CHAPTER

14

he Changing Climate

Columbia Glacier in Prince William Sound, Alaska. Glaciers cover about 10 percent of Earth's land area. By contrast, during the recent ice age, glacial ice covered up to three times as much land as today. (Photo by Pat O'Hara/DRK Photo)

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.

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.*[1]

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.) 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.

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.

Is Our Climate Changing?

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 (and is) 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.

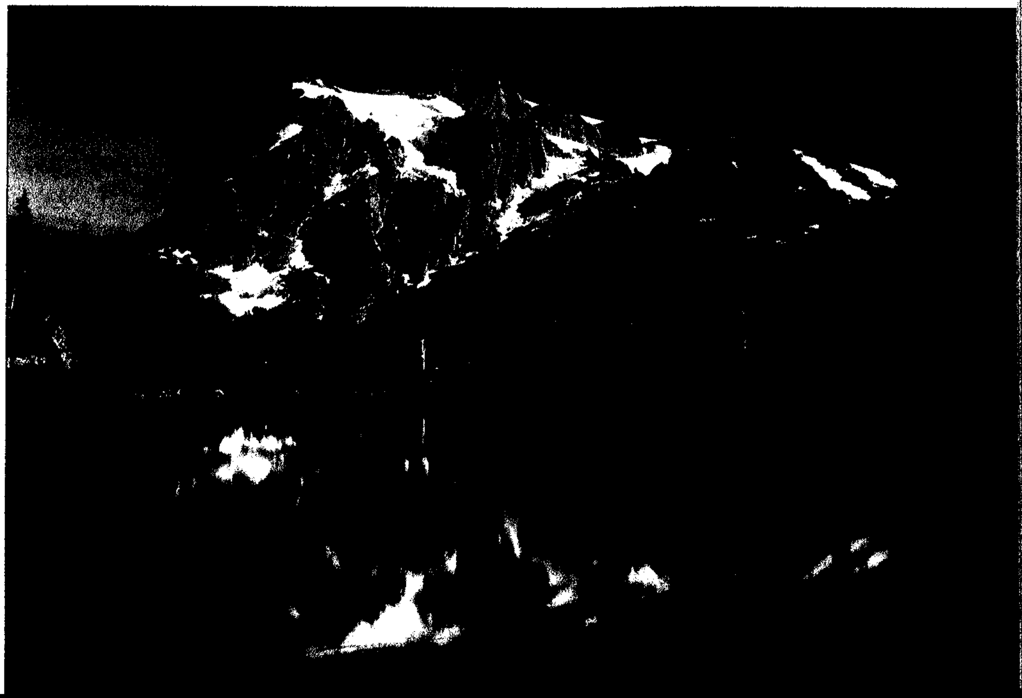

Figure 14–1 The climate system involves the complex interactions that occur among the atmosphere, hydrosphere, lithosphere, cryosphere, and biosphere. All of the components are represented in this scene in Washington's Mount Baker National Forest. (Photo by Charles Krebs/The Stock Market)

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[1] 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.

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.

How Do We Detect Climate Change?

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 climatic 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 more incomplete and unreliable the data become. To overcome this lack of direct measurements, scientists must decipher and reconstruct past climates by using indirect evidence. Such evidence is found in sea-floor sediment, oxygen isotope ratios in fossil shells and glacial ice, old soils, tree growth rings, and even historical documents. Scientists analyze these phenomena, which respond to and reflect changing atmospheric conditions. In the following discussion, we will briefly look at some of these techniques. But keep in mind that these reconstructions may capture no more than the most general features of climate.

Among the most interesting and important techniques for analyzing Earth's climate history on a scale of hundreds to thousands of years are the study of ocean-floor sediments and oxygen isotope analysis. Both methods are relatively recent developments used to reconstruct past temperatures, and each, in part, is related to the other.

Evidence from Sea-Floor Sediment

Most sea-floor 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 sea-floor 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 should be reflected in changes in organisms living near the surface of the deep sea. . . . When we recall that the sea-floor 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.*[2]

Thus, in seeking to understand climatic change, scientists have become increasingly interested in the huge reservoir of data concealed in sea-floor sediments. Since the late 1960s, the United States has been involved in major international projects. Presently the Ocean Drilling Program uses a specially designed research vessel, the *JOIDES Resolution*, that is capable of drilling into the ocean floor and collecting cores of deep-sea sediments (Figure 14–2). The sediment cores have proven to be excellent sources of useful data that have greatly expanded our understanding of past climates (see Box 14–1).

Evidence from Oxygen Isotope Analysis

The second technique, **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. Both types become part of water, of course. 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. Of course, 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 ($CaCO_3$), the prevailing $^{18}O/^{16}O$ ratio is reflected in the composition of these hard parts. When the organisms die, their hard parts fall to the ocean floor, becoming part of the sediment layers.

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

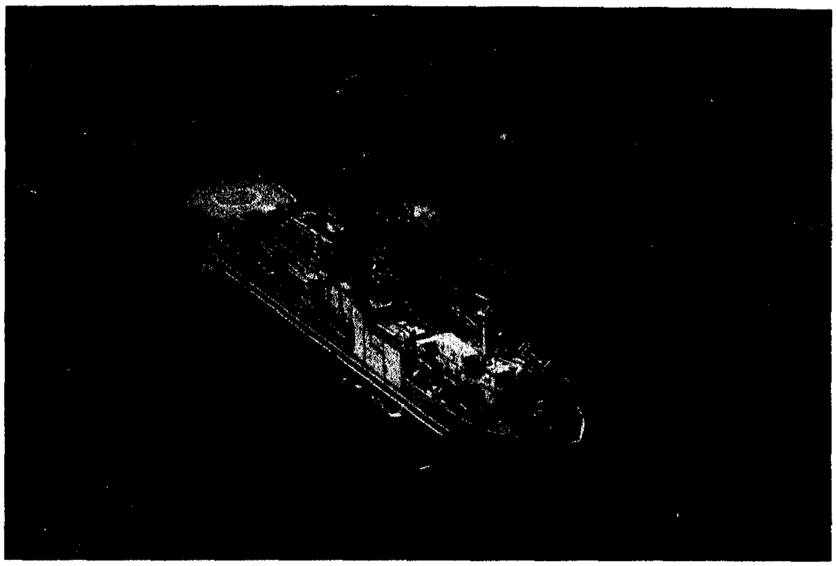

Figure 14–2 The *JOIDES Resolution*, drilling ship of the Ocean Drilling Program. The seafloor sediments recovered by this and other research vessels provide scientists with data that allow them to reconstruct past climates. (Photo courtesy of the Ocean Drilling Program)

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 (see Box 14–2).

Evidence from Other Sources

Several other methods have been used to gain insight into past climates. Because climate has a major effect on soil development and the growth of vegetation, the study of buried soils (*paleosols*), the analysis of the yearly growth rings of trees, and the study of pollen contained in sediments have been used to infer past climates. Figure 14–3 shows an example of tree rings.

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 influence of a changing climate.

Even modern instrument records can be problematic:

> *Climatic records are not readily subjected to objective study. In the first place, weather observers are subject to human failings, and even small errors affect calculations that may involve equally small trends. The exposure and height above ground of instruments also materially affect results. Removal of a weather station to a new location practically destroys the value of its records for purposes of studying climatic change. But even if a station remains in the same location for a century, the changes in vegetation, drainage, surrounding buildings, and atmospheric pollution are likely to produce a greater effect on climatic records than any true climatic changes. Thus, very careful checking and comparison of climatic records are necessary to detect climatic fluctuations.*[3]

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 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 physically reproduced in laboratory experiments. Rather, climate and its changes must be simulated mathematically (modeled) using powerful computers (Figure 14–4). Although such models are sophisticated tools for climate research, they cannot yet approach the actual complexity of the atmosphere. Computer models are powerful and essential aids, but climate forecasts based on such simulations are still fraught with uncertainty.

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[3] Howard J. Critchfield, *General Climatology*, 3rd ed. (Englewood Cliffs, N.J.: Prentice Hall, 1974), p. 376.

Box 14–1

Sampling the Ocean Floor

The *JOIDES Resolution* is the drilling ship of the Ocean Drilling Program. The "*JOIDES*" in the ship's name stands for Joint Oceanographic Institutions for Deep Earth Sampling and reflects the international commitment from the program's 19 member countries. The "*Resolution*" honors the *HMS Resolution*, commanded more than 200 years ago by the well-known explorer Captain James Cook.

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 is 143 meters long and 21 meters wide with a derrick that towers 62 meters above the waterline. A computer-controlled positioning system maintains the ship over a specific location. 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 (Figure 14–A).

