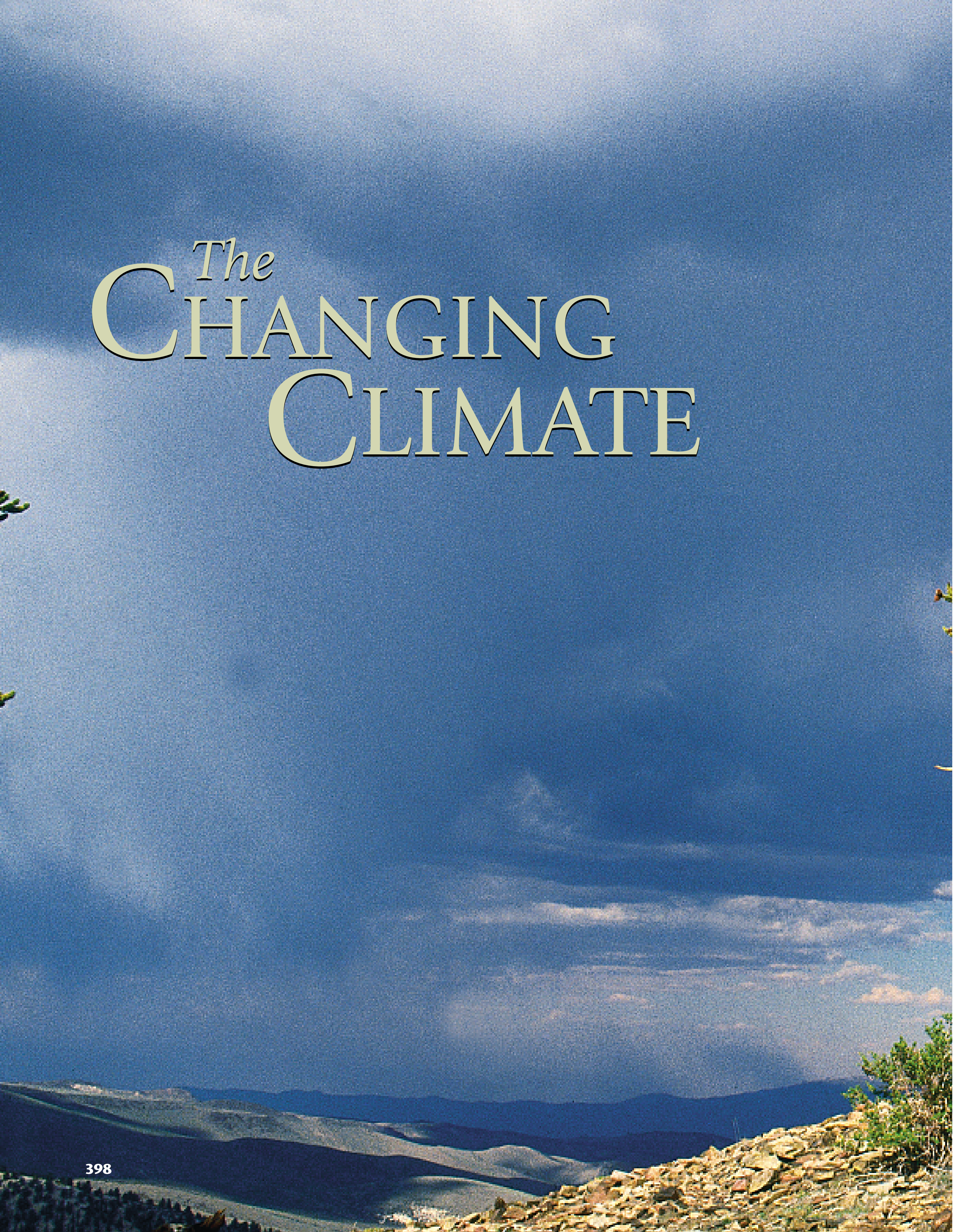
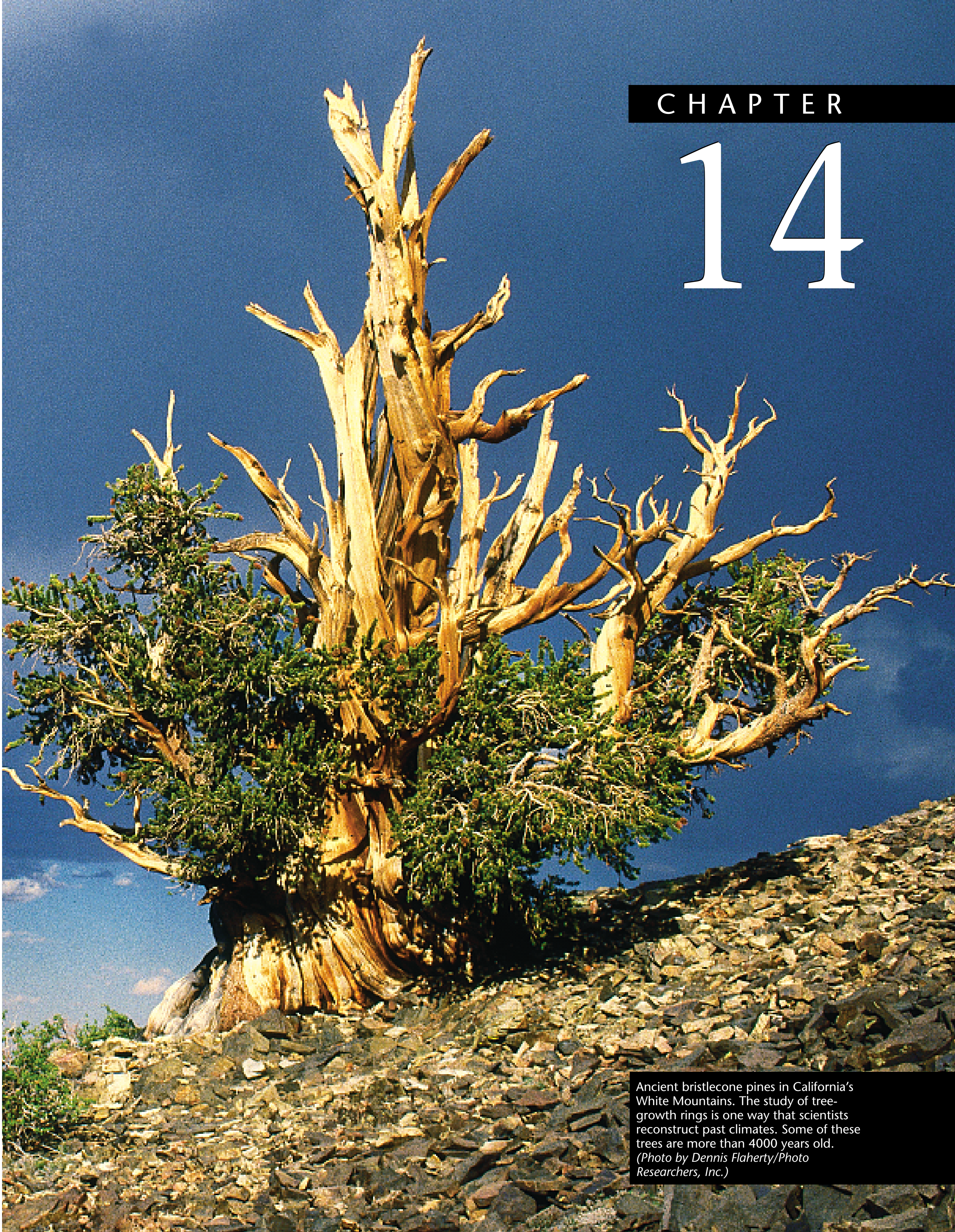
The Changing Climate



CHAPTER 14



Ancient bristlecone pines in California's White Mountains. The study of tree-growth rings is one way that scientists reconstruct past climates. Some of these trees are more than 4000 years old. *(Photo by Dennis Flaherty/Photo Researchers, Inc.)*

In Chapter 1 we characterized climate as an aggregate of weather. You learned that climate consists not only of average atmospheric values but also involves the variability of elements and the occurrence of extreme events. This is the first of two chapters that focus on *climate*. In this chapter we examine how climate changes and why. In the next chapter we take a tour of Earth's major climates, from steamy equatorial rain forests to the frigid poles.

Not too many years ago the concept of *climate change* seemed to have little but academic importance, for the problems most often investigated related to the remote past. "What caused the Ice Age?" was a major question. Today, however, climate change is a major topic in the scientific community and among the general public as well. What generated this current interest in past and future climates? We can point to the following:

1. Detailed reconstructions of past climates show that the climate has varied on all time scales, from decades to millions of years. This suggests that climate in the future is more likely to differ from the present than to stay the same.
2. Research focused on human activities and their effect on the environment has demonstrated that we are inadvertently changing the climate.
3. There is observational evidence that world climate has become more variable.

Clearly, much of the new attention to climate change comes from the realization that it may adversely affect people in the near future. Further, we have learned that a knowledge of past climates helps our understanding of potential future shifts in climate.

The Climate System

To understand and appreciate climate, it is important to realize that climate involves more than just the atmosphere:

> The atmosphere is the central component of the complex, connected, and interactive global environmental system upon which all life depends. Climate may be broadly defined as the long-term behavior of this environmental system. To understand fully and to predict changes in the atmospheric component of the climate system, one must understand the sun, oceans, ice sheets, solid earth, and all forms of life.*

Indeed, we must recognize that there is a **climate system** that includes the atmosphere, hydrosphere, solid Earth, biosphere, and cryosphere. (The *cryosphere* is the ice and snow that exist at Earth's surface. See Box 14–1.) The climate system *involves the exchanges of energy and moisture that occur among the five spheres.* These exchanges link the atmosphere to the other spheres so that the whole functions as an extremely complex interactive unit. The major components of the climate system are shown in Figure 14–1.

The climate system provides a framework for the study of climate. The interactions and exchanges among the parts of the climate system create a complex network that links the five spheres. Changes to the climate system do not occur in isolation. Rather, when one part of it changes, the other components also react. This well-established relationship will be demonstrated often as we study climate change and world climates.

How Is Climate Change Detected ?

High-technology and precision instrumentation are now available to study the composition and dynamics of the atmosphere. But such tools are recent inventions and therefore have been providing data for only a short time span. To understand fully the behavior of the atmosphere and to anticipate future climate change, we must somehow discover how climate has changed over broad expanses of time.

Instrumental records go back only a couple of centuries at best, and the further back we go, the less complete and more unreliable the data become. To overcome this lack of direct measurements, scientists must decipher and reconstruct past climates by using indirect evidence. Such **proxy data** comes from natural recorders of climate variability, such as seafloor sediments, glacial ice, fossil pollen, and tree-growth rings, as well as from historical documents. Scientists who analyze proxy data and reconstruct past climates are engaged in the study of **paleoclimatology.** The main goal of such work is to understand the climate of the past in order to assess the current and potential future climate in the context of natural climate variability. In the following discussion, we will briefly examine some of the important sources of proxy data.

Seafloor Sediment—A Storehouse of Climate Data

Most seafloor sediments contain the remains of organisms that once lived near the sea surface (the ocean–atmosphere interface). When such near-surface organisms die, their shells slowly settle to the floor of the ocean, where they become part of the sedimentary record. These seafloor sediments are useful recorders of worldwide climate change because the numbers and types of organisms living near the sea surface change with the climate:

> We would expect that in any area of the ocean/atmosphere interface the average annual temperature of the surface water of the ocean would approximate that of the contiguous atmosphere. The temperature equilibrium established between surface seawater and the air above it should mean that . . . changes in climate

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*The American Meteorological Society and the University Corporation for Atmospheric Research, "Weather and the Nation's Well-Being," *Bulletin of the American Meteorological Society*, 73, no. 12 (December 1991), 2038.

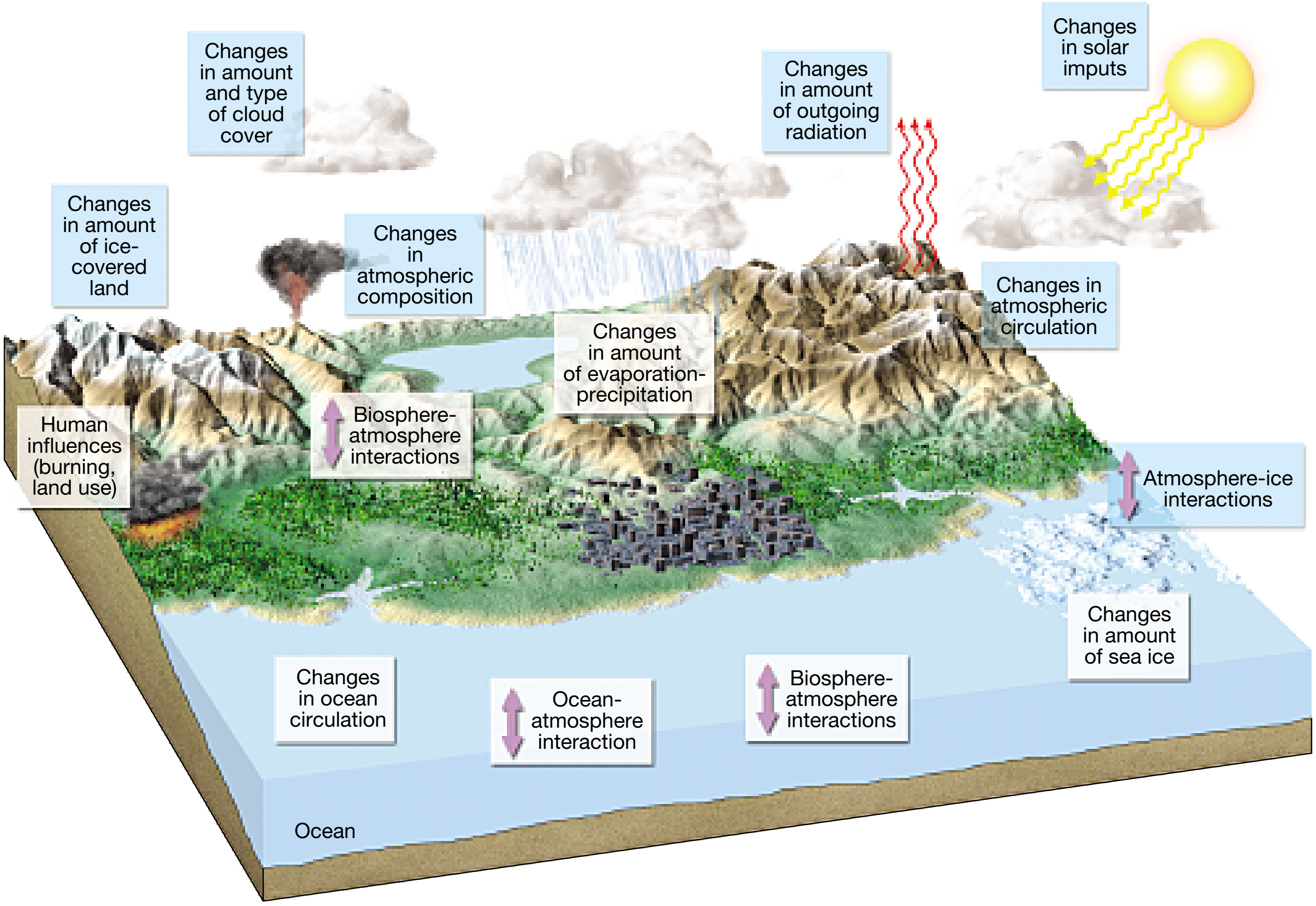

FIGURE 14-1 Schematic view showing several components of Earth's climate system. Many interactions occur among the various components on a wide range of space and time scales, making the system extremely complex.

> should be reflected in changes in organisms living near the surface of the deep sea. . . . When we recall that the seafloor sediments in vast areas of the ocean consist mainly of shells of pelagic foraminifers, and that these animals are sensitive to variations in water temperature, the connection between such sediments and climatic change becomes obvious.*

Thus, in seeking to understand climate change, scientists have become increasingly interested in the huge reservoir of data concealed in seafloor sediments. Since the late 1960s the United States has been involved in major international projects. The pioneering program was the Deep Sea Drilling Project, with its research vessel the *Glomar Challenger,* that began in 1968. In 1983 the Deep Sea Drilling Project was replaced by the Ocean Drilling Program and a new drilling ship, the *JOIDES Resolution* (Figure 14–2). In October 2003 the new Integrated Ocean Drilling Program began. Within a few years two new drilling ships will be in operation. The primary objective of this program is to collect cores from sites where they were previously unobtainable. The new data will expand our understanding of many aspects of the Earth system, including climate-change patterns.

