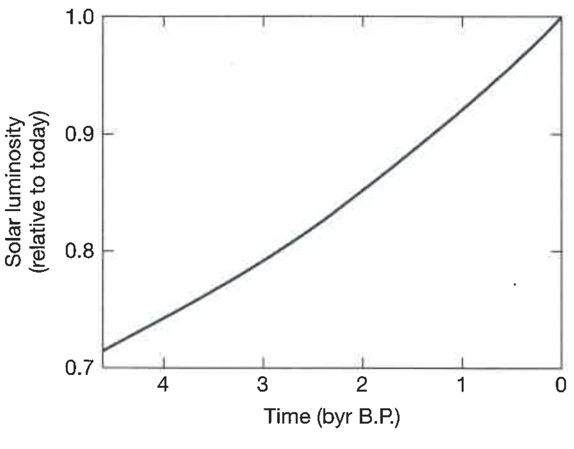


FIGURE 1-13 Estimated change in solar luminosity with time. The unit of age on the horizontal axis, byr B.P., stands for "billions of years before the present." (*Source:* D. O. Gough, *Solar Physics* 74, 1981, p. 21.)

THE EFFECTS OF SOLAR LUMINOSITY CHANGES How would reduced solar luminosity have affected the early Earth? If all other factors had remained constant, the early Earth should have been colder than it is today. Indeed, calculations (which we will do in Chapter 3) show that the entire ocean should have been ice-covered prior to 2 billion years ago. We know, however, that liquid water has existed on Earth's surface for at least the last 3.8 billion years, because sedimentary rocks (which form from sediments in liquid water) have been forming since that time. And organisms, which require liquid water to survive, have probably been around for at least 3.5 billion years. The early Earth could not have been a global iceball, at least not during the time for which a geologic record is available.

This apparent discrepancy is called the *"faint young Sun paradox."* We mention this paradox here because, like the Vostok CO_2 story, it is a problem that can be solved only by considering the Earth system as a whole. The most likely solution is that the level of greenhouse gases in Earth's primitive atmosphere was significantly higher than today. But why should this have been true, and why would greenhouse gas concentrations have declined as the Sun grew brighter? Does Earth's climate system have some built-in stability mechanism that has kept the mean surface temperature within survivable limits?

THE GAIA HYPOTHESIS James Lovelock, a British biochemist, and Lynn Margulis, an American biologist, have argued that life itself has been responsible for maintaining the stability of Earth's climate. In the process of **photosynthesis,** organisms such as green plants use sunlight, CO_2, and H_2O to produce organic matter and O_2. (*Organic matter* is the carbon-rich material of which organisms are composed.) Through photosynthesis, followed by carbon burial in sediments, Earth's biota may have lowered atmospheric CO_2 levels at just the right rate to counteract the gradual increase in solar luminosity. Alternatively, the biota may have affected the rate at which atmospheric CO_2 is sequestered in carbonate rocks. Carbonate rocks form from reactions of CO_2 with elements (primarily calcium and magnesium) derived from other types of rocks. This process is part of the *carbonate-silicate geochemical cycle,* which we will discuss in Chapter 9. In either case, Lovelock and Margulis suggest that Earth has remained habitable precisely because it is in some sense "alive."

This theory of long-term climate stabilization is part of what Lovelock and Margulis called the Gaia hypothesis. In ancient Greek mythology, Gaia (pronounced guy-ah) was the goddess of mother Earth. In its most basic form, the **Gaia hypothesis** states that Earth is a self-regulating system in which the biota play an integral role. Some proponents of this hypothesis further suggest that the biota manipulate their environment for their own benefit or even, by optimizing the conditions for life, for the benefit of all living things. Such assertions are difficult to justify. Lovelock himself is quick to point out that the biota cannot be expected to cope with all possible disturbances. As an example, we cannot assume that we can safely emit CFCs into the atmosphere because Gaia will somehow protect the stratospheric ozone layer. But it is clear that the Gaia hypothesis is correct at some level: Organisms do play an important role in the overall functioning of the Earth system.

Some form of self-regulation must exist in order for Earth's climate to remain stable over long time scales. Higher greenhouse gas concentrations in the past are the most likely solution to the faint young Sun paradox. But whether the biota are essential to the control mechanism remains controversial. *Abiotic* (nonbiological) *feedbacks* in the carbonate–silicate cycle could have stabilized Earth's climate even if life were not present. Explaining how such a climate control mechanism might work is a recurrent topic in later chapters. Before we attempt to do so, however, we need to look more closely at how the various components of the Earth system function.