The *JOIDES Resolution* has living quarters for 50 scientists and technicians plus a crew of 65. The 12 onboard laboratories are equipped with the largest and most varied array of seagoing research equipment in the world.

Since 1985, the ship has drilled in the Atlantic, Pacific, Indian, and Arctic oceans as well as several seas. The result has been the recovery of more than 187,000 meters (more than 115 miles!) of core samples. ■

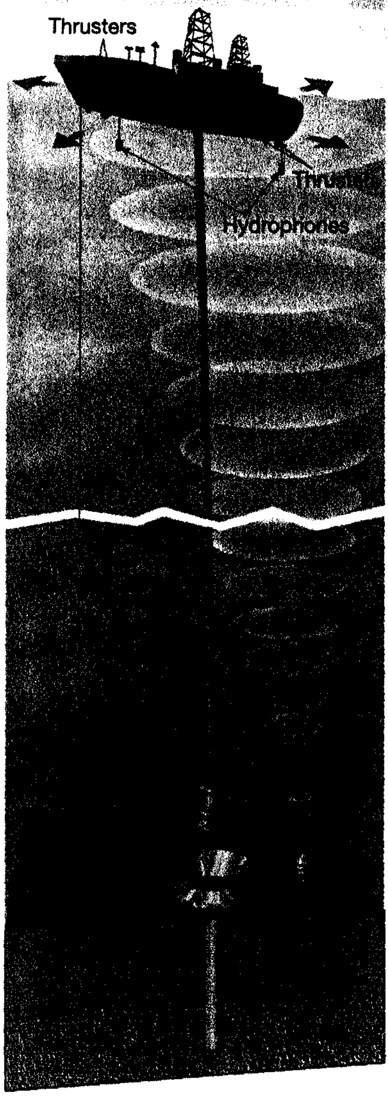

Figure 14–A *JOIDES Resolution* can reenter holes in the sea floor years after initial drilling. The ship's dynamic positioning system consists of powerful thrusters (small propellers) that allow it to remain in place. Previous drill sites are located by bouncing sound waves between the ship's hydrophones and sonar beacons. A remote television camera aids in positioning the drill pipe into the reentry cone.

In this section, we examine several current hypotheses that have gained some support 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 climatic 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

Box 14-2
Climate Change Recorded in Glacial Ice

Vertical cores taken from the Greenland and Antarctic ice sheets are important sources of data about climate change during and following the most recent cycle of glaciation. Scientists collect samples with a drilling rig, like a small version of an oil drill. A hollow shaft follows the drill head into the ice and an ice core is extracted. In this way, cores that sometimes exceed 2000 meters in length and may represent more than 200,000 years of climate history are acquired for study (Figure 14–B).

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 of past temperature changes. A portion of such a record is shown in Figure 14–C. ■

Figure 14–B Scientists at the National Ice Core Laboratory in Denver, Colorado, examine an ice core sample. Faint lines in the sample are annual dust layers deposited in summer months. Using these layers, the ice cores can be dated much like dating trees by studying their rings. (Photo by Ken Abbot/National Ice Core Laboratory)

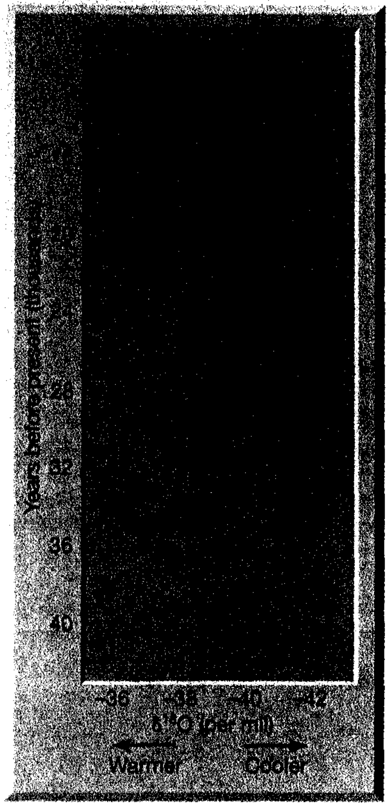

Figure 14–C Temperature variations as revealed by fluctuations in the $^{18}O/^{16}O$ ratio in a portion of a Greenland ice core. An increase in ^{18}O indicates an increase in air temperature. Levels of ^{18}O fall when cooler temperatures prevail.

climate change on all time scales. A proposal that explains variations over millions of years generally cannot explain fluctuations over hundreds 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 few decades a revolutionary idea has emerged from the science of geology: **plate tectonics theory**. This theory now has gained nearly universal acceptance among scientists. It states that the outer portion of Earth is made up of several vast slabs, called plates, which move in relation to one another over a plastic layer of rock 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. Examples are the North American, South American, and African plates (Figure 14–5). Thus, as plates ponderously grind along, the continents also change position. Not only does this theory allow the geologist to explain Earth's continents and oceans, but it also provides the climatologist with a probable explanation for some hitherto unexplainable climatic 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 proven, 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 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. 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 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 two hundred 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 (see Box 14–3). Similar, although apparently less

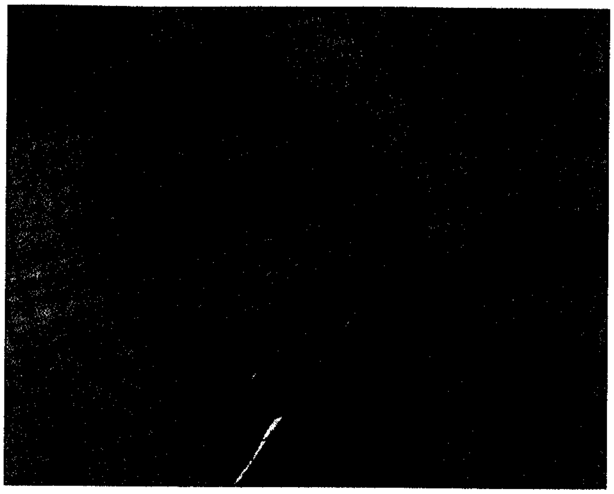

Figure 14–3 Each year a growing tree produces a layer of new cells beneath the bark. If the tree is felled and the trunk examined (or if a core is taken, to avoid cutting the tree), each year's growth can be seen as a ring. Because the amount of growth (thickness of a ring) depends upon precipitation and temperature, tree rings are useful records of past climates. (Photo by Stephen J. Krasemann/DRK Photo)

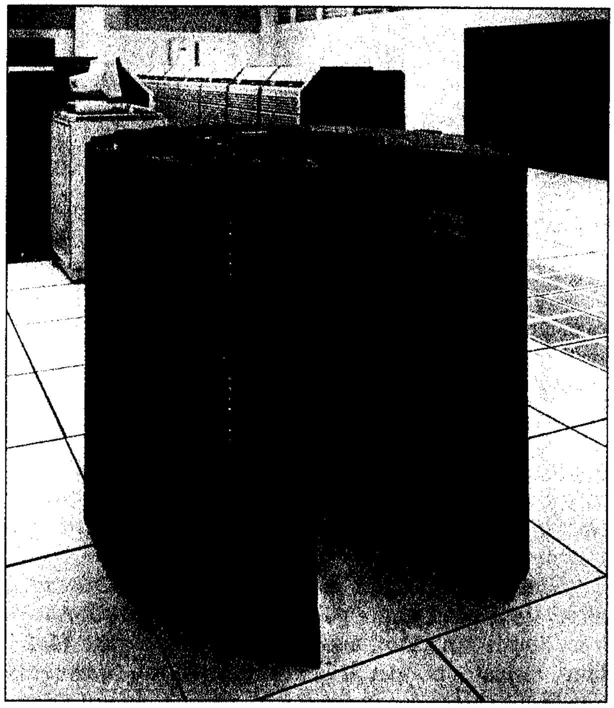

Figure 14–4 Because large-scale atmospheric processes do not fit into the laboratory and because controlled long-term experiments are not possible, computer models are essential in climate research. (Photo by Dale E. Boyer/Photo Researchers, Inc.)