Oxygen Isotope Analysis

Oxygen isotope analysis, is based on precise measurement of the ratio between two isotopes of oxygen: ^{16}O, which is the most common, and the heavier ^{18}O. A molecule of H_2O can form from either ^{16}O or ^{18}O. But the lighter isotope, ^{16}O, evaporates more readily from the oceans. Because of this, precipitation (and hence the glacial ice that it may form) is enriched in ^{16}O. This leaves a greater concentration of the heavier isotope, ^{18}O, in the ocean water. Thus, during periods when glaciers are extensive, more of the lighter ^{16}O is tied up in ice, so the concentration of ^{18}O in seawater increases. Conversely, during warmer interglacial periods when the amount of glacial ice decreases dramatically, more ^{16}O is returned to the sea, so the proportion of ^{18}O relative to ^{16}O in ocean water also drops. Now, if we had some ancient recording of the changes of the $^{18}O/^{16}O$ ratio, we could determine when there were glacial periods and therefore when the climate grew cooler.

Fortunately, we do have such a recording. As certain microorganisms secrete their shells of calcium carbonate

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*Richard F. Flint, *Glacial and Quaternary Geology* (New York: John Wiley & Sons, 1971), p. 718.

BOX 14-1 Cryosphere—The World of Ice*

The word *cryosphere* comes from the Greek word *kryos*, meaning “frost or icy cold.” It refers to that portion of Earth’s surface where water is in a solid form. This includes snow, glaciers, sea ice, freshwater ice, and frozen ground (termed *permafrost*).

Because most of the cryosphere occurs in remote locations, taking measurements in the field can be difficult. Fortunately, the last several decades have seen the development of sophisticated satellite technology that has enabled researchers to monitor the cryosphere on a routine basis. This is important because the cryosphere plays a significant role in the global climate system.

Snow. Seasonal snow cover, the largest component of the cryosphere, covers up to 33 percent of Earth’s total land surface. About 98 percent of the total seasonal snow cover is located in the Northern Hemisphere. Although snowdrifts and avalanches often pose hazards to humans, snow also provides much of the world’s water. For example, snowfall accounts for 60 to 70 percent of annual precipitation in the U.S. Sierra Nevada and Rocky Mountains, and is later released as water during spring snow melt and river runoff.

Glaciers. A *glacier* is a thick mass of ice that originates on land from the accumulation, compaction, and recrystallization of snow (Figure 14–A). Glaciers are moving masses that can be significant agents of erosion. Today glaciers cover about 10 percent of Earth’s land area; in the recent geologic past, ice sheets were three times more extensive.

A body of ice that covers a large area of land and flows outward in all directions is called an *ice cap* or *ice sheet.* Ice caps form in high mountain summit and plateau regions. Two ice sheets currently exist on Earth, one in Greenland and one in Antarctica (see Figure 3–5, p. 72). All continents except Australia have ice in the form of alpine glaciers, ice sheets, or ice caps. Today glaciers and ice sheets store about 75 percent of the world’s freshwater. Because glaciers are sensitive to variations in temperature and precipitation, the rate of their growth or decline can serve as an indicator of regional and global climate change.

Sea Ice. Unlike glacial ice that forms on land from the accumulation and recrystallization of snow, *sea ice* is simply frozen seawater that floats on the ocean surface. The extent of sea ice changes with the seasons. In late winter it typically covers about 14 to 16 million square kilometers in the Arctic and 17 to 20 million square kilometers in the ocean surrounding the Antarctica. The seasonal decrease is much larger in the Antarctic, with only about 3 to 4 million square kilometers remaining at summer’s end, compared to approximately 7 to 9 million square kilometers in the Arctic. Sea ice is of vital importance to marine mammals and birds for which it is habitat. It also plays a role in regulating climate.

Permafrost. *Permafrost,* or permanently frozen ground, is soil, sediment, or rock that remains below 0°C for at least two years. It occupies nearly 23 million square kilometers (about 24 percent of the land surface) of the Northern Hemisphere (see Figure 15–22, p. 462). Permafrost occurs as far north as 84°N latitude in Greenland and as far south as 26°N latitude in the Himalayas. It can contain over 30 percent ice, or practically no ice at all. It can be overlain by several meters of snow, or little or no snow. Understanding permafrost is not only important for civil engineers and architects, it is also a crucial part of studying global change and protecting the environment in cold regions.

*Based in part on material prepared by the National Snow and Ice Data Center (NSIDC), http://nsidc.org

($CaCO_3$), the prevailing $^{18}O/^{16}O$ ratio is reflected in the composition of these hard parts. When the organisms die, their hard parts settle to the ocean floor, becoming part of the sediment layers there. Consequently, periods of glacial activity can be determined from variations in the oxygen isotope ratio found in shells of certain microorganisms buried in deep-sea sediments.

The $^{18}O/^{16}O$ ratio also varies with temperature. Thus, more ^{18}O is evaporated from the oceans when temperatures are high, and less is evaporated when temperatures are low. Therefore, the heavy isotope is more abundant in the precipitation of warm eras and less abundant during colder periods. Using this principle, scientists studying the layers of ice and snow in glaciers have been able to produce a record of past temperature changes.

Climate Change Recorded in Glacial Ice

Ice cores are an indispensable source of data for reconstructing past climates. Research based on vertical cores taken from the Greenland and Antarctic ice sheets has changed our basic understanding of how the climate system works.

Scientists collect samples with a drilling rig, like a small version of an oil drill. A hollow shaft follows the drill head

FIGURE 14-A Aerial view of glaciers in Alaska's Denali National Park. *(Photo by Michael Collier)*

into the ice, and an ice core is extracted. In this way, cores that sometimes exceed 2000 meters (6500 feet) in length and may represent more than 200,000 years of climate history are acquired for study (Figure 14–3a).

The ice provides a detailed record of changing air temperatures and snowfall. Air bubbles trapped in the ice record variations in atmospheric composition. Changes in carbon dioxide and methane are linked to fluctuating temperatures. The cores also include atmospheric fallout such as wind-blown dust, volcanic ash, pollen, and modern-day pollution.

Past temperatures are determined by *oxygen isotope analysis.* Using this technique, scientists are able to produce a record to past temperature changes. A portion of such a record is shown in Figure 14–3b.

Tree Rings—Archives of Environmental History

If you look at the end of a log, you will see that it is composed of a series of concentric rings. Each of these *tree rings* becomes larger in diameter outward from the center (Figure 14–4). Every year in temperate regions trees add a layer of new wood under the bark. Characteristics of each tree ring, such as size and density, reflect the environmental conditions (especially climate) that prevailed

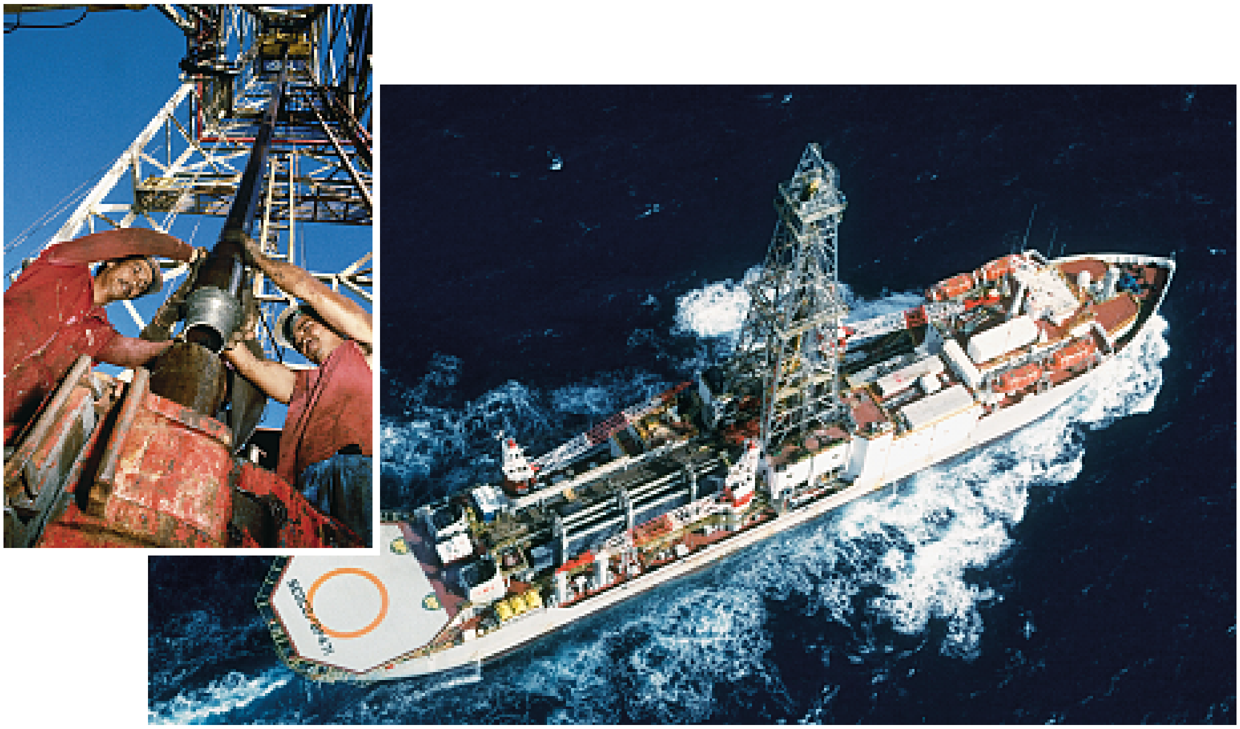
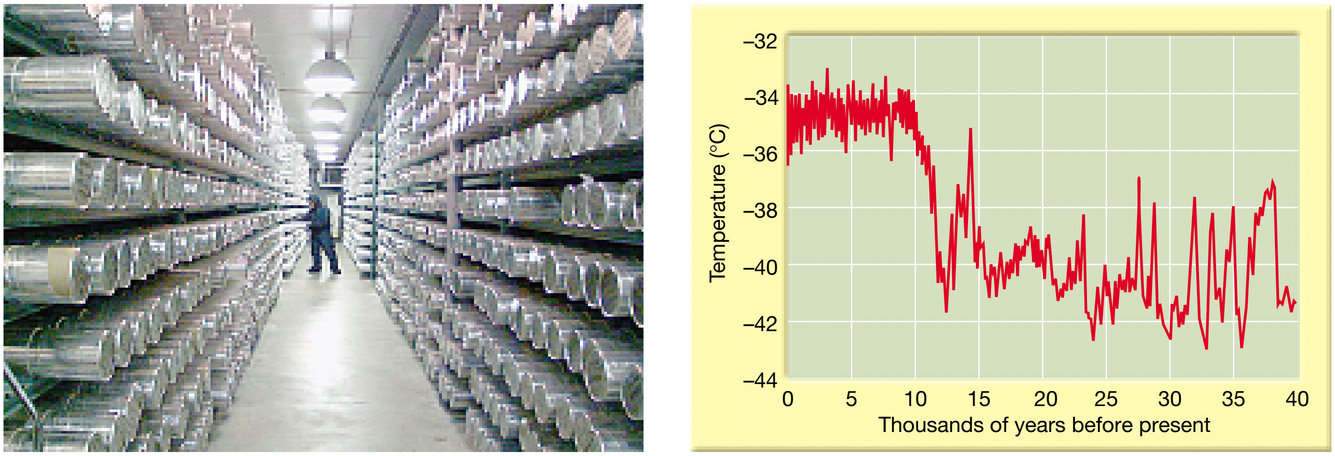


FIGURE 14-2 The *JOIDES Resolution*, drilling ship of the Ocean Drilling Program. During cruises, holes are drilled deep into the sea floor. The cores of sediment and rock that are recovered represent millions of years of Earth history and are used by scientists to study many aspects of Earth science, including changes in global climate. The ship can drill in water depths up to 8200 meters (about 27,000 feet) and can deploy as much as 9100 meters (about 30,000 feet) of drill pipe. *(Photos courtesy of the Ocean Drilling Program)*

during the year when the ring formed. Favorable growth conditions produce a wide ring; unfavorable ones produce a narrow ring. Trees growing at the same time in the same region show similar tree-ring patterns.

Because a single growth ring is usually added each year, the age of the tree when it was cut can be determined by counting the rings. If the year of cutting is known, the age of the tree and the year in which each ring formed can be determined by counting back from the outside ring. Scientists are not limited to working with trees that have been cut down. Small, nondestructive core samples can be taken from living trees.

FIGURE 14-3 (a) The National Ice Core Laboratory is a physical plant for storing and studying cores of ice taken from glaciers around the world. These cores represent a long-term record of material deposited from the atmosphere. The lab provides scientists with the capability to conduct examinations of ice cores, and it preserves the integrity of these samples in a repository for the study of global climate change and past environmental conditions. *(Photo by USGS/ National Ice Core Laboratory)* (b) This graph showing temperature variations over the past 40,000 years is derived from oxygen isotope analysis of ice cores recovered from the Greenland ice sheet. *(After U.S. Geological Survey)*



(a)

(b)

FIGURE 14-4 Each year a growing tree produces a layer of new cells beneath the bark. If the tree is felled and the trunk examined (or if a core is taken, to avoid cutting the tree), each year's growth can be seen as a ring. Because the amount of growth (thickness of a ring) depends upon precipitation and temperature, tree rings are useful records of past climates. *(Photo by Stephen J. Krasemann/DRK Photo)*

To make the most effective use of tree rings, extended patterns known as *ring chronologies* are established. They are produced by comparing the patterns of rings among trees in an area. If the same pattern can be identified in two samples, one of which has been dated, the second sample can be dated from the first by matching the ring patterns common to both. Tree-ring chronologies extending back for thousands of years have been established for some regions. To date a timber sample of unknown age, its ring pattern is matched against the reference chronology.

Tree-ring chronologies are unique archives of environmental history and have important applications in such disciplines as climate, geology, ecology, and archaeology. For example, tree rings are used to reconstruct climate variations within a region for spans of thousands of years prior to human historical records. Knowledge of such long-term variations is of great value in making judgments regarding the recent record of climate change.

Other Types of Proxy Data

Other sources of proxy data that are used to gain insight into past climates include fossil pollen, corals, and historical documents.

Fossil Pollen. Climate is a major factor influencing the distribution of vegetation, so knowing the nature of the plant community occupying an area is a reflection of the climate. Pollen and spores are parts of the life cycles of many plants, and because they have very resistant walls, they are often the most abundant, easily identifiable, and best-preserved plant remains in sediments. By analyzing pollen from accurately dated sediments, it is possible to obtain high-resolution records of vegetational changes in an area. From such information, past climates can be reconstructed.

Corals. Coral reefs consist of colonies of corals that live in warm shallow waters and form atop the hard material left behind by past corals (Figure 14–5). Corals build their hard skeletons from calcium carbonate ($CaCO_3$) extracted from seawater. The carbonate contains isotopes of oxygen that can be used to determine the temperature of the water in which the coral grew. Useful information on past climate conditions are determined by analyzing the changing chemistry of coral reefs with depth.

Historical Data. Historical documents sometimes contain helpful information. Although it might seem that such records should readily lend themselves to climate analysis, such is not the case. Most manuscripts were written for purposes other than climate description. Furthermore, writers understandably neglected periods of relatively stable atmospheric conditions and mention only droughts, severe storms, memorable blizzards, and other extremes. Nevertheless, records of crops, floods, and the migration of people have furnished useful evidence of the possible influences of changing climate.

Natural Causes of Climate Change

A great variety of hypotheses have been proposed to explain climate change. Several have gained wide support, only to lose it and then sometimes to regain it again. Some explanations are controversial. This is to be expected, because planetary atmospheric processes are so large-scale and complex that they cannot be reproduced physically in laboratory experiments. Rather, climate and its changes must be simulated mathematically (modeled) using powerful computers.

In this section we examine several current hypotheses that have earned serious consideration from the scientific community. These describe "natural" mechanisms of climatic change, causes that are unrelated to human activities:

- Plate tectonics (rearranging Earth's continents, moving them closer or farther from the equator and the poles).
- Volcanic activity (changing the reflectivity of the atmosphere and reducing the solar radiation that reaches the surface).
- Variations in Earth's orbit (the natural, cyclic change in our planet's orbit, axial tilt, and wobble).
- Solar variability (Does the Sun vary in its radiation output? Do sunspots affect the output?)

A later section examines human-made climate changes, including the effect of rising carbon dioxide levels caused primarily by our burning of fossil fuels.

As you read this section, you will find that more than one hypothesis may explain the same climatic change. In fact, several mechanisms may interact to shift climate. Also, no single hypothesis can explain climate change on all time scales. A proposal that explains variations over millions of years generally cannot explain fluctuations over hundreds

FIGURE 14-5 Coral colonies thrive in warm, shallow tropical waters. The tiny invertebrates extract calcium carbonate from seawater to build hard parts. They live atop the solid foundation left by past coral. Chemical analysis of the changing composition of coral reefs with depth can provide useful data on past near-surface water temperatures. Moreover, because corals are associated with shallow depths, relic reefs can sometimes provide clues to changes in sea level. *(Photo courtesy of Jeff Hunter/Photographer's Choice/Getty)*

of years. If our atmosphere and its changes ever become fully understood, we will probably see that climate change is caused by many of the mechanisms discussed here, plus new ones yet to be proposed.