Chapter Summary

1. We deal with three main themes: modern global environmental issues, past global change, and the behavior of Earth's systems. To understand present environmental problems, we must know something about Earth's past and something about the way different components of the Earth system interact.
2. Humans are modifying the global environment in several ways:
   a. Global warming may be the most pervasive environmental change that faces us today. The increase in concentrations of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFC_s), in the atmosphere is attributable to human activity. These gases are expected to warm Earth's climate over the next few decades to centuries by enhancing the natural greenhouse effect. They may have already begun to do so: Earth appears to have warmed by about 0.8°C over the past century, on the basis of surface temperature measurements made around the globe. It is still debated, however, whether this temperature rise is a consequence of increased greenhouse gas concentrations or simply a natural fluctuation in the climate system.
   b. The stratospheric ozone layer has already been severely affected by chlorine released from anthropogenic CFCs. The most dramatic impact has been confined to the Antarctic region during October. Strong regulatory steps have already been undertaken to ensure that the ozone layer will be protected in the future. Without such restrictions, the ozone layer's ability to absorb harmful ultraviolet rays from the Sun would be severely diminished.
   c. Massive deforestation is occurring in the tropics today, as it did in North America a century or more ago, when it contributed to the early rise in atmospheric CO_2. Deforestation both increases the buildup of atmospheric CO_2 and significantly decreases biodiversity. The effects of deforestation on biodiversity are permanent and irreversible.
3. Past changes in the Earth system may provide clues to how it will respond to global change in the future:
   a. Variations in surface temperature and atmospheric CO_2 concentrations recorded in ice cores illustrate the coupling between atmospheric CO_2 and climate and show how global warming today fits into the general pattern of glacial–interglacial cycles over the past 2.5 million years.
   b. Studies of the mass extinction at the end of the Cretaceous period 65 million years ago, when the dinosaurs and numerous other species forever vanished from Earth, may shed light on the loss of biodiversity that humans are causing today.
   c. Modeling studies of Earth's response to gradual increases in solar luminosity can help us understand how the climate system remains stable despite large changes in external forcing factors.

Key Terms

acid rain
anthropogenic
atmosphere
biodiversity
biota
chlorofluorocarbons (CFCs)
core
crust
cryosphere
deforestation
deuterium
Earth system
fossil fuels
Gaia hypothesis
glacial period
global warming
greenhouse effect
greenhouse gases
hydrosphere
interglacial period
Intergovernmental Panel on Climate Change (IPCC)
isotopes
K-T boundary
latent heat
luminosity
mantle
mass extinction
nuclear fusion
ozone (O_3)
ozone hole
ozone layer
photosynthesis
rocks
sediments
solid Earth
stratosphere
system
trace gases

Review Questions

1. a. What is meant by "anthropogenic greenhouse gases"?
   b. Name three such gases that are currently increasing in concentration in Earth's atmosphere.
2. What are the four fundamental components of the Earth system?
3. Explain the difference between global warming and the greenhouse effect.
4. a. By how much has Earth's atmospheric CO_2 concentration increased since the year 1800?
   b. How do we know this?
   c. What are thought to be the primary causes of this increase?
5. Cite two ways in which chlorofluorocarbons can affect the environment.
6. a. How far back in time do direct measurements of Earth's surface temperature extend?
   b. Why is it difficult to determine accurately the long-term temperature trend?
7. How might the burning of coal have had opposing effects on climate during the 20th century?
8. Why is stratospheric ozone important to humans?
9. To what two global environmental problems does tropical deforestation contribute?
10. How are hydrogen isotopes used to infer polar temperature records?
11. How is past surface temperature
    a. determined from the Vostok ice core?
    b. related to atmospheric CO_2 content?
12. Why is iridium a good indicator of impacts by extraterrestrial bodies?
13. a. How has solar luminosity changed during the past 4.6 billion years?
    b. What is the fundamental cause of this change?
14. What is the Gaia hypothesis, and what does it say about the importance of life on this planet?

Critical-Thinking Problems

Write a 1- to 2-page typewritten essay on the following questions:

1. Which of the three modern global change problems discussed in this chapter—global warming, ozone depletion, or loss of biodiversity—do you consider to be the most serious? Give reasons for your answer. If you wish, include information drawn from other sources.
2. How do global warming, ozone depletion, and loss of biodiversity compare with other environmental and social problems that the world faces today? You may wish to list the major problems, as you see them, in decreasing order of importance. Justify your answer with an explanation.

Further Reading

General

Intergovernmental Panel on Climate Change. 2007. *Climate change 2007,* Fourth Assessment Report (http://www.ipcc.ch).

Lovelock, James. 1995. *Gaia, a new look at life on Earth.* Oxford: Oxford University Press.

Schneider, S. H. 1997. *Laboratory Earth: The planetary gamble we can't afford to lose.* New York: Basic Books.