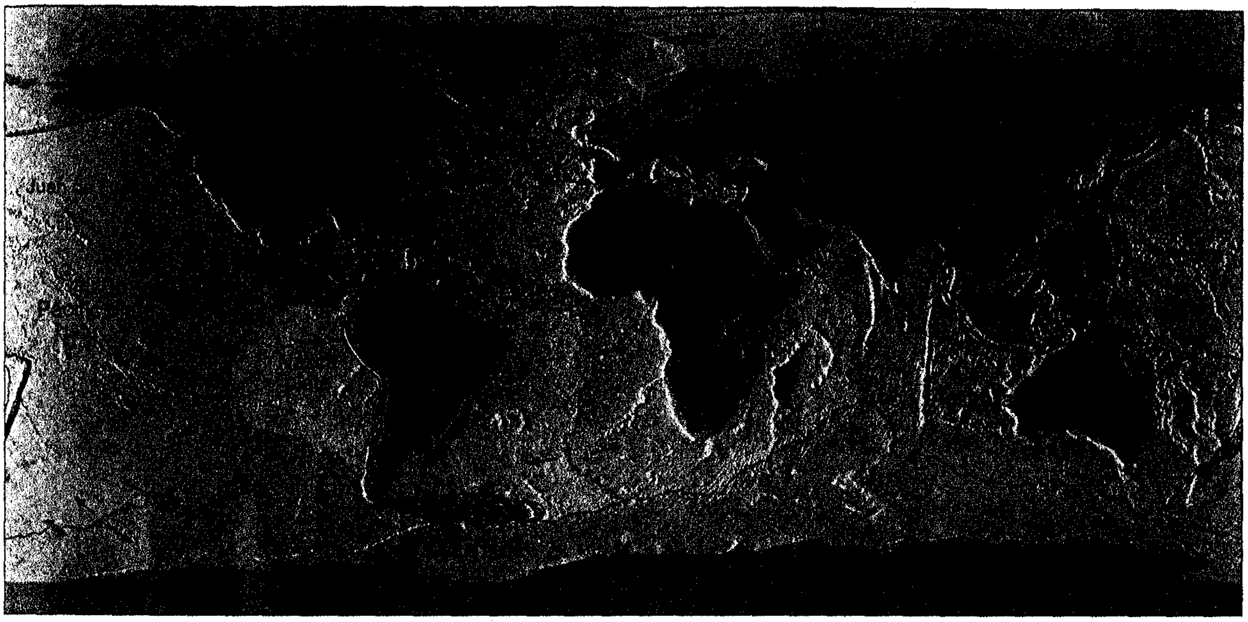

Figure 14–5 The outer portion of our planet consists of many large rigid slabs called *plates*. Driven by heat from Earth's interior, plates gradually move in relation to each other. As a result, continents are carried to different positions on the globe.

dramatic effects were associated with other great explosive volcanoes, including Indonesia's Krakatoa in 1883.

In recent years, 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 Philippine's 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. Here is a brief look at each of these eruptions.

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 (Figure 14–7). Still, studies indicated that any longer-term lowering of hemispheric temperatures was negligible. The cooling was so slight, probably less than 0.1°C, 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. 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 was 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. 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 but do not slow the loss of terrestrial radiation.

It now appears 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.

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 volcanic eruption using NASA's spaceborne Earth Radiation Budget Experiment. During the next year, the haze of tiny aerosols acted to lower global temperatures

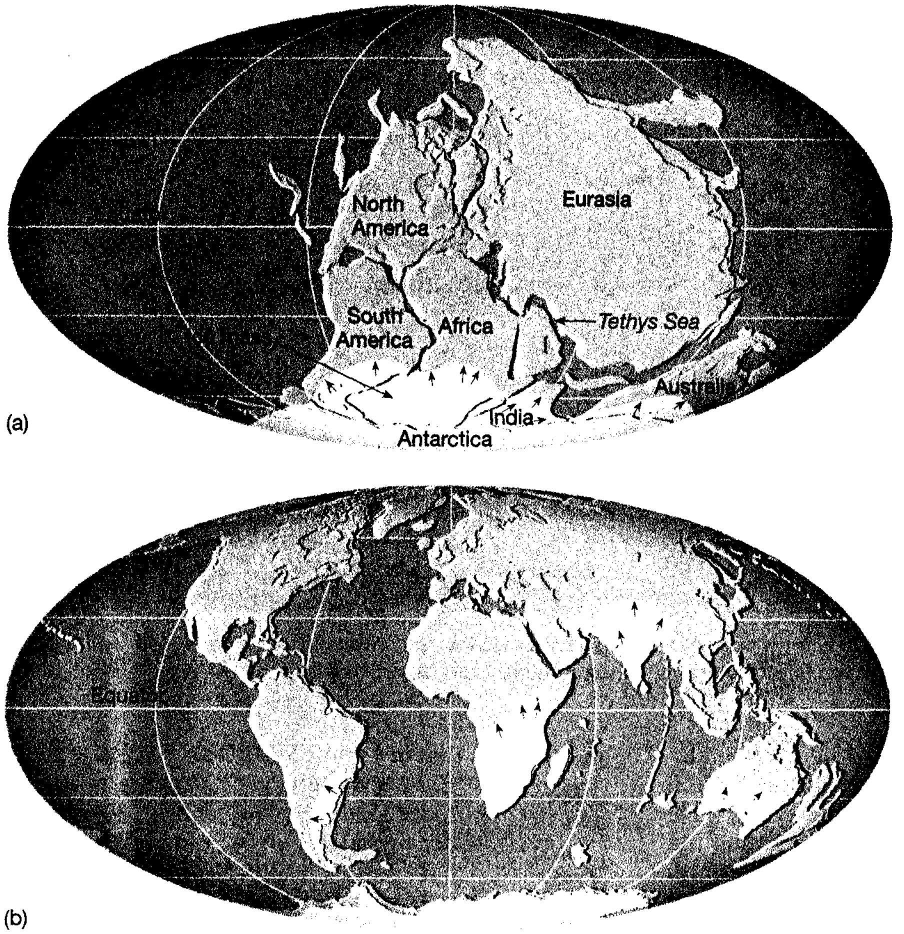

Figure 14–6 (a) The supercontinent Pangaea showing the area covered by glacial ice 300 million years ago. (b) The continents as they are today. The white areas indicate where evidence of the old ice sheets exists.

by 0.5°C. Scientists found that the aerosols influenced albedo and lowered temperatures in two ways.

First, the cooling was related to an increase in albedo over cloudless areas resulting directly from the presence of the volcanic aerosols. Second, they detected a higher cloud albedo. The latter effect occurred because the aerosols acted as cloud condensation nuclei. The added nuclei allowed more cloud droplets to form, which in turn made the clouds denser and thus "brighter" (more reflective) than they otherwise would have been.

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 such prehistoric climatic shifts as the Ice Age. However, as we shall see in the following section, there is convincing evidence that other mechanisms can better explain Ice Age climates. At present, there is little support in the scientific community for the view that explosive volcanism can significantly contribute to an ice age.

Orbital Variations

"Variations in the earth's orbit influence climate by changing the seasonal and latitudinal distribution of incoming solar radiation."[4] Proposals that link orbital

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

Box 14–3

The Year Without a Summer

The graph in Figure 14–D allows us to compare the volume of volcanic debris extruded during some well-known eruptions, beginning with Mt. Vesuvius in A.D. 79. The eruption of the volcano named Tambora is clearly the largest of modern times. During April 7–12, 1815, this nearly 4000-meter-high Indonesian volcano violently ejected an estimated 30 cubic kilometers of volcanic debris. That is 30 times more ash than was emitted during the eruption of Mount St. Helens in May 1980.

Although the Tambora eruption occurred in an isolated part of the world, stratospheric circulation spread its influence far and wide. The impact of the volcanic dust and gases on climate is believed to have been widespread in the Northern Hemisphere. According to one researcher, "The extreme cold that prevailed during the spring and summer of 1816 in some regions of the world represents one of the most unusual climatic episodes that has occurred since the advent of instrumental weather observations."* The effects were especially severe in New England, where 1816 came to be known as the "year without a summer."

From May through September 1816, an unprecedented series of cold spells affected the northeastern United States and adjacent portions of Canada. The result was a late spring, a cold summer, and an early fall. There was heavy snow in June and frost in July and August. Across the Northeast, crops were killed by the cold. Temperatures in New England averaged up to 3.5°C below normal in June and 1–2°C below normal in August. Although temperatures this cold had occurred before, there had never been such a protracted span of cold since recordkeeping began. The temperature reductions may seem modest, but they took place in a region where even a small drop in minimum temperatures can mean severe frost.