Plate Tectonics and Climate Change

Over the past several decades a revolutionary idea has emerged from the science of geology: **plate tectonics theory.** This theory now has gained nearly universal acceptance in the scientific community. It states that the outer portion of Earth is made up of several vast rigid slabs, called *plates,* which move in relation to one another over a weak plastic rock layer below. They move with incredible slowness, at only a few centimeters a year.

Most of the largest plates include an entire continent plus a lot of seafloor. Thus, as plates ponderously grind along, the continents also change position. Not only does this theory allow geologists to understand and explain many processes and features of Earth's continents and oceans, but it also provides the climatologist with a probable explanation for some hitherto unexplainable climate changes.

For example, glacial evidence in the present-day warm areas of Africa, Australia, South America, and India indicate that these regions experienced an ice age about 250 million years ago. This finding puzzled scientists for many years. How could the climate in these presently warm latitudes once have been frigid like Greenland and Antarctica?

Until the plate-tectonics theory was proved, no reasonable explanation existed. Today scientists realize that the areas containing these ancient glacial features were joined as a single "supercontinent" that was located toward the South Pole (Figure 14–6a). Later, as the plates spread apart, portions of the landmass, each moving on a different plate, slowly migrated toward their present locations. Thus, large fragments of glaciated terrain have ended up in widely scattered subtropical locations (Figure 14–6b).

It is now understood that during the geologic past, plate movements accounted for many other dramatic climate changes as landmasses shifted in relation to one another and moved to different latitudes. Changes in oceanic circulation must also have occurred, altering the transport of heat and moisture and, hence, the climate as well.

Because the rate of plate movement is so slow, appreciable changes in the positions of the continents occur only over *great* spans of geologic time. Thus, climatic changes brought about by plate movements are extremely gradual and happen on a scale of millions of years. As a result, the

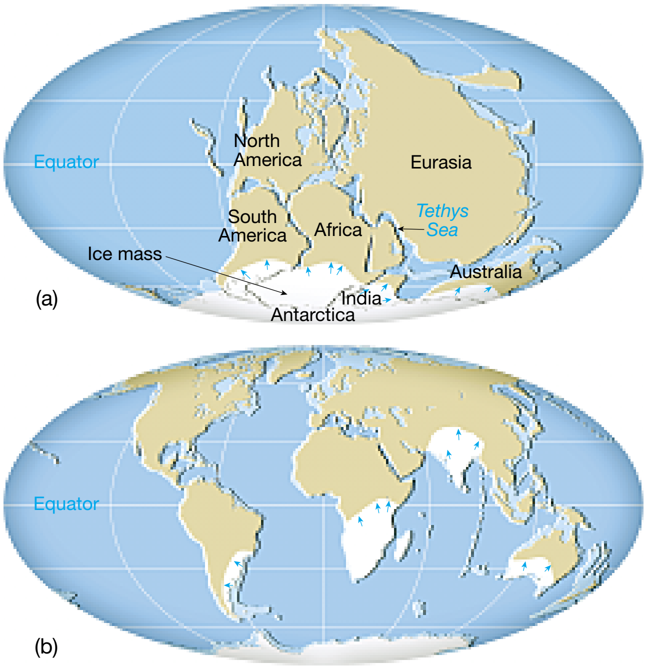


FIGURE 14-6 (a) The supercontinent Pangaea showing the area covered by glacial ice 300 million years ago. (b) The continents as they are today. The white areas indicate where evidence of old ice sheets exists.

theory of plate tectonics is not useful for explaining climate variations that occur on shorter time scales, such as tens, hundreds, or thousands of years. Other explanations must be sought to explain these changes.

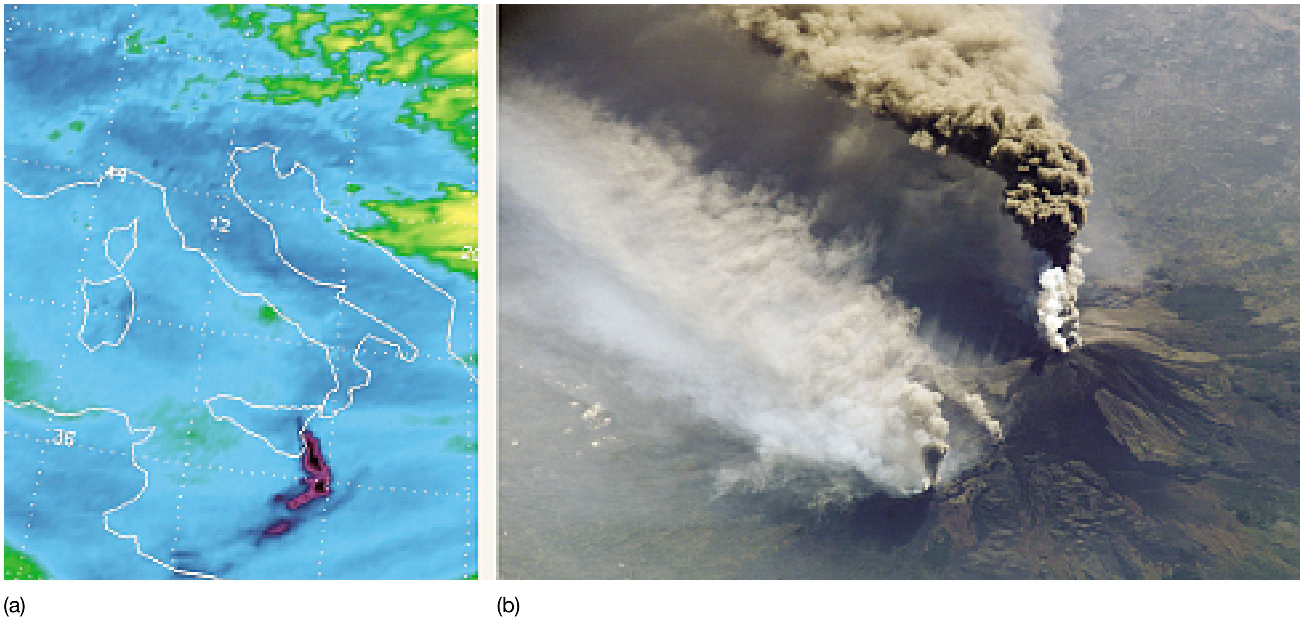
Volcanic Activity and Climate Change

The idea that explosive volcanic eruptions might alter Earth's climate was first proposed many years ago. It is still regarded as a plausible explanation for some aspects of climatic variability. Explosive eruptions emit huge quantities of gases and fine-grained debris into the atmosphere (Figure 14–7). The greatest eruptions are sufficiently powerful to inject material high into the stratosphere, where it spreads around the globe and remains for many months or even years.

The Basic Premise. The basic premise is that this suspended volcanic material will filter out a portion of the incoming solar radiation, which in turn will lower temperatures in the troposphere. More than 200 years ago Benjamin Franklin used this idea to argue that material from the eruption of a large Icelandic volcano could have reflected sunlight back to space and therefore might have been responsible for the unusually cold winter of 1783–1784.

Perhaps the most notable cool period linked to a volcanic event is the "year without a summer" that followed the 1815 eruption of Mount Tambora in Indonesia. The eruption of Tambora is the largest of modern times. During April 7–12, 1815, this nearly 4000-meter-high (13,000-foot) volcano violently expelled more than 100 cubic kilometers

FIGURE 14-7 Mount Etna, a volcano on the island of Sicily, erupting in late October 2002. Mount Etna is Europe's largest and most active volcano. (a) This image from the Atmospheric Infrared Sounder on NASA's *Aqua* satellite shows the sulfur dioxide (SO_2) plume in shades of purple and black. Climate may be affected when large quantities of SO_2 are injected into the atmosphere. (b) This photo of Mount Etna looking southeast was taken by a member of the International Space Station. It shows a plume of volcanic ash streaming southeastward from the volcano. *(Images courtesy of NASA)*



(24 cubic miles) of volcanic debris. The impact of the volcanic aerosols on climate is believed to have been widespread in the Northern Hemisphere. From May through September 1816 an unprecedented series of cold spells affected the northeastern United States and adjacent portions of Canada. There was heavy snow in June and frost in July and August. Abnormal cold was also experienced in much of Western Europe. Similar, although apparently less dramatic, effects were associated with other great explosive volcanoes, including Indonesia's Krakatoa in 1883.

Three major volcanic events have provided considerable data and insight regarding the impact of volcanoes on global temperatures. The eruptions of Washington State's Mount St. Helens in 1980, the Mexican volcano El Chichón in 1982, and the Philippines' Mount Pinatubo in 1991 have given scientists an opportunity to study the atmospheric effects of volcanic eruptions with the aid of more sophisticated technology than had been available in the past. Satellite images and remote-sensing instruments allowed scientists to monitor closely the effects of the clouds of gases and ash that these volcanoes emitted.

Mount St. Helens. When Mount St. Helens erupted, there was immediate speculation about the possible effects on our climate. Could such an eruption cause our climate to change? There is no doubt that the large quantity of volcanic ash emitted by the explosive eruption had significant local and regional effects for a short period. Still, studies indicated that any longer-term lowering of hemispheric temperatures was negligible. The cooling was so slight, probably less than 0.1°C (0.2°F), that it could not be distinguished from other natural temperature fluctuations.

El Chichón. Two years of monitoring and studies following the 1982 El Chichón eruption indicated that its cooling effect on global mean temperature was greater than that of Mount St. Helens, on the order of 0.3 to 0.5°C (0.5 to 0.9°F). The eruption of El Chichón was *less explosive* than the Mount St. Helens blast, so why did it have a greater impact on global temperatures? The reason is that the material emitted by Mount St. Helens was largely fine ash that settled out in a relatively short time. El Chichón, on the other hand, emitted far greater quantities of sulfur dioxide gas (an estimated 40 times more) than Mount St. Helens. This gas combines with water vapor in the stratosphere to produce a dense cloud of tiny sulfuric-acid particles (Figure 14–8). The particles, called *aerosols,* take several years to settle out completely. They lower the troposphere's mean temperature because they reflect solar radiation back into space.

We now understand that volcanic clouds that remain in the stratosphere for a year or more are composed largely of sulfuric-acid droplets and not of dust, as was once thought. Thus, the volume of fine debris emitted during an explosive event is not an accurate criterion for predicting the global atmospheric effects of an eruption.

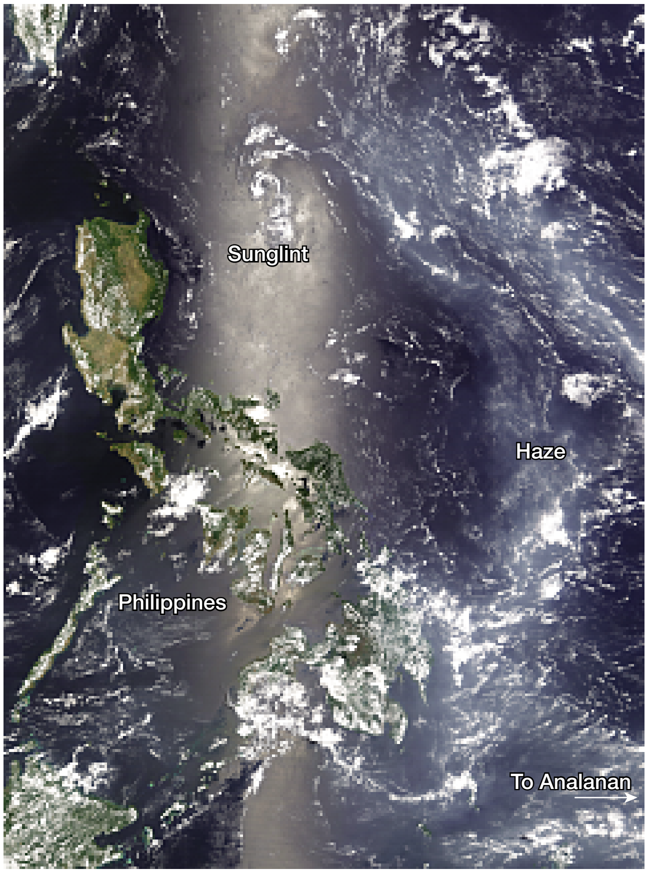


FIGURE 14-8 This satellite image shows a plume of white haze from Anatahan Volcano, blanketing a portion of the Philippine Sea following a large eruption in April 2005. The haze is *not* volcanic ash. Rather, it consists of tiny droplets of sulfuric acid formed when sulfur dioxide form the volcano combined with water in the atmosphere. The haze is bright and reflects sunlight back to space. To the left of the haze, the Sun is reflecting from the smooth surface of the ocean. The effect is a silvery mirror called *sunglint* that extends down a narrow strip of the image where the Sun's angle was just right to reflect light directly into the sensor. *(NASA image)*

Mount Pinatubo. The Philippines volcano, Mount Pinatubo, erupted explosively in June 1991, injecting 25 million to 30 million tons of sulfur dioxide into the stratosphere. The event provided scientists with an opportunity to study the climatic impact of a major explosive volcanic eruption using NASA's spaceborne Earth Radiation Budget Experiment. During the next year the haze of tiny aerosols increased albedo and lowered global temperatures by 0.5°C (0.9°F).

It may be true that the impact on global temperature of eruptions like El Chichón and Mount Pinatubo is relatively minor, but many scientists agree that the cooling produced could alter the general pattern of atmospheric circulation for a limited period. Such a change, in turn, could influence the weather in some regions. Predicting or even identifying specific regional effects still presents a considerable challenge to atmospheric scientists.

The preceding examples illustrate that the impact on climate of a single volcanic eruption, no matter how great, is relatively small and short-lived. Therefore, if volcanism is to have a pronounced impact over an extended period, many great eruptions, closely spaced in time, need to occur. If this happens, the stratosphere would be loaded with enough gases and volcanic dust to seriously diminish the amount of solar radiation reaching the surface. Because no such period of explosive volcanism is known to have occurred in historic times, it is most often mentioned as a possible contributor to prehistoric climatic shifts. Another way in which volcanism may influence climate is described in Box 14–2.

Students Sometimes Ask…

Could a meteorite colliding with Earth cause the climate to change?

Yes, it is possible. For example, the most strongly supported hypothesis for the extinction of dinosaurs (about 65 million years ago) is related to such an event. When a large (about 10 kilometers in diameter) meteorite struck Earth, huge quantities of debris were blasted high into the atmosphere. For months the encircling dust cloud greatly restricted the amount of light reaching Earth's surface. Without sufficient sunlight for photosynthesis, delicate food chains collapsed. When the sunlight returned, more than half of the species on Earth, including the dinosaurs and many marine organisms, had become extinct.

Orbital Variations

"Variations in the earth's orbit influence climate by changing the seasonal and latitudinal distribution of incoming solar radiation."* Proposals that link orbital variations and climate change have been around since early in the nineteenth century. However, credit for developing the modern theory that relates Earth motions and climate change is given to the Yugoslavian astronomer Milutin Milankovitch (1879–1954). He formulated a comprehensive mathematical model based on the following elements:

1. Variations in the shape (**eccentricity**) of Earth's orbit about the Sun.
2. Changes in **obliquity**—changes in the angle that Earth's axis makes with the plane of Earth's orbit.
3. **Precession**—the wobbling of Earth's axis, like a spinning top that is winding down.

The three motions together are called **Milankovitch cycles.** We will now look at each.

Orbital Eccentricity. Although variations in the distance between Earth and Sun are of minor significance in understanding current seasonal temperature differences, they may play an important role in producing global climate changes on a time scale of thousands of years. A difference of only 3 percent exists between aphelion, which occurs about July 4 in the middle of the Northern Hemisphere summer, and perihelion, which takes place in the midst of the Northern Hemisphere winter about January 3.

This small difference in distance means that Earth receives about 6 percent more solar energy in January than in July. Such is not always the case, however. The shape of Earth's orbit changes during a cycle that astronomers say takes between 90,000 and 100,000 years: It stretches into a longer ellipse and then returns to a more circular shape (Figure 14–9a). When the orbit is most elliptical, the amount of radiation received at closest approach (perihelion) would be on the order of 20 to 30 percent greater than at aphelion. This would most certainly result in a substantially different climate from what we now have.