New England and adjacent Canada were not the only areas to experience a "year without a summer." As one writer observed, "Although the New England farmer considered it a local tragedy, the abnormal weather was widespread throughout the Northern Hemisphere. In England it was almost as cold as in the United States, and 1816 was a famine year there, as it was in France and Germany."†

The unusual meteorological events of 1816, which followed the massive 1815 eruption of Tambora, are regarded by many as a spectacular example of the influence of explosive volcanism on climate. Although the effects were relatively short-lived, this geologic event had a significant impact on both the atmosphere and humanity. ■

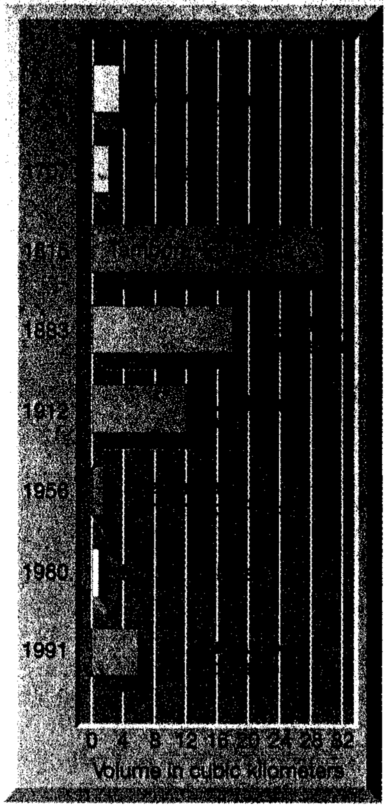

Figure 14–D Approximate volume of volcanic debris emitted during some well-known eruptions. The 1815 eruption of Tambora, the largest-known eruption in historic time, ejected over 30 times more ash than did Mount St. Helens in 1980.

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*Kevin Hamilton, "Early Canadian Weather Observers and the 'Year Without a Summer,' " *Bulletin of the American Meteorological Society*, 67, no. 5 (May 1986), 524.

†Patrick Hughes, *American Weather Stories* (Washington, D.C.; National Oceanic and Atmospheric Administration, 1976), p. 43.

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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.

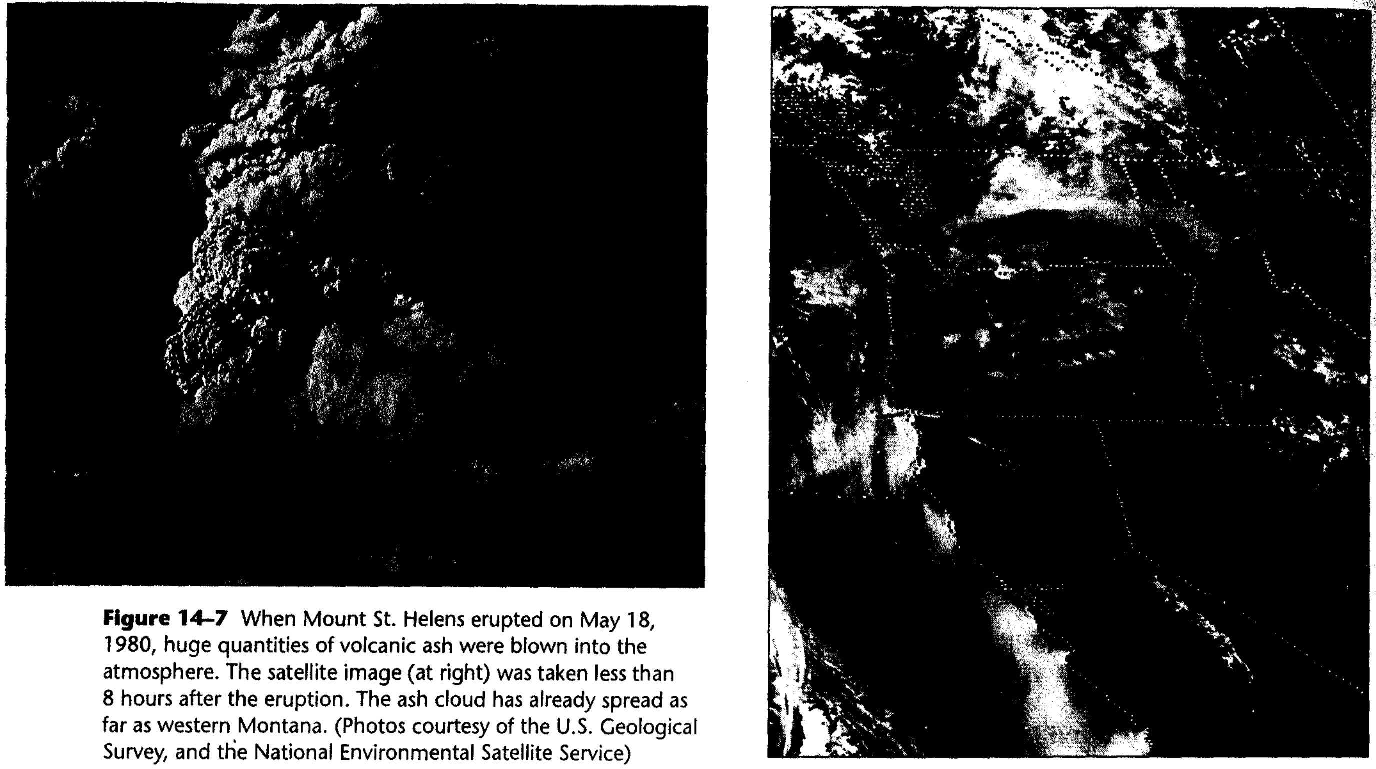

Figure 14–7 When Mount St. Helens erupted on May 18, 1980, huge quantities of volcanic ash were blown into the atmosphere. The satellite image (at right) was taken less than 8 hours after the eruption. The ash cloud has already spread as far as western Montana. (Photos courtesy of the U.S. Geological Survey, and the National Environmental Satellite Service)

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 14–8a). 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 14–8b). Because this angle varies, the severity of the seasons must also change. The smaller our tilt, the smaller is 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 run-down 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

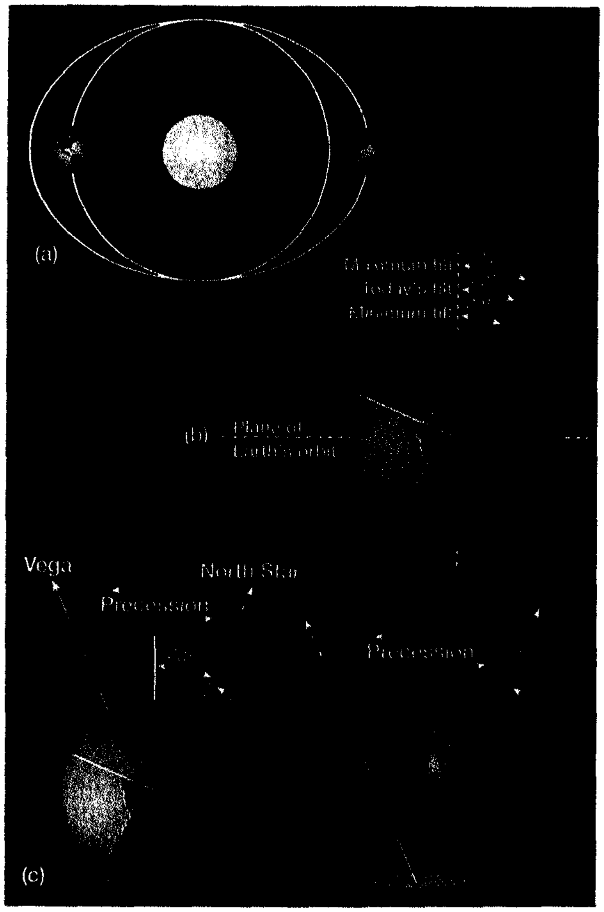

Figure 14–8 Orbital variations. (a) The shape of Earth's orbit changes during a cycle that spans about 100,000 years. It gradually changes from nearly circular to one that is more elliptical and then back again. This diagram greatly exaggerates the amount of change. (b) Today the axis of rotation is 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.

then become the North Star (Figure 14–8c). Because the period of precession is about 26,000 years, Polaris will once again be the North Star by the year 27,000.

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 insolation 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 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.[5] 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."[6]

Also, the study went on to predict the future trend of climate, toward a cooler climate and extensive

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

[6] Ibid., p. 1131. The term "Quaternary" refers to the period on the geologic time scale that encompasses the last 1.6 million years.

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 that

> *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.*[7]

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 14–9). Although their origin is uncertain, it has been established that 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 1–16).

Along with other solar activity, the number of sunspots increases and decreases on a regular basis, creating a cycle of about 11 years. A curve of the annual number of sunspots, beginning in the early 1700s, appears to be very regular (Figure 14–10). In fact, until recently, few scientists doubted that sunspots and the 11-year cycle were enduring features of the Sun. Today, however, we know that there have been periods when the Sun was essentially free of these blemishes. 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 excellent matches, one solar astronomer stated: "These early results in comparing solar history with climate make it appear that changes on the sun are the dominant agent of climatic changes lasting between 50 and several hundred years."[8] But other scientists seriously questioned this conclusion. Their hesitation stems in part from subsequent investigations using different climate records from around the world that failed to find a significant correlation between solar activity and climate. Even more troubling is that no testable physical mechanism exists to explain the purported effect.

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

[8] John Eddy, "The Case of the Missing Sunspots," *Scientific American*, 236, no. 5 (1977). 88, 92.

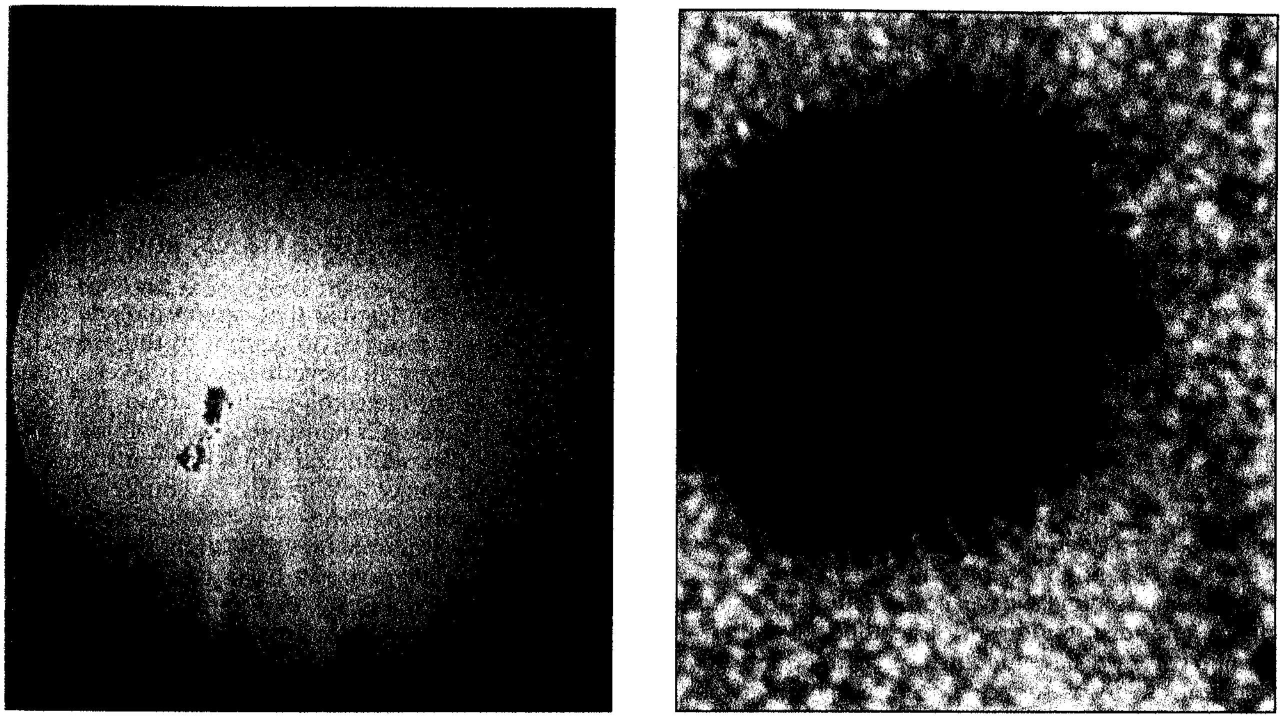

Figure 14–9
Large sunspot group (left) on the solar disk. (Celestron 8 photo courtesy of Celestron International)
Sunspots (right) having visible umbra (dark central area) and penumbra (lighter area surrounding umbra).
(Courtesy of National Optical Astronomy Observatories)

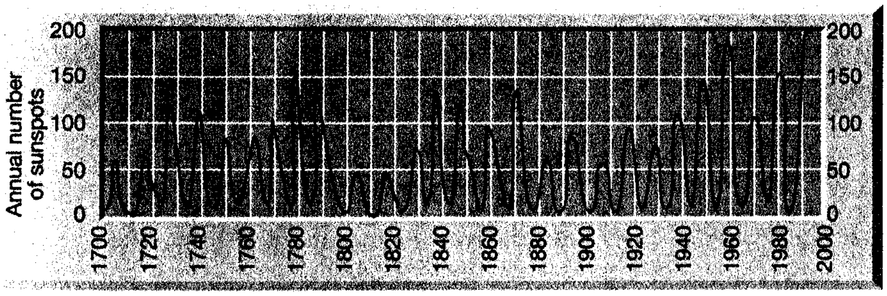

Figure 14–10 Mean annual sunspot numbers.

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 that:

> *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.*[9]

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. The National Research Council sums up the situation this way:

> *Despite much research, no connection between solar variations and weather has ever been unequivocally established. Apparent correlations have almost always*

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

faltered when put to critical statistical examination or have failed when tested with different data sets. As a result the subject has been one of continual controversy and debate.[10]

Human Impact on Global Climate

So far we have examined four potential causes of climatic change, each of them natural. In this section, we discuss how humans may contribute to global climate change. This impact largely results from the addition of carbon dioxide and other greenhouse gases to the atmosphere.

One often hears 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 we 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, we have modified such important climatological factors as surface albedo, evaporation rates, and surface winds (see Box 14–4). 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."[11]

Carbon Dioxide, Trace Gases, and Climate Change

In Chapter 1, you learned that carbon dioxide (CO_2) represents only about 0.036 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 terrestrial radiation. A portion of the energy leaving the ground is absorbed by atmospheric CO_2. This 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

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[10] National Research Council, *Solar Variability*, p. 4.

[11] Carl Sagan et al., "Anthropogenic Albedo Changes and the Earth's Climate," *Science*, 206, no. 4425 (1980), 1367.

Box 14–4
Desertification

On nearly any list of major environmental issues facing the world, one is likely to find reference to the problem of *desertification*. The term used to mean the expansion of desertlike conditions into nondesert areas. Such transformations can result from natural processes that act gradually over extended spans of time. In recent years, the term desertification has narrowed to mean situations where land is altered rapidly to desertlike conditions as the result of human activities.

Desertification commonly takes place on the margins of deserts. The advance of desertlike conditions into previously productive areas is not a uniform process. Rather, degeneration into desert usually occurs as a patchy transformation of dry but habitable land into dry and uninhabitable land. It is primarily the product of inappropriate land use and is accelerated by drought. The process may halt during wet years, only to advance rapidly during succeeding dry years.

On marginal land used for crops, farmers clear away the natural vegetation. Then, during periods of drought, crops fail and the unprotected soil is exposed to erosion. Gullying of slopes and accumulations of sediment in stream channels are visible signs on the landscape, as are the clouds of dust created as topsoil is removed by the wind.

Where livestock are raised, land degradation also occurs. The modest vegetation on marginal land may maintain local wildlife, but it cannot support the intensive grazing of large domesticated herds. Overgrazing reduces or eliminates plant cover. When the vegetative cover is destroyed beyond the minimum required to hold the soil against erosion, destruction becomes irreversible.

Desertification first received worldwide attention when drought struck a region in Africa called the Sahel in the late 1960s (Figure 14–E). During that period and others since, the people in this vast expanse that borders the Sahara

Desert have suffered from malnutrition and death by starvation. Livestock herds have been decimated, and the loss of productive land has been great. Hundreds of thousands of people have been forced to migrate. As agricultural lands shrink, people must rely on smaller areas for food production. This, in turn, places greater stress on the environment and accelerates the desertification process.

Although human suffering associated with desertification is most serious along the southern margins of the Sahara, the problem is by no means confined to the Sahel. The problem also exists in other parts of Africa and on every other continent except Antarctica. Each year millions of acres are lost beyond any hope for reclamation. Recurrent drought may seem to be the obvious reason for desertification, but the stress placed by people on a tenuous environment with fragile soils is the chief cause. ■

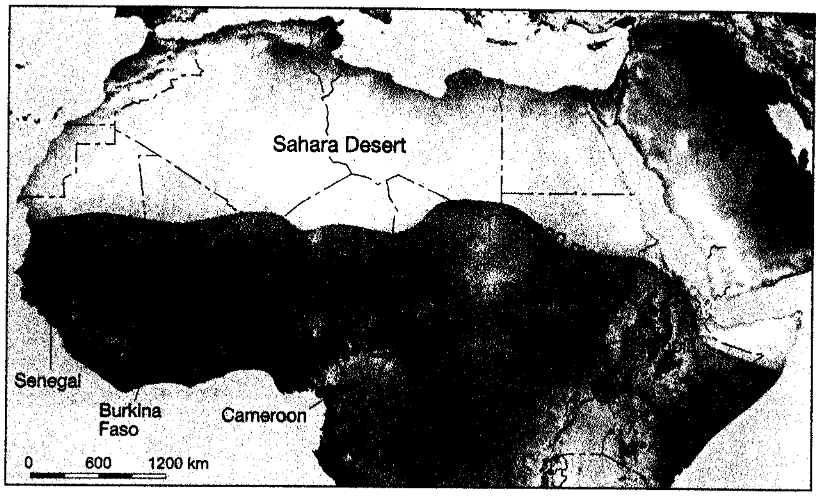

Figure 14–E Desertification is most serious along the southern margin of the Sahara in a region known as the Sahel. The lines defining the approximate boundaries of the Sahel represent average annual rainfall in millimeters.