Change in Axial Tilt. In Chapter 2 the inclination of Earth's axis to the plane of its orbit was shown to be the most significant cause for seasonal temperature change. At present the angle that Earth's axis makes with the plane of its orbit is about 23.5°. But this angle changes. During a cycle that averages about 41,000 years, the tilt of the axis varies between 22.1 and 24.5° (Figure 14–9b). Because this angle varies, the severity of the seasons must also change. The smaller our tilt, the smaller the temperature difference between winter and summer.

It is believed that such a reduced seasonal contrast could promote the growth of ice sheets. Because winters could be warmer, more snow would fall because the capacity of air to hold moisture increases with temperature. Conversely, summer temperatures would be cooler, meaning that less snow would melt. The result could be the growth of ice sheets.

Precession. Like a partly rundown top, Earth is wobbling slowly as it spins on its axis. At present, the axis points toward the star Polaris (often called the North Star). However, about the year A.D. 14,000, the axis will point toward the bright star Vega, which will then become the North Star (Figure 14–9c). Because the period of precession is about 26,000 years, Polaris will once again be the North Star by the year 28,000.

As a result of this cyclical wobble of the axis, a climatically significant change must take place. When the axis is tilted toward Vega in about 12,000 years, the orbital positions at which the winter and summer solstices occur will be reversed. Consequently, the Northern Hemisphere will experience winter near aphelion (when Earth is farthest from the Sun), and summer will occur near perihelion (when our planet is closest to the Sun). Thus, seasonal contrasts will be greater because winters will be colder and summers will be warmer than at present.

Milankovitch Cycles. Using these factors, Milankovitch calculated variations in the receipt of solar energy and the corresponding surface temperature of Earth back into time in an attempt to correlate these changes with the climate fluctuations of the Ice Age. In explaining climate changes that result from these three variables, it should be

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*John Imbrie and John Z. Imbrie, "Modeling the Climatic Response to Orbital Variations," *Science*, 207, no. 4434 (1980), 943.

BOX 14-2

A Possible Link Between Volcanism and Climate Change in the Geologic Past

The Cretaceous Period is the last period of the Mesozoic Era, the era of *middle life* that is often called the Age of Dinosaurs. It began about 144 million years ago and ended about 65 million years ago with the extinction of the dinosaurs (and many other life forms as well).

The Cretaceous climate was among the warmest in Earth's long history. Dinosaurs, which are associated with mild temperatures, ranged north of the Arctic Circle. Tropical forests existed in Greenland and Antarctica, and coral reefs grew as much as 15 degrees latitude closer to the poles than at present. Deposits of peat that would eventually form widespread coal beds accumulated at high latitudes. Sea level was as much as 200 meters (650 feet) higher than today, indicating that there were no polar ice sheets.

What was the cause of the unusually warm climates of the Cretaceous Period? Among the significant factors that may have contributed was an enhancement of the greenhouse effect due to an increase in the amount of carbon dioxide in the atmosphere.

Where did the additional CO_2 come from that contributed to the Cretaceous warming? Many geologists suggest that the probable source was volcanic activity. Carbon dioxide is one of the gases emitted during volcanism, and there is now considerable geologic evidence that the Middle Cretaceous was a time when there was an unusually high rate of volcanic activity. Several huge oceanic lava plateaus were produced on the floor of the western Pacific during this span. These vast features were associated with hot spots, zones where mobile plumes of material rise to the surface from deep in Earth's interior. Massive outpourings of lava over millions of years would have been accompanied by the release of huge quantities of CO_2, which in turn would have enhanced the atmospheric greenhouse effect. *Thus, the warmth that characterized the Cretaceous may have had is origins deep in Earth's interior.*

There were other probable consequences of this extraordinarily warm period that are linked to volcanic activity. For example, the high global temperatures and enriched atmospheric CO_2 in the Cretaceous led to increases in the quantity and types of phytoplankton (tiny, mostly microscopic plants, such as algae) and other life forms in the ocean. The expansion in marine life is reflected in the widespread chalk deposits associated with the Cretaceous Period (Figure 14–B). Chalk consists of the calcium-carbonate ($CaCO_3$) rich hard parts of microscopic marine organisms. Oil and gas originate from the alteration of biological remains (chiefly phytoplankton). Some of the world's most important oil and gas fields occur in marine sediments of Cretaceous age, a consequence of the greater abundance of marine life during this warm time.

This list of possible consequences linked to the extraordinary period of volcanism during the Cretaceous Period is far from complete, yet it serves to illustrate the interrelationships among parts of the Earth system. Materials and processes that at first might seem to be completely unrelated turn out to be linked. Here you have seen how processes originating deep in Earth's interior are connected directly or indirectly to the atmosphere, the oceans, and the biosphere.

FIGURE 14-B These famous chalk deposits, known as the White Cliffs of Dover, are associated with the expansion of marine life that occurred during the exceptional warmth of the Cretaceous Period. *(Laguna Photo/Getty Images, Inc./Liaison)*

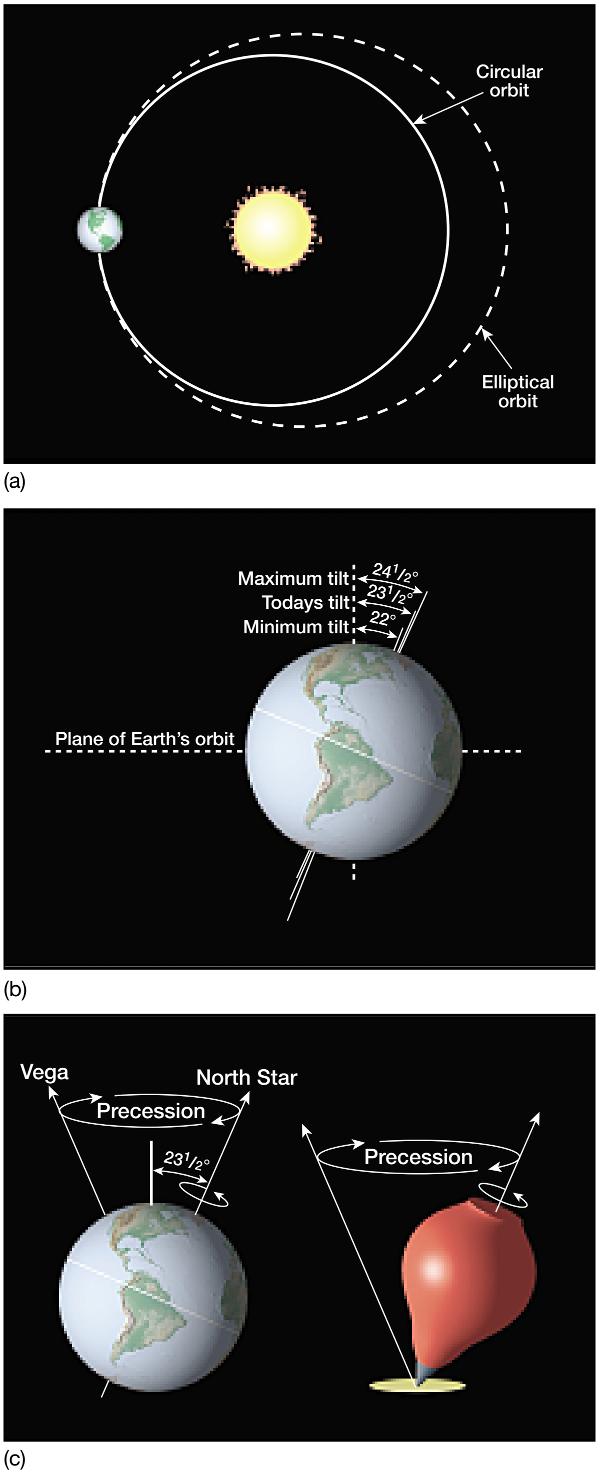

FIGURE 14-9 Orbital variations. (a) The shape of Earth's orbit changes during a cycle that spans about 100,000 years. It gradually changes from nearly circular to one that is more elliptical and then back again. This diagram greatly exaggerates the amount of change. (b) Today the axis of rotation is tilted about 23.5° to the plane of Earth's orbit. During a cycle of 41,000 years, this angle varies from 21.5° to 24.5°. (c) Precession. Earth's axis wobbles like that of a spinning top. Consequently, the axis points to different spots in the sky during a cycle of about 26,000 years.

pointed out that they cause little or no variation in the total annual solar energy reaching the ground. Instead, their impact is felt because they change the degree of contrast between the seasons.

Ever since Milankovitch's pioneering work, the time scales for orbital and insolational changes have been recalculated several times. Past errors have been corrected and measurements have been made with greater precision. Over the years, the Milankovitch cycles, as they are known, have become widely accepted, then largely rejected, and now, in light of recent investigations, have been shown to be a viable explanation for some aspects of climate change.

Among the studies that added credibility to Milankovitch cycles is one that examined deep-sea sediments.[*] Through oxygen isotope analysis and statistical analyses of climatically sensitive microorganisms, the study established a chronology of temperature change going back 450,000 years. This time scale of climate change was then compared to astronomical calculations of eccentricity, obliquity, and precession to determine if a correlation did indeed exist. (Note that the study was not aimed at identifying or evaluating the *mechanisms* by which the climate is modified by the three orbital variables. The goal simply was to see whether past changes in climate and the orbital variables corresponded.)

Although the study was involved and mathematically complex, its conclusions were straightforward. The authors found that major variations in climate over the past several hundred thousand years were closely associated with changes in the geometry of Earth's orbit. Cycles of climate change were shown to correspond closely with the periods of obliquity, precession, and orbital eccentricity. More specifically, they stated: "It is concluded that changes in the earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages."[**]

Also, the study went on to predict the future trend of climate, toward a cooler climate and extensive glaciation in the Northern Hemisphere. But there are two qualifications: (1) that the prediction apply only to the *natural* component of climate change and ignore any human influence and (2) that it be a forecast of *long-term trends* because it must be linked to factors that have periods of 20,000 years and longer. Thus, even if the prediction is correct, it contributes little to our understanding of climate changes over briefer periods of tens to hundreds of years because the cycles are too long for this purpose. Since the time of this study, subsequent research has supported its basic conclusions, namely:

> Orbital variations remain the most thoroughly examined mechanism of climatic change on time scales of tens of thousands of years and are by far the clearest case of a direct effect of changing insolation on the lower atmosphere of Earth.[***]

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[*] J. D. Hays, John Imbrie, and N. J. Shackleton, "Variations in the Earth's Orbit: Pacemaker of the Ice Ages," *Science*, 194, no. 4270 (1976), 1121–1132.

[**] J. D. Hays, et al., p. 1131. The term "Quaternary" refers to the period on the geologic time scale that encompasses the last 1.8 million years.

[***] National Research Council, *Solar Variability, Weather, and Climate* (Washington, D.C.: National Academy Press, 1982), p. 7.

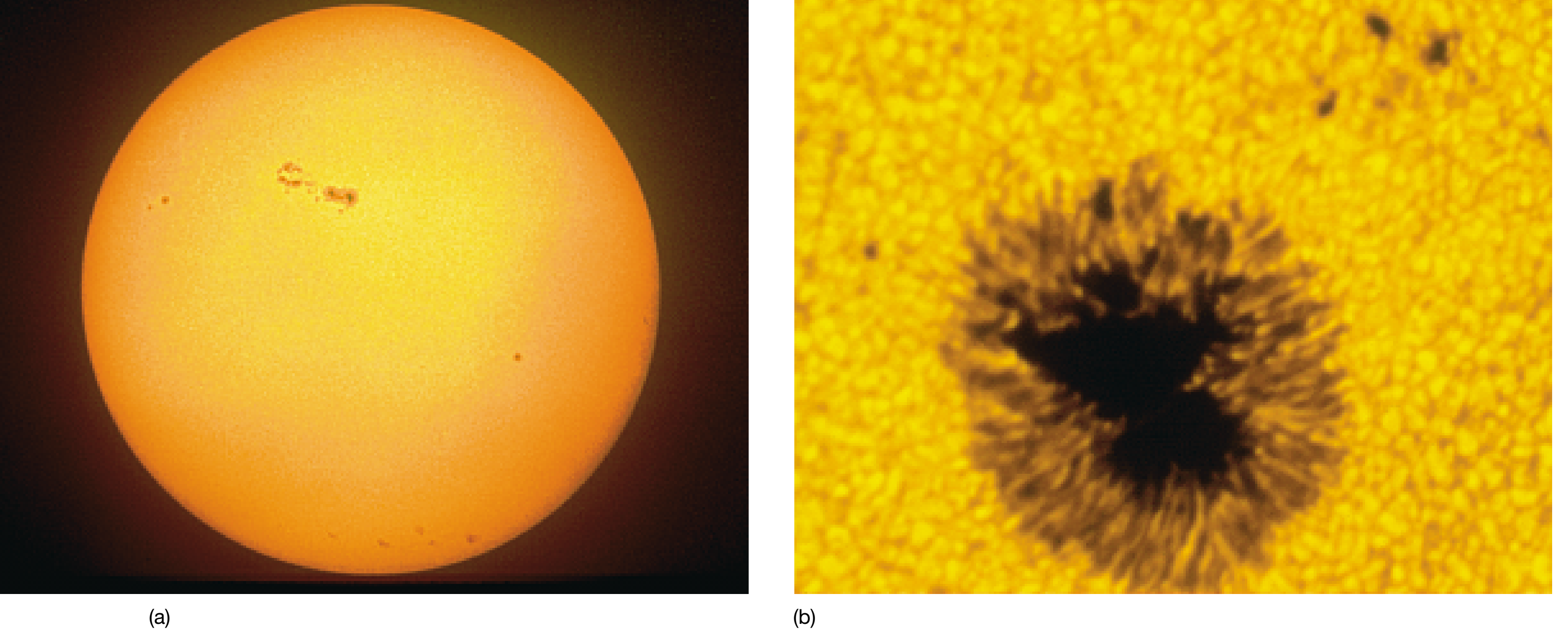

FIGURE 14-10 (a) Large sunspot group on the solar disk. *(Celestron 8 photo courtesy of Celestron International)* (b) Sunspots having visible umbra (dark central area) and penumbra (lighter area surrounding umbra). *(Courtesy of National Optical Astronomy Observatories)*

If the Milankovitch cycles indeed explain alternating glacial–interglacial periods, a question immediately arises: Why have glaciers been absent throughout most of Earth's history? Prior to plate-tectonics theory, there was no widely accepted answer. In fact, this question was a major obstacle for the supporters of Milankovitch's hypothesis. Today we have a plausible answer. Because glaciers can form only on the continents, landmasses must exist somewhere in the higher latitudes before an ice age can commence. Long-term temperature fluctuations are not great enough to create widespread glacial conditions in the tropics. Thus, many now suggest that ice ages have occurred only when Earth's shifting crustal plates carried the continents from tropical latitudes to more poleward positions.

Solar Variability and Climate

Among the most persistent hypotheses of climate change have been those based on the idea that the Sun is a variable star and that its output of energy varies through time. The effect of such changes would seem direct and easily understood: Increases in solar output would cause the atmosphere to warm, and reductions would result in cooling. This notion is appealing because it can be used to explain climate change of any length or intensity. However, no major *long-term* variations in the total intensity of solar radiation have yet been measured outside the atmosphere. Such measurements were not even possible until satellite technology became available. Now that it is possible, we will need many years of records before we begin to sense how variable (or invariable) energy from the Sun really is.

Several proposals for climate change, based on a variable Sun, relate to sunspot cycles. The most conspicuous and best-known features on the surface of the Sun are the dark blemishes called **sunspots** (Figure 14–10). Sunspots are huge magnetic storms that extend from the Sun's surface deep into the interior. Moreover, these spots are associated with the Sun's ejection of huge masses of particles that, on reaching Earth's upper atmosphere, interact with gases there to produce auroral displays (see Figure 1–27, p. 26).

Along with other solar activity, the numbers of sunspots seem to increase and decrease in a regular way, creating a cycle of about 11 years. The graph in Figure 14–11 shows the annual number of sunspots, beginning in the early 1700s. However, this pattern does not always occur. There have been periods when the Sun was essentially free of sunspots. In addition to the well-known 11-year cycle, there is also a 22-year cycle. This longer cycle is based on the fact that the magnetic polarities of sunspot clusters reverse every successive 11 years.

Interest in possible Sun–climate effects has been sustained by an almost continuous effort to find correlations on time scales ranging from days to tens of thousands of years. Two widely debated examples are briefly described here.

Sunspots and Temperature. Studies indicate prolonged periods when sunspots have been absent or nearly so. Moreover, these events correspond closely with cold periods in Europe and North America. Conversely, periods characterized by plentiful sunspots have correlated well with warmer times in these regions.