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.

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 14–11). 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 United Nations estimates, the destruction of tropical forests averaged 15.4 million hectares (38 million acres) per year between 1981 and 1990.

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 14–12 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 obvious and has closely followed the increase in CO_2 emissions from burning fossil fuels. Figure 14–12b shows this parallel growth.

We might expect that global temperature has increased as a result of the growing carbon dioxide level. In fact, since the late 1800s the mean global temperature has risen by about 0.3 to 0.6°C and by about 0.2 to 0.3°C over the last 45 years (Figure 14–13). Moreover, recent years have been among the warmest since the mid-1800s despite the cooling effect of the 1991 Mount Pinatubo eruption. Are these temperature trends caused by human activities or would they have occurred anyway? Scientists are cautious, but now they seem convinced that "the observed trend in global mean temperature over the past 100 years is unlikely to be natural in origin," and that the data "point towards a human influence on global climate."[12]

If fossil fuel use continues to increase at projected rates, current estimates are that the atmosphere's CO_2 content will approach 400 ppm by the year 2010 and 600 ppm during the second half of the 21st century. With such an increase, the greenhouse effect would become much more dramatic and measurable than in the past. The most realistic models predict an increase in the mean

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

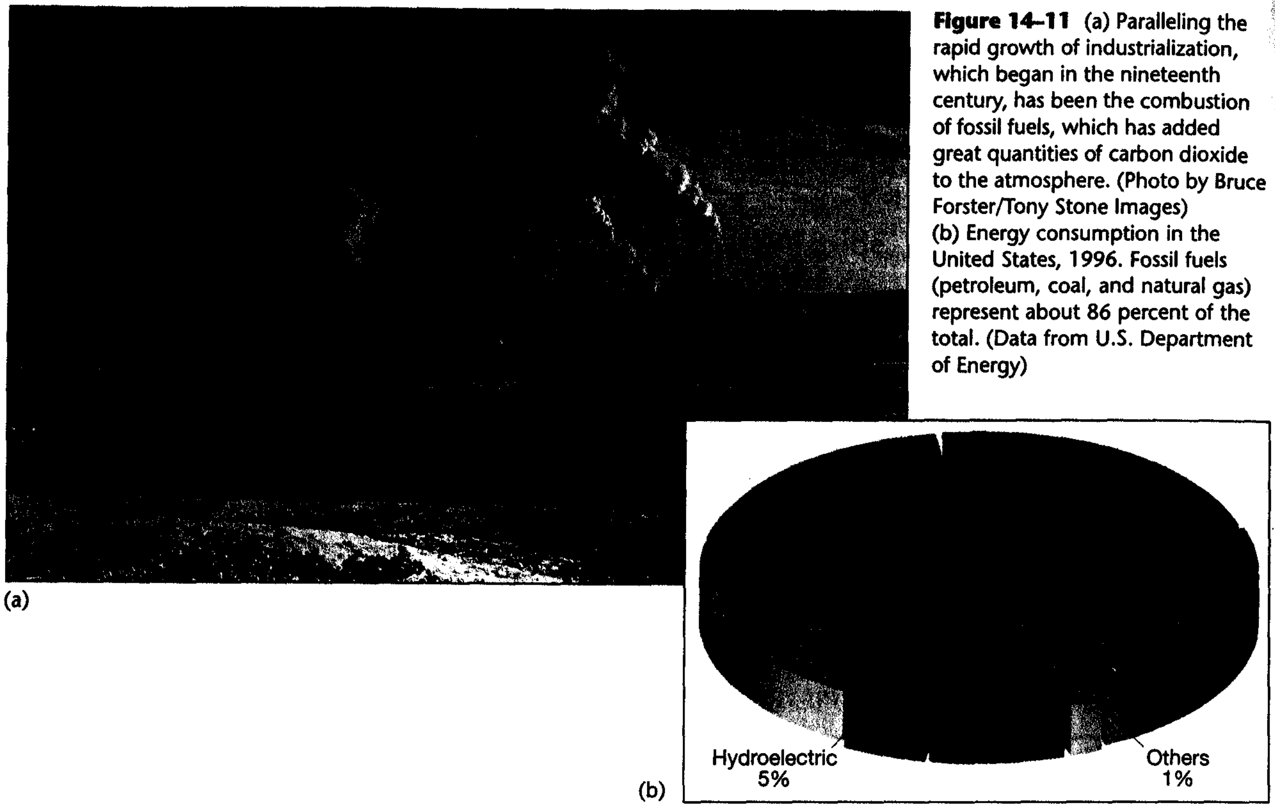


Figure 14–11 (a) Paralleling the rapid growth of industrialization, which began in the nineteenth century, has been the combustion of fossil fuels, which has added great quantities of carbon dioxide to the atmosphere. (Photo by Bruce Forster/Tony Stone Images) (b) Energy consumption in the United States, 1996. Fossil fuels (petroleum, coal, and natural gas) represent about 86 percent of the total. (Data from U.S. Department of Energy)

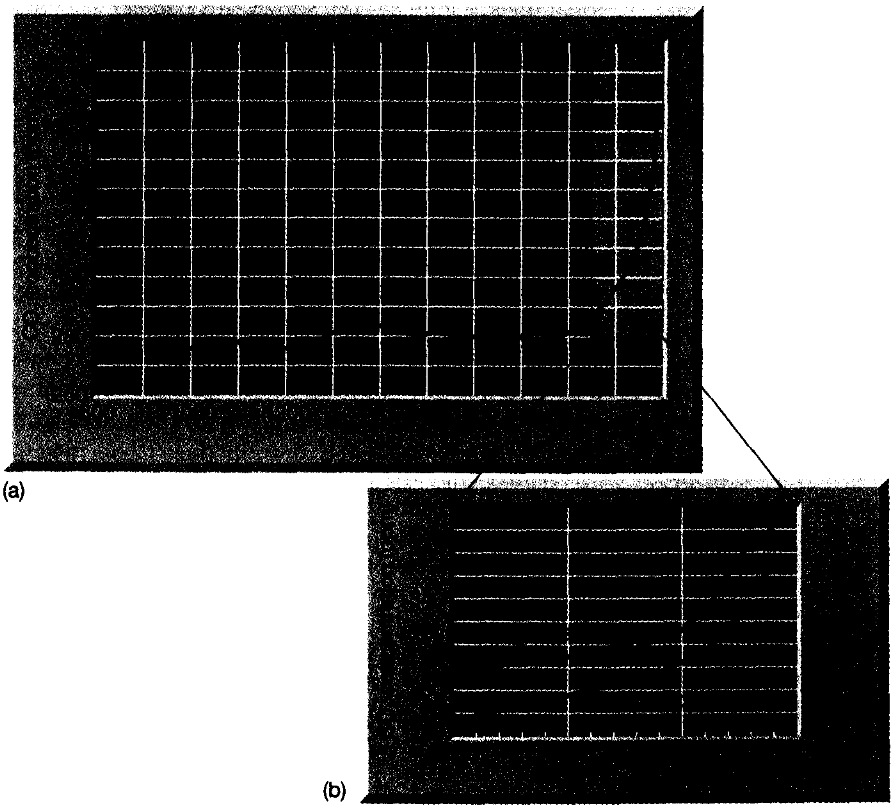


Figure 14–12 (a) Carbon dioxide (CO_2) concentrations over the past 1000 years. Most of the record is based on data obtained from Antarctic ice cores. Bubbles of air trapped in the glacial ice provide samples of past atmospheres. The record since 1958 comes from direct measurements of atmospheric CO_2 taken at Mauna Loa Observatory, Hawaii. (b) The rapid increase in CO_2 concentration since the onset of industrialization in the late 1700s is clear and has followed closely the rise in CO_2 emissions from fossil fuels.

global surface temperature of about 2.5°C. A change of this magnitude would be unprecedented in human history. It would approach the warming that has taken place since the peak of the most recent glacial stage 18,000 years ago, but it would occur *much more rapidly*.

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 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 (see Box 14–5).

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 later in this section.