Referring to these matches, some scientists have suggested that such correlations make it appear that changes on the Sun are an important cause of climate change. But other scientists seriously question this notion. Their hesitation stems in part from subsequent investigations using different climate records from around the world that failed to find a

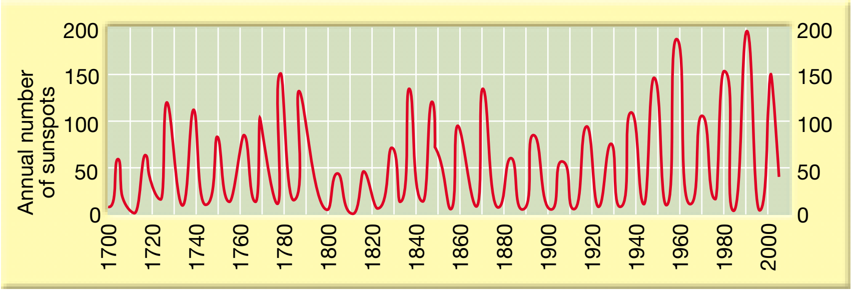

FIGURE 14-11 Mean annual sunspot numbers.

significant correlation between solar activity and climate. Even more troubling is that no testable physical mechanism exists to explain the purported effect.

Sunspots and Drought. A second possible Sun–climate connection, on a time scale different from the preceding example, relates to variations in precipitation rather than temperature. An extensive study of tree rings revealed a recurrent period of about 22 years in the pattern of droughts in the western United States. This periodicity coincides with the 22-year magnetic cycle of the Sun mentioned earlier.

Commenting on this possible connection, a panel of the National Research Council pointed out:

> No convincing mechanism that might connect so subtle a feature of the sun to drought patterns in limited regions has yet appeared. Moreover, the cyclic pattern of droughts found in tree rings is itself a subtle feature that shifts from place to place within the broad region of the study.*

Possible connections between solar variability and climate would be much easier to determine if researchers could identify physical linkages between the Sun and the lower atmosphere. But despite much research, no connection between solar variations and weather has yet been well established. Apparent correlations have almost always faltered when put to critical statistical examination or when tested with different data sets. As a result, the subject has been characterized by ongoing controversy and debate.

Human Impact on Global Climate

So far we have examined four potential causes of climate change, each of them natural. In this section we discuss how humans may contribute to global climate change (see Box 14–3). One impact largely results from the addition of carbon dioxide and other greenhouse gases to the atmosphere. A second impact is related to the addition of human-generated aerosols to the atmosphere.

Many people assume that human influence on regional and global climate began with the onset of the modern industrial period, but this probably is not so. There is good evidence that people have been modifying the environment over extensive areas for thousands of years. The use of fire and the overgrazing of marginal lands by domesticated animals have both reduced the abundance and distribution of vegetation. By altering ground cover, humans have modified such important climatological factors as surface albedo, evaporation rates, and surface winds. Commenting on this aspect of human-induced climate modification, the late astronomer Carl Sagan noted: “In contrast to the prevailing view that only modern humans are able to alter climate, we believe it is more likely that the human species has made a substantial and continuing impact on climate since the invention of fire.”*

Recently, Carl Sagan’s ideas were reinforced and expanded upon by a study that used data collected from Antarctic ice cores. This research suggested that humans may have started to have a significant impact on atmospheric composition and global temperatures thousands of years ago.

> Humans started slowly ratcheting up the thermostat as early as 8000 years ago, when they began clearing forests for agriculture, and 5000 years ago with the arrival of wet-rice cultivation. The greenhouse gases carbon dioxide and methane given off by these changes would have warmed the world. . . .**

Carbon Dioxide, Trace Gases, and Climate Change

In Chapter 1 you learned that carbon dioxide (CO_2) represents only about 0.038 percent of the gases that make up clean, dry air. Nevertheless, it is a very significant component meteorologically. Carbon dioxide is influential because it is transparent to incoming short-wavelength solar radiation, but it is not transparent to some of the longer-wavelength outgoing Earth radiation. A portion of the energy leaving the ground is absorbed by atmospheric CO_2. This

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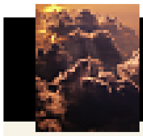
Solar Variability, Weather, and Climate (Washington, D.C.: National Academy Press, 1982), p. 7.

*Carl Sagan et al., “Anthropogenic Albedo Changes and the Earth’s Climate,” *Science*, 206, no. 4425 (1980), 1367.

**”An Early Start for Greenhouse Warming?”, Science, Vol. 303, 16 January 2004. This article is a report on a paper given by paleoclimatologist William Ruddiman at a meeting of the American Geophysical Union in December 2003.



BOX 14-3 Computer Models of Climate: Important Yet Imperfect Tools

Earth's climate system is amazingly complex. Comprehensive state-of-the-science climate simulation models are among the basic tools used to develop possible climate-change scenarios. Called *General Circulation Models,* or *GCMs*, they are based on fundamental laws of physics and chemistry and incorporate human and biological interactions. GCMs are used to simulate many variables, including temperature, rainfall, snow cover, soil moisture, winds, clouds, sea ice, and ocean circulation over the entire globe through the seasons and over spans of decades.

In many other fields of study, hypotheses can be tested by direct experimentation in the laboratory or by observations and measurements in the field. However, this is often not possible in the study of climate. Rather, scientists must construct computer models of how our planet's climate system works. If we understand the climate system correctly and construct the model appropriately, then the behavior of the model climate system should mimic the behavior of Earth's climate system.

What factors influence the accuracy of climate models? Clearly, mathematical models are *simplified* versions of the real Earth and cannot capture its full complexity, especially at smaller geographic scales. Moreover, when computer models are used to simulate future climate change, many assumptions have to be made that significantly influence the outcome. They must consider a wide range of possibilities for future changes in population, economic growth, consumption of fossil fuels, technological development, improvements in energy efficiency, and more.

Despite many obstacles, our ability to use supercomputers to simulate climate continues to improve. Although today's models are far from infallible, they are powerful tools for understanding what Earth's future climate might be like.

energy is subsequently reemitted, part of it back toward the surface, thereby keeping the air near the ground warmer than it would be without CO_2.

Thus, along with water vapor, carbon dioxide is largely responsible for the *greenhouse effect* of the atmosphere. Carbon dioxide is an important heat absorber, and it follows logically that any change in the air's CO_2 content could alter temperatures in the lower atmosphere.

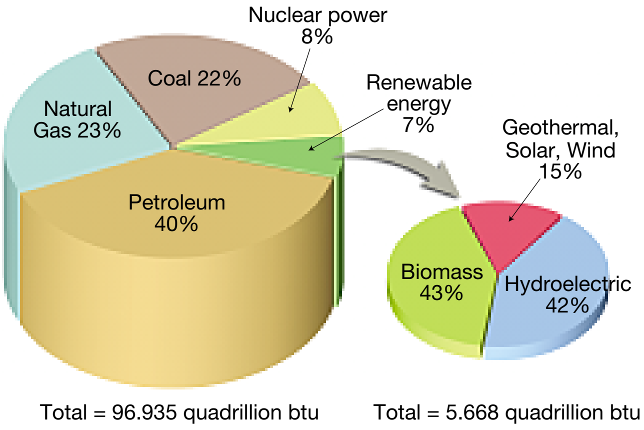
CO_2 Levels Are Rising

Earth's tremendous industrialization of the past two centuries has been fueled—and still is fueled—by burning fossil fuels: coal, natural gas, and petroleum (Figure 14–12). Combustion of these fuels has added great quantities of carbon dioxide to the atmosphere.

The use of coal and other fuels is the most prominent means by which humans add CO_2 to the atmosphere, but it is not the only way. The clearing of forests also contributes substantially because CO_2 is released as vegetation is burned or decays. Deforestation is particularly pronounced in the tropics, where vast tracts are cleared for ranching and agriculture or subjected to inefficient commercial logging operations. According to U.N. estimates, the destruction of tropical forests exceeded 15 million hectares (38 million acres) per year during the 1990s.

Although some of the excess CO_2 is taken up by plants or is dissolved in the ocean, it is estimated that 45 to 50 percent remains in the atmosphere. Figure 14–13a shows CO_2 concentrations over the past thousand years based on ice-core records and (since 1958) measurements taken at Mauna Loa Observatory, Hawaii. The rapid increase in CO_2 concentration since the onset of industrialization is

FIGURE 14-12 Paralleling the rapid growth of industrialization, which began in the nineteenth century, has been the combustion of fossil fuels, which has added great quantities of carbon dioxide to the atmosphere. The graph shows energy consumption in the United States, 2004. The total was nearly 100 quadrillion Btu. A quadrillion is 10 raised to the 12th power, or a million million. A quadrillion Btu is a convenient unit for referring to U.S. energy use as a whole. Fossil fuels (petroleum, coal, and natural gas) represent about 85 percent of the total. *(Data from U.S. Department of Energy)*



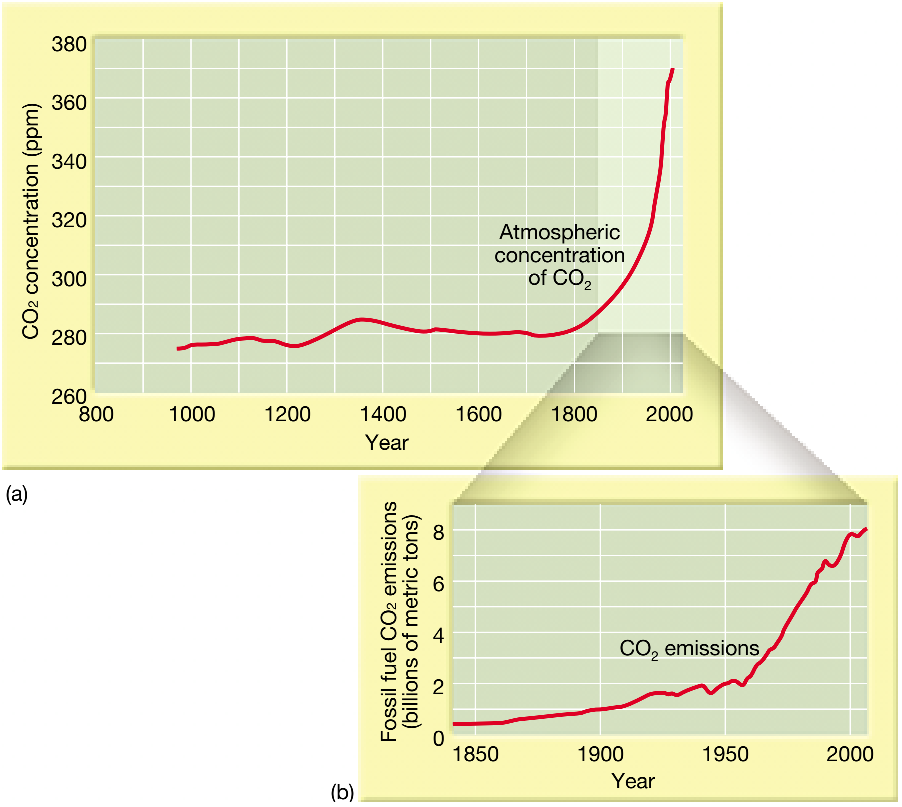


FIGURE 14-13 (a) Carbon dioxide (CO_2) concentrations over the past 1000 years. Most of the record is based on data obtained from Antarctic ice cores. Bubbles of air trapped in the glacial ice provide samples of past atmospheres. The record since 1958 comes from direct measurements of atmospheric CO_2 taken at Mauna Loa Observatory, Hawaii. (b) Fossil-fuel CO_2 emissions. The rapid increase in CO_2 concentration since the onset of industrialization has followed closely the rise in CO_2 emissions from fossil fuels.

obvious and has closely followed the increase in CO_2 emissions from burning fossil fuels (Figure 14–13b).

The Atmosphere's Response

Given the increase in the atmosphere's carbon dioxide content, have global temperatures actually increased? The answer is yes. A report by the Intergovernmental Panel on Climate Change (IPCC)[*] indicates the following:

- During the twentieth century, the global average surface temperature increased by about 0.6°C (1°F).
- Globally it is very likely that the 1990s was the warmest decade and 1998 the warmest year since 1861. The next four warmest years all occurred after 1998 (Figure 14–14).
- New analyses of data for the Northern Hemisphere indicate that the increase in temperature in the twentieth century is likely to have been the largest in any century during the past 1000 years (Figure 14–15).

Are these temperature trends caused by human activities, or would they have occurred anyway? Scientists are cautious but seem convinced that human activities have played a significant role. An IPCC report in 1996 stated that "the balance of evidence suggests a discernible human influence on global climate.[*] Five years later the IPCC stated that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[**] What about the future? By the year 2100, models project atmospheric CO_2 concentrations of 540 to 970 ppm. With such an increase, how will global temperatures change? Here is some of what the 2001 IPCC report has to say:[***]

- The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C by the year 2100.
- The projected rate of warming is much larger than the observed changes during the twentieth century and is very likely to be without precedent during at least the last 10,000 years.
- It is very likely that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season.

The Role of Trace Gases

Carbon dioxide is not the only gas contributing to a possible global increase in temperature. In recent years atmospheric scientists have come to realize that the industrial and agricultural activities of people are causing a buildup of

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[*] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis.* Cambridge, UK: Cambridge University Press, 2001, p. 2.

[*] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change,* New York: Cambridge University Press, 1996, p. 4.

[**] IPCC, *Climate Change 2001: The Scientific Basis,* p. 10.

[***] IPCC, *Climate Change 2001: The Scientific Basis,* p. 13.

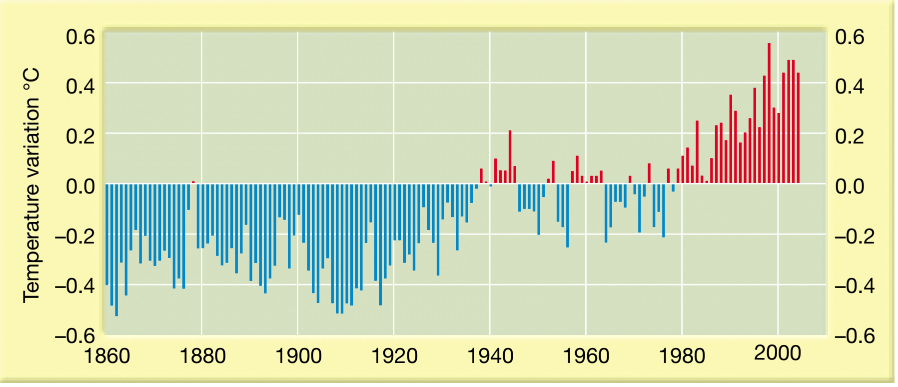


FIGURE 14-14 Annual average global temperature variations for the period 1860–2004. The basis for comparison is the average for the 1961–90 period (the 0.0 line on the graph). Each narrow bar on the graph represents the departure of the global mean temperature from the 1961–90 average for one year. For example, the global mean temperature for 1862 was more than 0.5°C (1°F) *below* the 1961–90 average, whereas the global mean for 1998 was more than 0.5°C above. (Specifically, 1998 was 0.56° C warmer.) The bar graph clearly indicates that there can be *significant variations from year to year.* But the graph also shows a trend. Estimated global mean temperatures have been above the 1961–90 average every year since 1978. Globally the 1990s was the warmest decade—and the years 1998, 2002, 2003, 2001, and 2004 the warmest years—since 1861. *(Modified and updated after G. Bell, et al. "Climate Assessment for 1998," Bulletin of the American Meteorological Society, Vol. 80, No. 5, May 1999, p. 54)*

several trace gases that may also play a significant role. The substances are called *trace gases* because their concentrations are so much smaller than that of carbon dioxide. The trace gases that appear to be most important are methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). These gases absorb wavelengths of outgoing radiation from Earth that would otherwise escape into space. Although individually their impact is modest, taken together the effects of these trace gases may be as great as CO_2 in warming the troposphere.

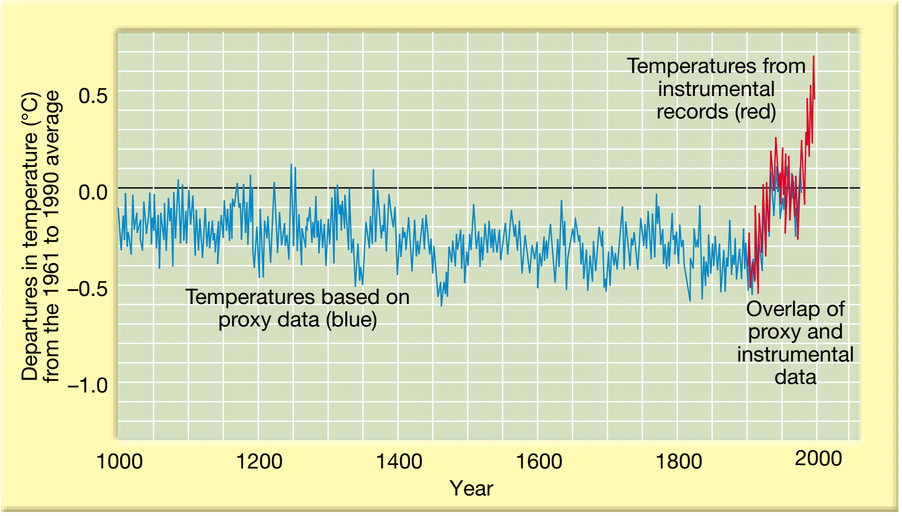
Methane is present in much smaller amounts than CO_2, but its significance is greater than its relatively small concentration of about 1.7 ppm (parts per million) would indicate. The reason is that methane is 20 to 30 times more effective than CO_2 at absorbing infrared radiation emitted by Earth.