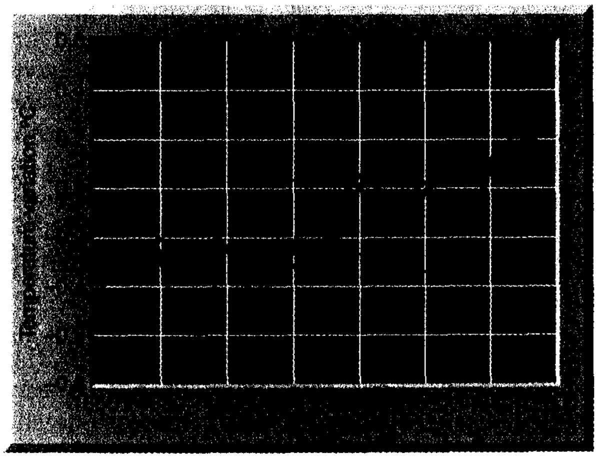


Figure 14–13 Land–surface air temperature and sea–surface temperature variations 1861–1994 relative to the 1961–90 period (0.0 line). The global mean land–surface air temperature in 1890 was about 0.2° *cooler* than the 1961–90 mean global temperature, whereas the 1990 global mean land–surface air temperature was about 0.4°C *warmer*. Clearly the trend is toward higher global mean temperatures. (After IPCC)

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? The most 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 terrestrial radiation 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 14–14). 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 terrestrial radiation. 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 terrestrial radiation that would otherwise be lost from the troposphere (see Figure 3–11).

Which effect, if either, is stronger? Atmospheric modeling shows that the negative effect of a higher

Box 14-5

Other Greenhouse Gases and Climate Change

Methane is among the gases that contribute to the greenhouse effect. It 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.

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–F).

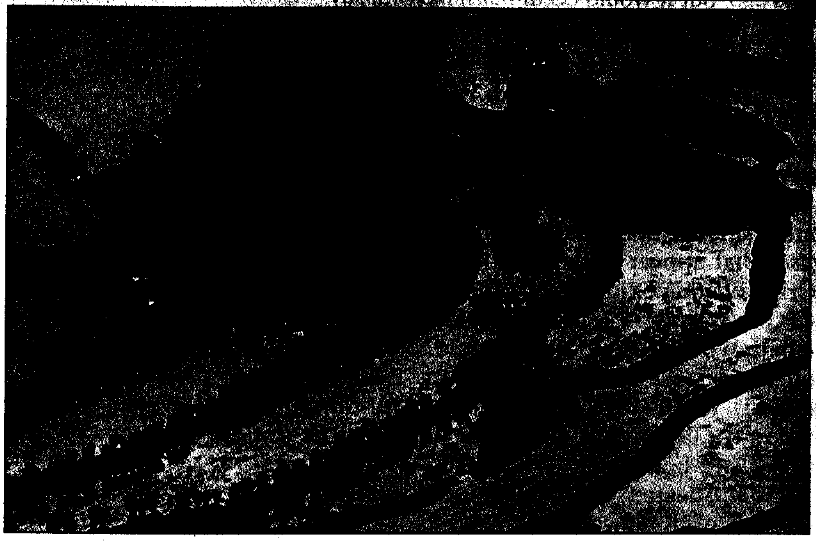


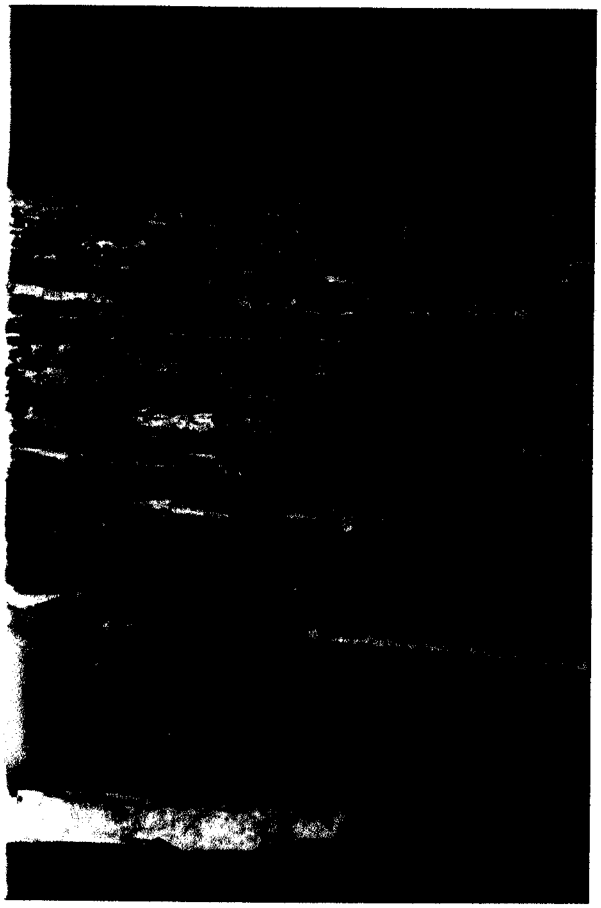
Figure 14–F The formation of methane is associated with the stagnant, oxygen-poor water in swamps and flooded rice paddies ("artificial swamps"). These paddies are in India's Ganges lowlands. (Photo by George Holton/Photo Researchers, Inc.)

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.

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 (air conditioning, for example) 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 from the burning of fossil fuels and deforestation is clearly the most important single cause for the projected global greenhouse warming. However, as this box has shown, 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. ■



ɜure 14–14 A reduction in sea ice would act as a positive ·dback mechanism because the amount of solar energy absorbed the surface would increase. (Photo by Wolfgang Kaehler)

ɔedo is dominant. Therefore, the net result of an crease in cloudiness should be a decrease in air mperature. The magnitude of this negative feedıck, however, is not believed to be as great as the ɔsitive feedback caused by added moisture and ːcreased sea ice. Thus, although increases in cloud ·ver may partly offset a global temperature increase, imate models show that the ultimate effect of the ·ojected increase in CO_2 and trace gases will still be temperature increase.

The problem of global warming caused by humanduced changes in atmospheric composition contin·s to be one of the most studied aspects of climate ıange. Although no models yet incorporate the full nge of potential factors and feedbacks, the scientific nsensus is that the increasing levels of atmospheric ırbon dioxide and trace gases will lead to a warmer anet with a different distribution of climate regimes.

Some Possible Consequences of a Greenhouse 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 computers grow in power and as data improve, scientists will gradually develop models that provide more specific and reliable results.

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).

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 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 14–15). Many other rivers are the basis for extensive irrigated agriculture, and the projected reduction of their flow could have equally grave consequences. 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 high 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

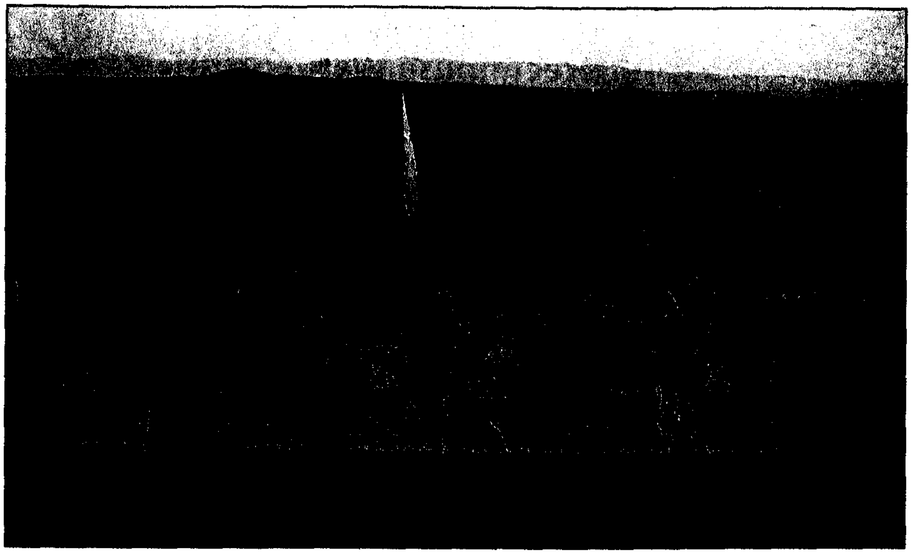


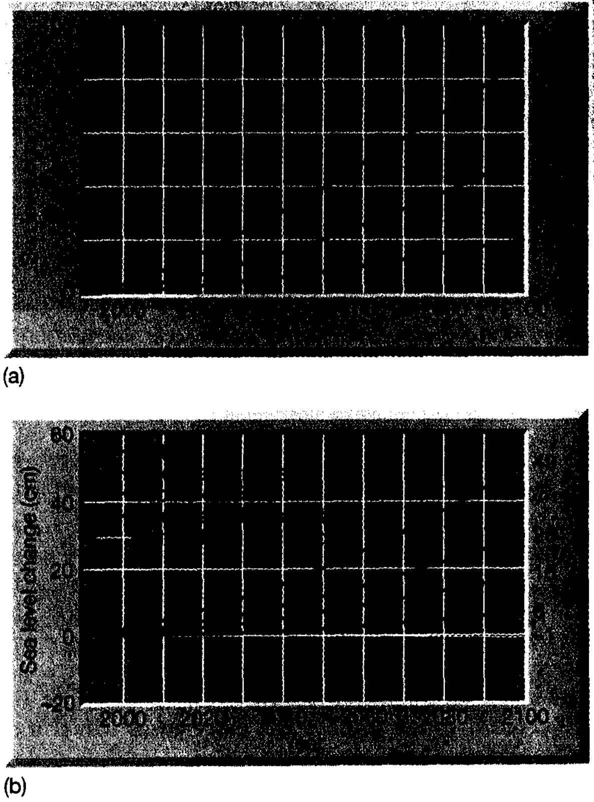
Figure 14–15 It is not yet possib to specify the magnitude and location of particular climate changes that may result from greenhouse warming. Many consequences are possible. Decreased rainfall and increased evaporation rates could diminish the flow of certain rivers and force the abandonment of some present productive irrigated farmland. (Photo by E. J. Tarbuck)

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 sea level to rise.