Students Sometimes Ask…

What is the Intergovernmental Panel on Climate Change?

Recognizing the problem of potential global climate change, the World Meteorological Organization and the United Nation's Environment Program established the *Intergovernmental Panel on Climate Change* (*IPCC,* for short). The IPCC assesses the scientific, technical, and socio-economic information that is relevant to an understanding of human-induced climate change. This authoritative group provides advice to the world community through periodic reports that assess the state of knowledge of causes of climate change.

FIGURE 14-15 Year-by-year variations in average surface temperatures for the Northern Hemisphere for the past 1000 years reconstructed from tree rings, ice cores, corals, and historical records (blue portion of line) and air temperatures directly measured (red portion of line). The warming during the twentieth century was much greater than in any of the previous nine centuries. *(After U.S. Global Change Research Program and IPCC)*



Methane is produced by *anaerobic* bacteria in wet places where oxygen is scarce (anaerobic means "without air," specifically oxygen). Such places include swamps, bogs, wetlands, and the guts of termites and grazing animals like cattle and sheep. Methane is also generated in flooded paddy fields ("artificial swamps") used for growing rice. Mining of coal and drilling for oil and natural gas are other sources because methane is a product of their formation (Figure 14–16).

The concentration of methane in the atmosphere is believed to have about doubled since 1800, an increase that has been in step with the growth in human population. This relationship reflects the close link between methane formation and agriculture. As population has risen, so have the number of cattle and rice paddies.

Nitrous oxide, sometimes called "laughing gas," is also building in the atmosphere, although not as rapidly as methane. The increase is believed to result primarily from agricultural activity. When farmers use nitrogen fertilizers to boost crop yield, some of the nitrogen enters the air as nitrous oxide. This gas is also produced by high-temperature combustion of fossil fuels. Although the annual release into the atmosphere is small, the lifetime of a nitrous oxide molecule is about 150 years! If the use of nitrogen fertilizers and fossil fuels grows at projected rates, nitrous oxide may make a contribution to greenhouse warming that approaches half that of methane.

FIGURE 14-16 Methane is produced by anaerobic bacteria in wet places, where oxygen is scarce (anaerobic means "without air," specifically oxygen). Such places include swamps, bogs, wetlands, and the guts of termites and grazing animals, like cattle and sheep. Methane is also generated in flooded paddy fields ("artificial swamps") used for growing rice. These paddies are in India's Ganges lowlands. Mining of coal and drilling for oil and natural gas are other sources because methane is a product of their formation. *(Photo by George Holton/Photo Researchers, Inc.)*

Unlike methane and nitrous oxide, chlorofluorocarbons (CFCs) are not naturally present in the atmosphere. As you learned in Chapter 1, CFCs are manufactured chemicals with many uses that have gained notoriety because they are responsible for ozone depletion in the stratosphere. The role of CFCs in global warming is less well known. CFCs are very effective greenhouse gases. They were not developed until the 1920s and were not used in great quantities until the 1950s, but they already contribute to the greenhouse effect at a level equal to methane. Although the Montreal Protocol represents strong corrective action, CFC levels will *not* drop rapidly (see the section on the Montreal Protocol in Chapter 1). CFCs remain in the atmosphere for decades, so even if all CFC emissions were to stop immediately, the atmosphere would not be free of them for many years.

Carbon dioxide is clearly the most important single cause for the projected global greenhouse warming. However, it is not the only contributor. When the effects of all human-generated greenhouse gases other than CO_2 are added together and projected into the future, their collective impact significantly increases the impact of CO_2 alone.

Sophisticated computer models show that the warming of the lower atmosphere caused by CO_2 and trace gases will not be the same everywhere. Rather, the temperature response in polar regions could be two to three times greater than the global average. One reason is that the polar troposphere is very stable, which suppresses vertical mixing and thus limits the amount of surface heat that is transferred upward. In addition, an expected reduction in sea ice would also contribute to the greater temperature increase. This topic will be explored more fully in the next section.

Students Sometimes Ask…

If Earth's atmosphere had no greenhouse gases, what would surface-air temperatures be like?

Cold! Earth's average surface temperature would be a chilly −18°C (−0.4°F) instead of the relatively comfortable 14.5°C (58°F) that it is today.

Climate-Feedback Mechanisms

Climate is a very complex interactive physical system. Thus, when any component of the climate system is altered, scientists must consider many possible outcomes. These possible outcomes are called **climate-feedback mechanisms.** They complicate climate-modeling efforts and add greater uncertainty to climate predictions.

What climate-feedback mechanisms are related to carbon dioxide and other greenhouse gases? One important mechanism is that warmer surface temperatures increase evaporation rates. This in turn increases the water vapor in the atmosphere. Remember that water vapor is an even more powerful absorber of radiation emitted by Earth than is carbon dioxide. Therefore, with more water vapor in the air, the temperature increase caused by carbon dioxide and the trace gases is reinforced.

Recall that the temperature increase at high latitudes may be two to three times greater than the global average. This assumption is based in part on the likelihood that the area covered by sea ice will decrease as surface temperatures rise. Because ice reflects a much larger percentage of incoming solar radiation than does open water, the melting of the sea ice would replace a highly reflecting surface with a relatively dark surface (Figure 14–17). The result would be a substantial increase in the solar energy absorbed at the surface. This in turn would feed back to the atmosphere and magnify the initial temperature increase created by higher levels of greenhouse gases.

So far the climate-feedback mechanisms discussed have magnified the temperature rise caused by the buildup of carbon dioxide. Because these effects reinforce the initial change, they are called **positive-feedback mechanisms.** However, other effects must be classified as **negative-feedback mechanisms** because they produce results that are just the opposite of the initial change and tend to offset it.

One probable result of a global temperature rise would be an accompanying increase in cloud cover due to the higher moisture content of the atmosphere. Most clouds are good reflectors of solar radiation. At the same time, however, they are also good absorbers and emitters of radiation emitted by Earth. Consequently, clouds produce two opposite effects. They are a negative-feedback mechanism because they increase albedo and thus diminish the amount of solar energy available to heat the atmosphere. On the other hand, clouds act as a positive-feedback mechanism by absorbing and emitting radiation that would otherwise be lost from the troposphere.

Which effect, if either, is stronger? Atmospheric modeling shows that the negative effect of a higher albedo is dominant. Therefore, the net result of an increase in cloudiness should be a decrease in air temperature. The magnitude of this negative feedback, however, is not believed to be as great as the positive feedback caused by added moisture and decreased sea ice. Thus, although increases in cloud cover may partly offset a global temperature increase, climate models show that the ultimate effect of the projected increase in CO_2 and trace gases will still be a temperature increase.

The problem of global warming caused by human-induced changes in atmospheric composition continues to be one of the most studied aspects of climate change. Although no models yet incorporate the full range of potential factors and feedbacks, the scientific consensus is that the increasing levels of atmospheric carbon dioxide and trace gases will lead to a warmer planet with a different distribution of climate regimes.

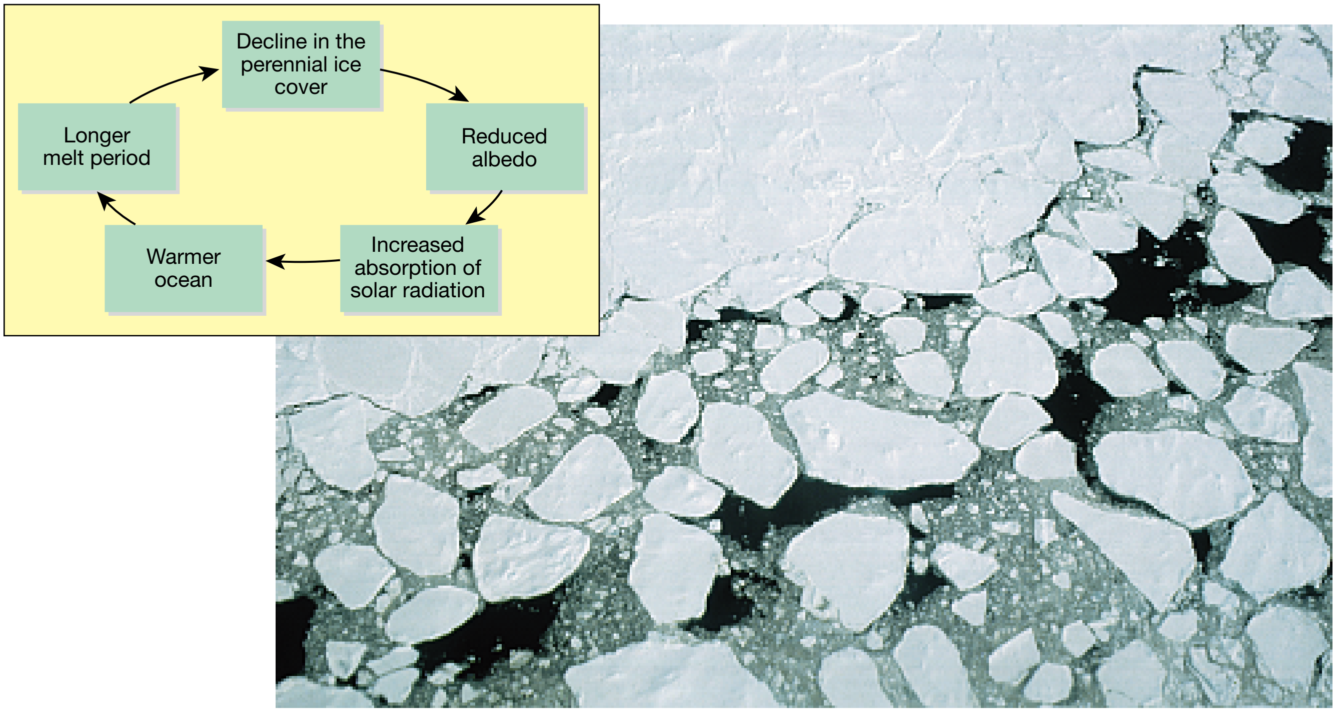


FIGURE 14-17 This satellite image shows the springtime breakup of sea ice near Antarctica. The inset shows a likely feedback loop. A reduction in sea ice acts as a positive-feedback mechanism because surface albedo would decrease and the amount of energy absorbed at the surface would increase. *(Reproduced with permission from "Science" (Cover, January 25, 2002). Copyright American Association for the Advancement of Science. Photo: D.N. Thomas.)*

How Aerosols Influence Climate

Increasing the levels of carbon dioxide and other greenhouse gases in the atmosphere is the most direct human influence on global climate. But it is not the only impact. Global climate is also affected by human activities that contribute to the atmosphere's aerosol content. Recall that *aerosols* are the tiny, often microscopic, liquid and solid particles that are suspended in the air. Unlike cloud droplets, aerosols are present even in relatively dry air. Atmospheric aerosols are composed of many different materials, including soil, smoke, sea salt, and sulfuric acid. Natural sources are numerous and include such phenomena as dust storms and volcanoes.

Presently the human contribution of aerosols to the atmosphere *equals* the quantity emitted by natural sources. Most human-generated aerosols come from the sulfur dioxide emitted during the combustion of fossil fuels and as a consequence of burning vegetation to clear agricultural land. Chemical reactions in the atmosphere convert the sulfur dioxide into sulfate aerosols, the same material that produces acid precipitation.

How do aerosols affect climate? Aerosols act directly by reflecting sunlight back to space and indirectly by making clouds "brighter" reflectors. The second effect relates to the fact that many aerosols (such as those composed of salt or sulfuric acid) attract water and thus are especially effective as cloud condensation nuclei. The large quantity of aerosols produced by human activities (especially industrial emissions) trigger an increase in the number of cloud droplets that form within a cloud. A greater number of small droplets increases the cloud's brightness—that is, more sunlight is reflected back to space.

By reducing the amount of solar energy available to the climate system, aerosols have a net cooling effect. Studies indicate that the cooling effect of human-generated aerosols could offset a portion of the global warming caused by the growing quantities of greenhouse gases in the atmosphere. Unfortunately, the magnitude and extent of the cooling effect of aerosols is highly uncertain. This uncertainty is a significant hurdle in advancing our understanding of how humans alter Earth's climate.

It is important to point out some significant differences between global warming by greenhouse gases and aerosol cooling. After being emitted, greenhouse gases such as carbon dioxide remain in the atmosphere for many decades. By contrast, aerosols released into the troposphere remain there for only a few days or, at most, a few weeks before they are "washed out" by precipitation. Because of their short lifetime in the troposphere, aerosols are distributed unevenly over the globe. As expected, human-generated aerosols are concentrated near the areas that produce them, namely industrialized regions that burn fossil fuels and land areas where vegetation is burned (Figure 14–18).

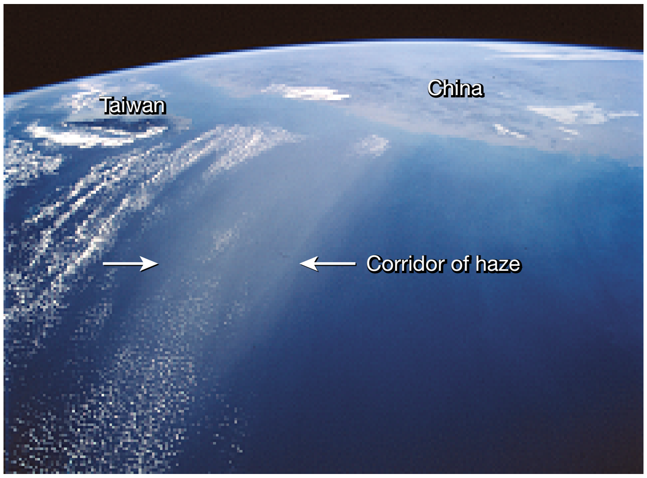


FIGURE 14-18 Human-generated aerosols are concentrated near the areas that produce them. Because aerosols reduce the amount of solar energy available to the climate system, they have a net cooling effect. This satellite image shows a dense blanket of pollution moving away from the coast of China. The plume is about 200 kilometers wide and more than 600 kilometers long. *(NASA Image)*

Because their lifetime in the atmosphere is short, the effect of aerosols on today's climate is determined by the amount emitted during the preceding couple of weeks. By contrast, the carbon dioxide and trace gases released into the atmosphere remain for much longer spans and thus influence climate for many decades.

Some Possible Consequences of Global Warming

What consequences can be expected if the carbon dioxide content of the atmosphere reaches a level that is twice what it was early in the twentieth century? Because the climate system is so complex, predicting the distribution of particular regional changes is very speculative. It is not yet possible to pinpoint specifics, such as where or when it will become drier or wetter. Nevertheless, plausible scenarios can be given for larger scales of space and time.

As noted, the magnitude of the temperature increase will not be the same everywhere. The temperature rise will probably be smallest in the tropics and increase toward the poles. As for precipitation, the models indicate that some regions will experience significantly more precipitation and runoff. However, others will experience a decrease in runoff (due to reduced precipitation or greater evaporation caused by higher temperatures).

Table 14–1 summarizes some of the more likely effects and their possible consequences. The table also provides the IPCC's estimate of the probability of each effect. Levels of confidence for these projections vary from *"likely"* (67 to 90 percent probability) to *"very likely"* (90 to 99 percent probability). Box 14–4 looks at key findings regarding the possible consequences of climate change for the United States in the twenty-first century.

TABLE 14-1 Projected changes and effects of global warming in the 21st century

Projected changes and estimated probability*	**Examples of projected impacts**
Higher maximum temperatures; more hot days and heat waves over nearly all land areas (*very likely*).	• Increased incidence of death and serious illness in older age groups and urban poor. • Increased heat stress in livestock and wildlife. • Shift in tourist destinations. • Increased risk of damage to a number of crops. • Increased electric cooling demand and reduced energy-supply reliability.
Higher minimum temperatures; fewer cold days, frost days, and cold waves over nearly all land areas (*very likely*).	• Decreased cold-related human morbidity and mortality. • Decreased risk of damage to a number of crops, and increased risk to others. • Extended range and activity of some pest and disease vectors. • Reduced heating energy demand.
More intense precipitation events (*very likely* over many areas).	• Increased flood, landslide, avalanche, and mudslide damage. • Increased soil erosion. • Increased flood runoff could increase recharge of some floodplain aquifers. • Increased pressure on government and private flood insurance systems and disaster relief.
Increased summer drying over most mid-latitude continental interiors and associated risk of drought (*likely*).	• Decreased crop yields. • Increased damage to building foundations caused by ground shrinkage. • Decreased water-resource quantity and quality. • Increased risk of forest fire.
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities (*likely* over some areas).	• Increased risks to human life, risk of infectious-disease epidemics, and many other risks. • Increased coastal erosion and damage to coastal buildings and infrastructure. • Increased damage to coastal ecosystems, such as coral reefs and mangroves.
Intensified droughts and floods associated with El Niño events in many different regions (*likely*).	• Decreased agricultural and rangeland productivity in drought- and flood-prone regions. • Decreased hydropower potential in drought-prone regions.
Increased Asian summer monsoon precipitation variability (*likely*).	• Increased flood and drought magnitude and damages in temperate and tropical Asia.
Increased intensity of mid-latitude storms (*uncertain*).	• Increased risks to human life and health. • Increased property and infrastructure losses. • Increased damage to coastal ecosystems.

**Very likely* indicates a probability of 90–99 percent. *Likely* indicates a probability of 67–90 percent.
Source: IPCC, 2001

Students Sometimes Ask…

What are scenarios, and why are they used?

A scenario is an example of what might happen under a particular set of assumptions. Scenarios are a way of examining questions about an uncertain future. For example, future trends in fossil-fuel use and other human activities are uncertain. Therefore, scientists have developed a set of scenarios for how climate may change based on a wide range of possibilities for these variables.

Water Resources and Agriculture

Such changes could profoundly alter the distribution of the world's water resources and hence affect the productivity of agricultural regions that depend on rivers for irrigation water. For example, a 2°C (3.6°F) warming and 10 percent precipitation decrease in the region drained by the Colorado River could diminish the river's flow by 50 percent or more. Because the present flow of the river barely meets current demand for irrigation agriculture, the negative effect would be serious (Figure 14–19). Many other rivers are the basis for extensive irrigated agriculture, and the projected reduction of their flow could have equally grave consequences.

FIGURE 14-19 It is not yet possible to specify the magnitude and location of particular climate changes that may result from greenhouse warming. Many consequences are possible. Decreased rainfall and increased evaporation rates could diminish the flow of certain rivers and force the abandonment of some presently productive irrigated farmland. *(Photo by E. J. Tarbuck)*

In contrast, large precipitation increases in other areas would increase the flow of some rivers and bring more frequent destructive floods.

Harder to estimate is the effect on nonirrigated crops that depend on direct rainfall and snowfall for moisture. Some places will no doubt experience productivity loss due to a decrease in rainfall or increase in evaporation. Still, these losses may be offset by gains elsewhere. Warming in the higher latitudes could lengthen the growing season, for instance. This in turn could allow expansion of agriculture into areas presently unsuited to crop production.

Sea-Level Rise

Another impact of a human-induced global warming is a probable rise in sea level. How is a warmer atmosphere related to a global rise in sea level? The most obvious connection, the melting of glaciers, is important, but *not* the most significant. Far more significant is that a warmer atmosphere causes an increase in ocean volume due to thermal expansion. Higher air temperatures warm the adjacent upper layers of the ocean, which in turn causes the water to expand and the sea level to rise.

Research indicates that sea level has risen between 10 and 25 centimeters (4 and 8 inches) over the past century and that the trend will continue at an accelerated rate. Some models indicate that the rise may approach or even exceed 50 centimeters (20 inches) by the end of the twenty-first century. Such a change may seem modest, but scientists realize that any rise in sea level along a *gently* sloping shoreline, such as the Atlantic and Gulf coasts of the United States, will lead to significant erosion and severe, permanent inland flooding (Figure 14–20). If this happens, many beaches and wetlands will be eliminated and coastal civilization would be severely disrupted.

Because rising sea level is a gradual phenomenon, it may be overlooked by coastal residents as an important contributor to shoreline erosion problems. Rather, the blame may be assigned to other forces, especially storm activity. Although a given storm may be the immediate cause, the magnitude of its destruction may result from the relatively small sea-level rise that allowed the storm's power to cross a much greater land area (Figure 14–20c).

As mentioned, a warmer climate will cause glaciers to melt. In fact, a portion of the 10- to 25-centimeter (4- to 8-inch) rise in sea level over the past century is attributed to the melting of mountain glaciers (Figure 14–21). This contribution is projected to continue through the twenty-first century. Of course, if the Greenland and Antarctic ice sheets were to experience a significant increase in melting, it would lead to a much greater rise in sea level and a major encroachment by the sea in coastal zones (see Box 14–5). It should be emphasized, however, that a significant melting of major ice sheets, although possible at some future date, is *not* expected during the next century.

Students Sometimes Ask…

You mentioned that melting mountain glaciers are contributing to a rise in sea level. Has there been a noticeable reduction in the numbers or size of these glaciers?

Yes. A recent research project called Global Land Ice Measurements from Space (GLIMS) concluded that the great majority of the world's glaciers appear to be shrinking. For example, 150 years ago there were 147 glaciers in Montana's Glacier National Park. Today only 37 remain, and these may vanish by 2030.

The Changing Arctic

A recent study of climate change in the Arctic began with the following statement:

BOX 14-4 Possible Consequences of Climate Change on the United States

What might people living in the United States expect as a consequence of climate change during the twenty-first century? This box summarizes the key findings from *Climate Change Impacts on the United States.** It is a report prepared by the National Assessment Synthesis Team (NAST) as part of the United States Global Change Research Program (USGCRP). Its purpose was to "synthesize, evaluate, and report on what we presently know about the potential consequences of climate variability and change for the U.S. in the 21st century." The report's key findings are as follows:

1. *Increased warming.* Assuming continued growth in world greenhouse-gas emissions, the primary climate models used in this assessment project that temperatures in the United States will rise 5–9°F (3–5°C) on average in the next 100 years. A wider range of outcomes is possible.

2. *Differing regional impacts.* Climate change will vary widely across the United States. Temperature increases will vary somewhat from one region to the next. Heavy and extreme precipitation events are likely to become more frequent, yet some regions will get drier. The potential impacts of climate change will also vary widely across the nation.

3. *Vulnerable ecosystems.* Many ecosystems are highly vulnerable to the projected rate and magnitude of climate change. A few, such as alpine meadows in the Rocky Mountains and some barrier islands, are likely to disappear entirely in some areas. Others, such as forests of the Southeast, are likely to experience major species shifts or break up into a mosaic of grasslands, woodlands, and forests. The goods and services lost through the disappearance or fragmentation of certain ecosystems are likely to be costly or impossible to replace.

4. *Widespread water concerns.* Water is an issue in every region, but the nature of the vulnerabilities varies. Drought is an important concern in every region. Floods and water quality are concerns in many regions. Snowpack changes are especially important in the West, Pacific Northwest, and Alaska.

5. *Secure food supply.* At the national level the agriculture sector is likely to be able to adapt to climate change. Overall, U.S. crop productivity is very likely to increase over the next few decades, but the gains will not be uniform across the nation. Falling prices and competitive pressures

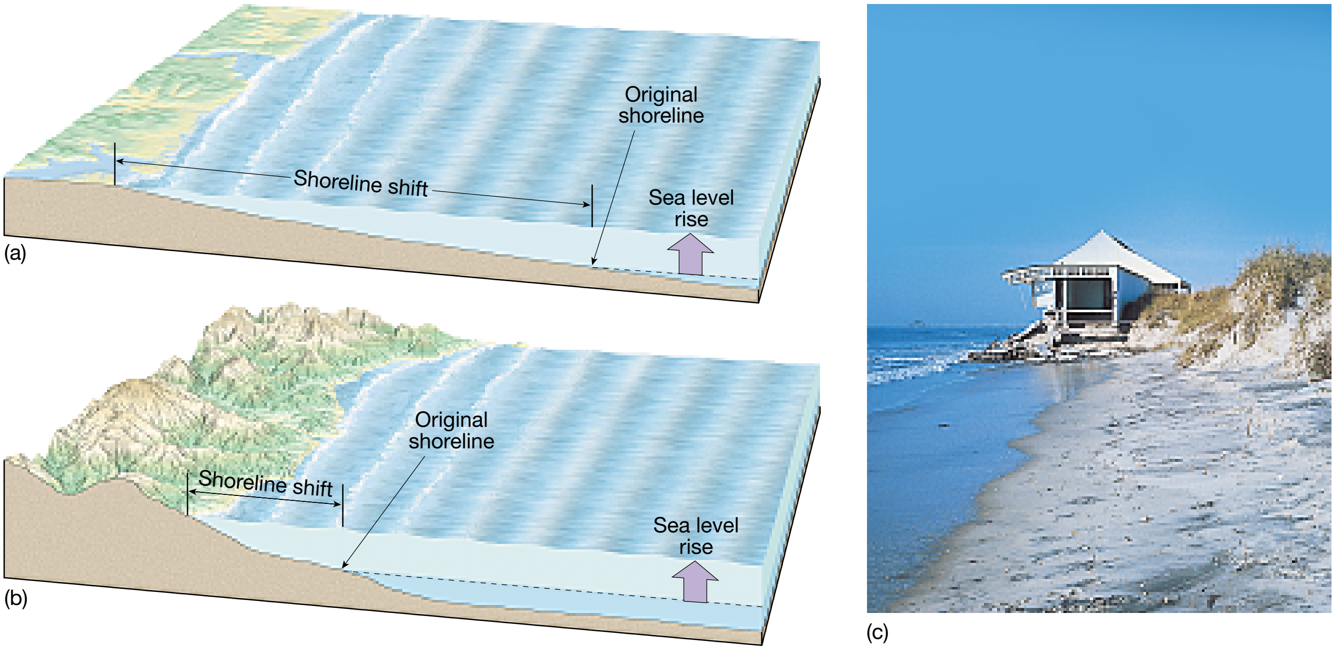


FIGURE 14-20 The slope of a shoreline is critical to determining the degree to which sea-level changes will affect it. (a) When the slope is gentle, small changes in the sea level cause a substantial shift. (b) The same sea-level rise along a steep coast results in only a small shoreline shift. (c) As sea level gradually rises, the shoreline retreats, and structures that were once thought to be safe from wave attack are exposed to the force of the sea. *(Photo by Kenneth Hasson)*

are very likely to stress some farmers while benefiting consumers.

6. *Near-term increase in forest growth.* Forest productivity is likely to increase over the next several decades in some areas as trees respond to higher carbon dioxide levels. Over the longer term, changes in larger-scale processes, such as fire, insects, droughts, and disease, will possibly decrease forest productivity. In addition, climate change is likely to cause long-term shifts in forest species, such as sugar maples moving north out of the United States.

7. *Increased damage in coastal and permafrost areas.* Climate change and the resulting rise in sea level are likely to exacerbate threats to buildings, roads, powerlines, and other infrastructure in climatically sensitive places. For example, infrastructure damage is related to permafrost melting in Alaska and to sea-level rise and storm surge in low-lying coastal areas.

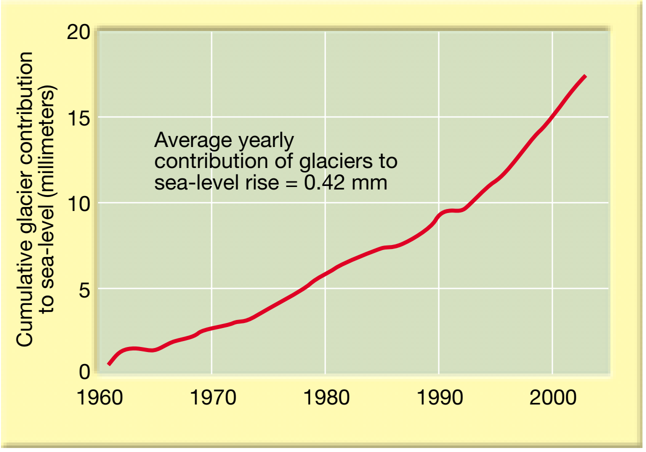
8. *Adaptation determines health outcomes.* A range of negative health impacts is possible from climate change, but adaptation is likely to help protect much of the U.S. population. Maintaining our nation's public health and community infrastructure, from water-treatment systems to emergency shelters, will be important for minimizing the impacts of water-borne diseases, heat stress, air pollution, extreme weather events, and diseases transmitted by insects, ticks, and rodents.

9. *Other stresses magnified by climate change.* Climate change will very likely magnify the cumulative impacts of other stresses, such as air and water pollution and habitat destruction due to human-development patterns. For some systems, such as coral reefs, the combined effects of climate change and other stresses are very likely to exceed a critical threshold, bringing large, possibly irreversible, impacts.

10. *Uncertainties remain and surprises are expected.* Significant uncertainties remain in the science underlying regional climate changes and their impacts. Further research would improve understanding and our ability to project societal and ecosystem impacts and provide the public with additional useful information about options for adaptation. However, it is likely that some aspects and impacts of climate change will be totally unanticipated as complex systems respond to ongoing climate change in unforeseeable ways.

*National Assessment Synthesis Team. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change.* Washington, DC: US Global Change Research Program, 2000, p. 19.

FIGURE 14-21 The contribution of melting glacial ice to the rise in sea level 1961–2003. Mountain glaciers cover an area of about 785,000 square kilometers—about 4 percent of the total land area covered by glacial ice. It is estimated that these glaciers contributed approximately 20 to 30 percent of the total sea-level rise over the past 100 years. Since 1990, the relative contribution of melting glaciers has increased. As much as 40 percent of the overall sea-level rise during that span may have come from melting glacial ice. *(National Snow and Ice Data Center)*



For nearly 30 years, Arctic sea ice extent and thickness have been falling dramatically. Permafrost temperatures are rising and coverage is decreasing. Mountain glaciers and the Greenland ice sheet are shrinking. Evidence suggests we are witnessing the early stage of an anthropogenically induced global warming superimposed on natural cycles, reinforced by reductions in Arctic ice.*

Arctic Sea Ice. Climate models are in general agreement that one of the strongest signals of global warming should be a loss of sea ice in the Arctic. This is indeed occurring. The map in Figure 14–22 compares the extent of sea ice in September, at the end of the summer melt period, for the years 1979 and 2005. Over this span, September sea ice extent has decreased more than 20 percent. The trend is also clear when you examine the graph in Figure 14–23. Is it possible that this trend may be part of a natural cycle? Yes, but it is more likely that the sea-ice decline represents a combination of natural variability and human-induced

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*J. T. Overpeck, et al. "Arctic System on Trajectory to New, Seasonally Ice-Free States," *EOS, Transactions, American Geophysical Union,* Vol 86, No. 34, 23 August 2005, p. 309.

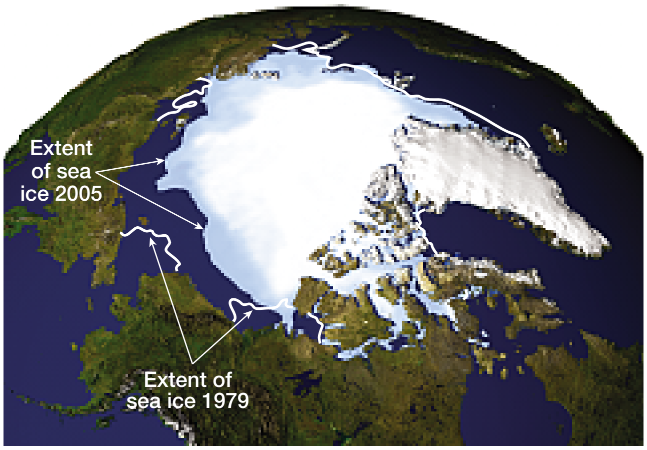


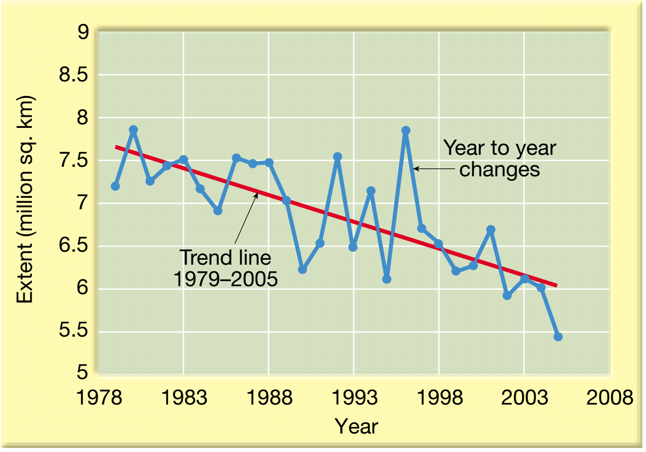
FIGURE 14-22 A comparison of the extent of sea ice at the end of the summer melting period—1979 vs. 2005. The decrease in the area covered by sea ice exceeds 20 percent *(NASA)*

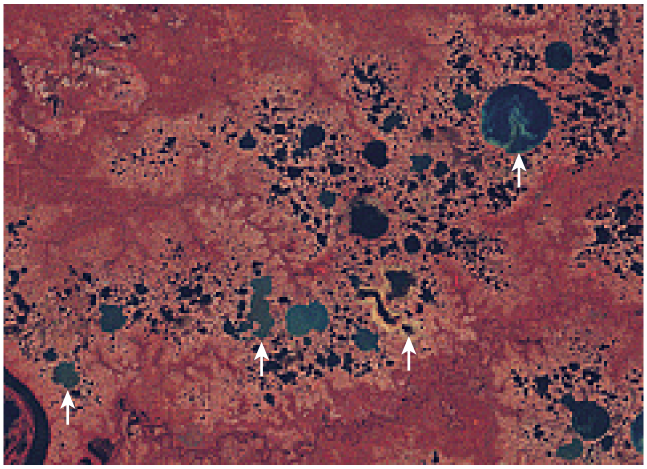
global warming, with the latter being increasingly evident in coming decades. As was noted in the section on "Climate Feedback Mechanisms," a reduction in sea ice represents a positive feedback mechanism that reinforces global warming.

Permafrost. During the past decade, evidence has mounted to indicate that the extent of permafrost in the Northern Hemisphere has decreased, as would be expected under long-term warming conditions. Figure 14–24 presents one example that such a decline is occurring.

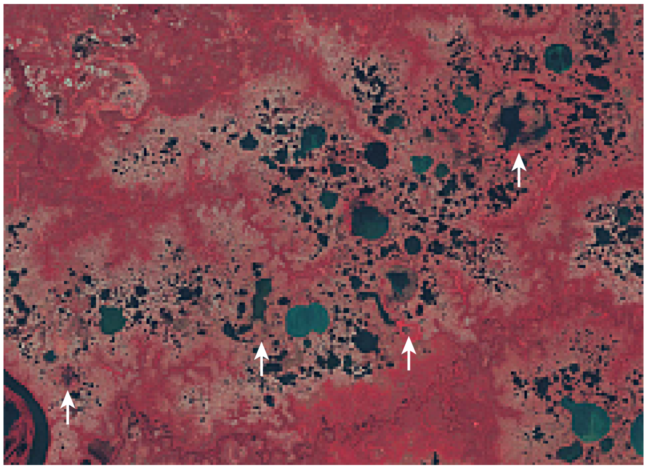
In the Arctic, short summers thaw only the top layer of frozen ground. The permafrost beneath this *active layer* is like the cement bottom of a swimming pool. In summer, water cannot percolate downward, so it saturates the soil above the permafrost and collects on the surface in thousands of lakes. However, as Arctic temperatures climb, the bottom of the "pool" seems to be "cracking." Satellite imagery shows that over a 20-year span, a significant number of lakes have shrunk or disappeared altogether. As the permafrost thaws, lake water drains deeper into the ground.

FIGURE 14-23 This graph depicts the decline in Arctic sea ice from 1979 to 2005. The rate of decline exceeds 8 percent per decade. The year 2005 exhibited the smallest area of Arctic sea ice yet measured in the satellite record up to that time. *(National Snow and Ice Data Center)*





(a) June 27, 1973



(b) July 2, 2002

FIGURE 14-24 This image pair shows lakes dotting the tundra in northern Siberia in 1973 and 2002. The tundra vegetation is colored a faded red, whereas lakes appear blue or blue-green. Many lakes have clearly disappeared or shrunk considerably between 1973 and 2002. After studying satellite imagery of about 10,000 large lakes in a 500,000-square-kilometer area in northern Siberia, scientists documented an 11 percent decline in the number of lakes, with at least 125 disappearing completely.

Thawing permafrost represents a potentially significant positive feedback mechanism that may reinforce global warming. When vegetation dies in the Arctic, cold temperatures inhibit its total decomposition. As a consequence, over thousands of years a great deal of organic matter has become stored in the permafrost. When the permafrost thaws, organic matter that may have been frozen for millennia comes out of "cold storage" and decomposes. The result is the release of carbon dioxide and methane—greenhouse gases the contribute to global warming.

The Potential for "Surprises"

In summary, you have seen that climate in the twenty-first century, unlike the preceding thousand years, is not

BOX 14-5 Polar Warming and the Collapse of Antarctic Ice Shelves

Along portions of the Antarctic coast, glacial ice advances into the adjacent ocean, creating features called ice shelves. These large, relatively flat masses of floating ice extend seaward from the coast but remain attached to the land along one or more sides (Figure 14–C).

Studies using recent satellite imagery show that portions of some ice shelves are breaking apart. For example, during a 35-day span in February and March 2002 an ice shelf on the eastern side of the Antarctic Peninsula, known as the Larsen B ice shelf, broke apart and separated from the continent (Figure 14–D). The event sent thousands of icebergs adrift in the adjacent Weddell Sea. In all, about 3250 square kilometers (1250 square miles) of the ice shelf broke apart. (For reference, the entire state of Rhode Island covers 2717 square kilometers.) This was not an isolated event but part of a trend. Over a five-year span, the Larsen B ice shelf shrunk by 5700 square kilometers (more the 2200 square miles). Moreover, since 1974 the extent of seven ice shelves surrounding the Antarctic Peninsula declined by about 13,500 square kilometers (nearly 5300 square miles).

Why did these masses of floating ice break apart? What if the trend continues? Could there be any serious consequence?

Scientists attribute the breakup of the ice shelves to a strong regional climate warming. Since about 1950, Antarctic temperatures have risen by 2.5°C (4.3°F). The rate of warming has been about 0.5°C (nearly 1°F) per decade. If temperatures continue to rise, an ice shelf adjacent to Larsen B may start to recede in coming decades. Moreover, regional warming of just a few degrees Celsius may be sufficient to cause portions of the huge Ross Ice Shelf to become unstable and begin to break apart (Figure 14–C).

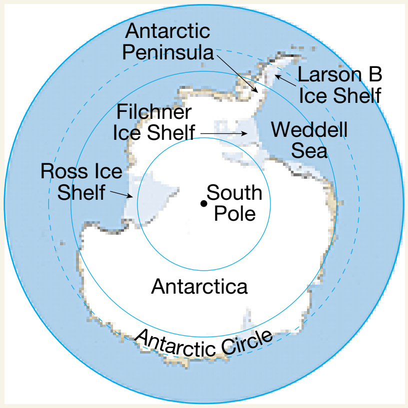


FIGURE 14-C Antarctica's ice shelves extend for more than 1.4 million square kilometers. The Ross and Filchner ice shelves are largest, with the Ross Ice Shelf alone covering an area approximately the size of Texas.

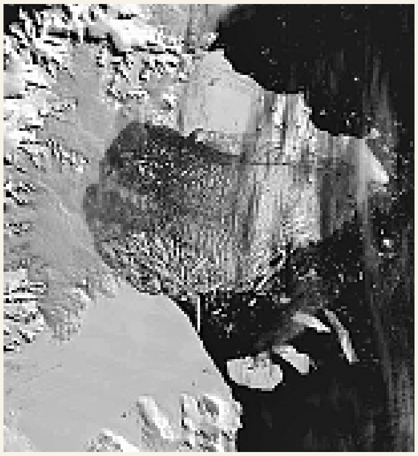


FIGURE 14-D This satellite image shows the Larson B ice shelf during its collapse in 2002. *(NASA image)*

What might the consequences be? Scientists at the National Snow and Ice Data Center NSIDC) suggest the following:

> While the breakup of the ice shelves in the Peninsula has little consequence for sea level rise, the breakup of other shelves in the Antarctic could have a major effect on the rate of ice flow off the continent. Ice shelves act as a buttress, or braking system, for glaciers. Further, the shelves keep warmer marine air at a distance from the glaciers; therefore, they moderate the amount of melting that occurs on the glaciers' surfaces. Once their ice shelves are removed, the glaciers increase in speed due to meltwater percolation and/or a reduction of braking forces, and they may begin to dump more ice into the ocean. Glacier ice speed increases are already observed in Peninsula areas where ice shelves disintegrated in prior years[*]

The addition of large quantities of glacial ice to the ocean could indeed cause a significant rise in sea level.

Remember that what is being suggested here is still speculative because our knowledge of the dynamics of Antarctica's ice shelves and glaciers is incomplete. Additional satellite monitoring and field studies will be necessary if we are to more accurately predict potential rises in global sea level triggered by the mechanism described here.

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[*] National Snow and Ice Data Center, Antarctic Ice-Shelf Collapses," 21 March 2002. **http://nsidc.org/iceshelves/larsenb2002**

expected to be stable. Rather, a constant state of change is very likely. Many of the changes will probably be gradual environmental shifts, imperceptible from year to year. Nevertheless, the effects, accumulated over decades, will have powerful economic, social, and political consequences.

Despite our best efforts to understand future climate shifts, there is also the potential for "surprises." This simply means that due to the complexity of Earth's climate system, we might experience relatively sudden, unexpected changes or see some aspects of climate shift in an unexpected manner. The report on *Climate Change Impacts on the United States* describes the situation like this:

> Surprises challenge humans' ability to adapt, because of how quickly and unexpectedly they occur. For example, what if the Pacific Ocean warms in such a way that El Niño events become much more extreme? This could reduce the frequency, but perhaps not the strength, of hurricanes along the East Coast, while on the West Coast, more severe winter storms, extreme precipitation events, and damaging winds could become common. What if large quantities of methane, a potent greenhouse gas currently frozen in icy Arctic tundra and sediments, began to be released to the atmosphere by warming, potentially creating an amplifying "feedback loop" that would cause even more warming? We simply do not know how far the climate system or other systems it affects can be pushed before they respond in unexpected ways.
>
> There are many examples of potential surprises, each of which would have large consequences. Most of these potential outcomes are rarely reported, in this study or elsewhere. Even if the chance of any particular surprise happening is small, the chance that at least one such surprise will occur is much greater. In other words, while we can't know which of these events will occur, it is likely that one or more will eventually occur.*

Clearly, the impact on climate of an increase in atmospheric CO_2 and trace gases is obscured by many unknowns and uncertainties. Policymakers are confronted with responding to the risks posed by emissions of greenhouse gases in the face of significant scientific uncertainties. However, they are also faced with the fact that climate-induced environmental changes cannot be reversed quickly, if at all, owing to the lengthy time scales associated with the climate system. Addressing this issue, the Intergovernmental Panel on Climate Change states:

> Uncertainty does not mean that a nation or the world community cannot position itself better to cope with the broad range of possible climate changes or protect against potentially costly future outcomes. Delaying such measures may leave a nation or the world poorly prepared to deal with adverse changes and may increase the possibility of irreversible or very costly consequences. Options for adapting to change or mitigating change that can be justified for other reasons today (e.g., abatement of air and water pollution) and make society more flexible or resilient to anticipated adverse effects of climate change appear particularly desirable.**

*National Assessment Synthesis Team. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change.* Washington, DC: U.S. Global Research Program, 2000, p. 19.

**Intergovernmental Panel on Climate Change, *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific–Technical Analysis.* New York: Cambridge University Press, 1996, p. 23.

Chapter Summary

- Current interest in past and future climates is due to several factors. Detailed reconstructions of past climates show that the climate has varied on all time scales from decades to millions of years. Also, research focused on human activities and their effect on the environment has demonstrated that people are inadvertently changing climate. And finally, there is observational evidence that world climate has become more variable.
- The *climate system* includes the atmosphere, hydrosphere, solid Earth, biosphere, and cryosphere (the ice and snow that exists at Earth's surface). The system involves the exchanges of energy and moisture that occur among the five spheres.
- Techniques for analyzing Earth's climate history on a scale of hundreds to thousands of years include evidence from *seafloor sediments* and *oxygen isotope analysis.* Seafloor sediments are useful recorders of worldwide climate change because the numbers and types of organic remains included in the sediment are indicative of past sea-surface temperatures. Using oxygen isotope analysis, scientists can use the $^{18}O/^{16}O$ ratio found in the shells of microorganisms in sediment and layers of ice and snow to detect past temperatures. Other sources of data used for the study of past climates include the growth rings of trees, pollen contained in sediments, coral reefs, and information contained in historical documents.
- Several explanations have been formulated to explain climate change. Current hypotheses for the "natural" mechanisms (causes unrelated to human activities) of climate change include (1) plate tectonics, rearranging Earth's continents closer or farther from the equator, (2) volcanic activity, reducing the solar radiation that reaches the surface, (3) variations in Earth's orbit, involving changes in the shape of the orbit (*eccentricity*), angle that Earth's axis makes with the plane of its orbit (*obliquity*), and/or the wobbling of the axis (*precession*), and (4) changes in the Sun's output associated with *sunspots.*
- Humans have been modifying the environment for thousands of years. By altering ground cover with the use of fire and the overgrazing of land, people have modified such important climatological factors as surface albedo, evaporation rates, and surface winds. Along with water vapor, carbon dioxide is largely responsible for the *greenhouse effect* of the atmosphere. Therefore, by adding carbon dioxide and other trace gases (methane, nitrous oxide, and chlorofluorocarbons) to the atmosphere, humans are likely contributing to global warming in a significant way.

- When any component of the climate system is altered, scientists must consider the many possible outcomes, called *climate-feedback mechanisms.* Changes that reinforce the initial change are called *positive-feedback mechanisms.* For example, warmer surface temperatures cause an increase in evaporation, which further increases temperature as the additional water vapor absorbs more radiation emitted by Earth. On the other hand, *negative-feedback mechanisms* produce results that are the opposite of the initial change and tend to offset it. An example would be the negative effect that increased cloud cover has on the amount of solar energy available to heat the atmosphere.
- Global climate is also affected by human activities that contribute to the atmosphere's *aerosol* (tiny, often microscopic, liquid and solid particles that are suspended in air) content. By reflecting sunlight back to space, aerosols have a net cooling effect. The effect of aerosols on today's climate is determined by the amount emitted during the preceding couple of weeks, while carbon dioxide remains for much longer spans and influences climate for many decades.
- Because the climate system is so complex, predicting specific regional changes that may occur as the result of increased levels of carbon dioxide in the atmosphere is highly speculative. However, some possible consequences of greenhouse warming include (1) altering the distribution of the world's water resources (2) a probable rise in sea level, (3) a greater intensity of tropical cyclones, and (4) changes in the extent of Arctic sea ice and permafrost.
- Due to the complexity of the climate system, not all future shifts can be foreseen. Thus, "surprises" (relatively sudden unexpected changes in climate) are possible.

Vocabulary Review

climate system (p. 400)
climate-feedback mechanism (p. 417)
eccentricity (p. 409)
Milankovitch cycles (p. 409)
negative-feedback mechanis (p. 418)
obliquity (p. 409)
oxygen isotope analysis (p. 401)
paleoclimatology (p. 400)
plate-tectonics theory (p. 406)
positive-feedback mechanism (p. 418)
precession (p. 409)
proxy data (p. 400)
sunspot (p. 412)

Review Questions

1. List the five parts of the climate system.
2. List and describe some methods and sources of data that scientists use to gain insight into the climates of the past.
3. How does plate-tectonics theory help explain the previously "unexplainable" glacial features in present-day Africa, South America, and Australia?
4. Can plate tectonics account for short-term climate changes? Explain.
5. The volcanic eruptions of El Chichón in Mexico and Mount Pinatubo in the Philippines had measurable short-term effects on global temperatures. Describe and briefly explain these effects.
6. List and describe each of the three variables that link Earth's motions (Milankovitch cycles) and climate change.
7. Do recent studies of seafloor sediments tend to confirm or refute the importance of Milankovitch cycles? What do these studies predict for the future?
8. List two examples of possible climate change linked to solar variability. Are these Sun–climate connections widely accepted?
9. Why has the carbon dioxide level of the atmosphere been rising for more than 150 years?
10. How are temperatures in the lower atmosphere likely to change as carbon dioxide levels continue to increase?
11. Aside from carbon dioxide, what other trace gases are contributing to a future global temperature change?
12. What are climate-feedback mechanisms? Give some examples.
13. What are the main sources of human-generated aerosols? What effect do these aerosols have on temperatures in the troposphere? How long do aerosols remain in the lower atmosphere before they are removed?
14. List four potential consequences of a greenhouse warming.

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

- **Online review quizzes**
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- **Links to chapter-specific web resources**
- **Internet-wide key term searches**

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