Research indicates that sea level has risen between 10 and 25 centimeters 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 by the end of the twenty-first century (Figure 14–16a). 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 14–17). 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 14–18).

As mentioned, a warmer climate will cause glaciers to melt. In fact, a portion of the 10- to 25-centimeter rise in sea level over the past century is attributed to the melting of alpine glaciers. This contribution is projected to continue through the twenty-first century, as shown in Figure 14–16b. Of course, if the Greenland and Antarctic ice sheets were to experience



(a)

(b)

Figure 14–16 (a) High, middle, and low projections of global sea-level rise, 1990–2100. (b) Projected individual contributions to global sea-level change, 1990–2100 for the middle projection in part A. Thermal expansion is responsible for 28 centimeters of the sea-level rise. Melting alpine glaciers and ice caps contribute another 16 centimeters. The impact shown for Antarctica indicates that this massive ice sheet is projected to grow larger during this period.

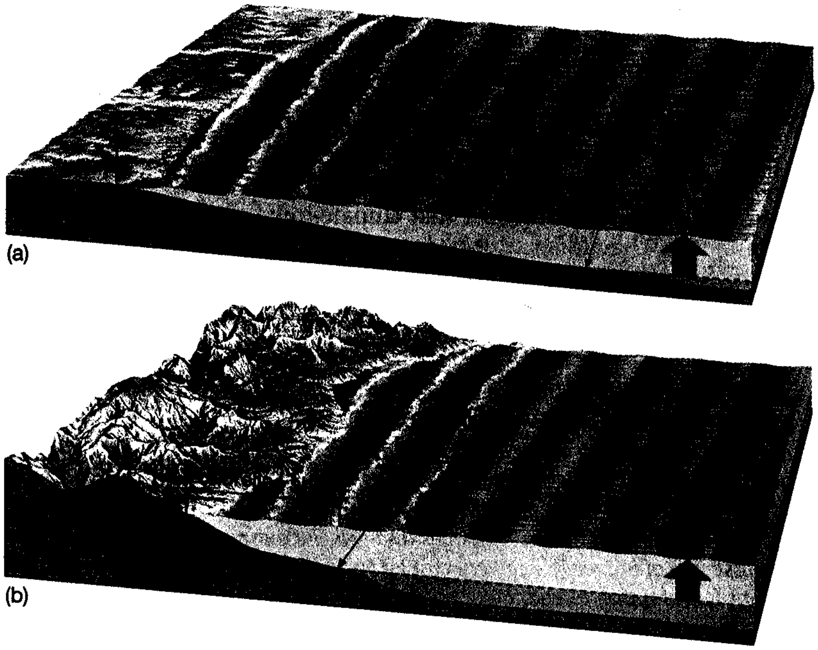


Figure 14–17 The slope of a shoreline is critical to determining the degree to which sea-level changes will affect it. (a) When the slope is gentle, small changes in sea level cause a substantial shift. (b) The same sea-level rise along a steep coast results in only a small shoreline shift.

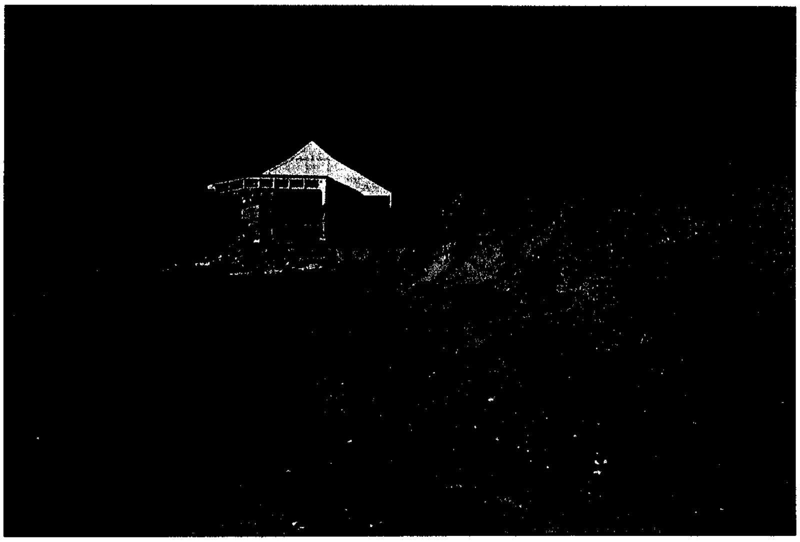


Figure 14–18 As sea level gradually rises, the shoreline retreats, and structures that were once thought to be safe from wave attack are exposed to the force of the sea. (Photo by Kenneth Hasson)

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. 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.

New Weather Patterns

Atmospheric scientists also expect that weather patterns will change with global warming. Potential weather changes include:

1. A higher frequency and greater intensity of hurricanes because of warmer ocean temperatures.
2. Shifts in the paths of large-scale cyclonic storms, which, in turn, would affect the distribution of precipitation and the occurrence of severe storms, including tornadoes.
3. More intense heat waves and droughts in some regions and fewer such events in other places.

The impact on climate of an increase in atmospheric CO_2 and trace gases is obscured by many unknowns and uncertainties. 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.

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.*[13]

The Climate of Cities

The most apparent human impact on climate is the building of cities. The construction of every factory, road, office building, and house destroys existing microclimates and creates new ones of great complexity. As far back as the early nineteenth century, Luke Howard, the Englishman who is most remembered for his cloud-classification scheme, recognized that the weather in London was different from that of the surrounding rural countryside, at least in terms of reduced visibility and increased temperature. Indeed, with the coming of the Industrial Revolution in the late 1700s, the trend toward urbanization accelerated, leading to significant changes in the climate in and around most cities.

At the beginning of the 1800s, only about 2 percent of the world's population lived in cities of more than 100,000 people. Today, a far greater percentage of people reside in cities, plus world population has ballooned. The graph in Figure 14–19 shows that nearly 3 billion people will live in urban areas by the year 2000,

Figure 14–19 Urban population growth, 1950–2025. Nearly 3 billion people will live in urban areas by the year 2000, or nearly 40 percent of the world's population will live in cities. These figures are projected to rise substantially over the next several decades. Most of this growth will be in developing countries. (Data from the United Nations)

Table 14–1 Average climate changes produced by cities

[illegible]	[illegible]
Particulate matter	10 times more
Temperature	
Annual mean	0.5–1.5°C higher
Winter	1–2°C higher
Heating degree-days	10% fewer
Solar radiation	15–30% less
Ultraviolet, winter	30% less
Ultraviolet, summer	5% less
Precipitation	5–15% more
Thunderstorm frequency	16% more
Winter	5% more
Summer	29% more
Relative humidity	6% lower
Winter	2% lower
Summer	8% lower
Cloudiness (frequency)	5–10% more
Fog (frequency)	60% more
Winter	100% more
Summer	30% more
Wind speed	25% lower
Calms	5–20% more

Source: Helmut E. Landsburg, "City Air—Better or Worse," *Symposium: Air Over Cities,* U.S. Public Health Service, Taft Sanitary Eng. Center, Cincinnati, Ohio, Tech. Rept. A62-5; Helmut E. Landsburg, "Man-Made Climate Changes," *Science,* 170, 3964; Stanley A. Changnon, Jr., "Atmospheric Alterations from Man-Made Biospheric Changes," *Modifying the Weather,* Western Geographical Series, Vol. 9 (Toronto: University of Victoria, 1973).

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[13] 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. *Note:* The Intergovernmental Panel on Climate Change was jointly established by the World Meteorological Organization and the United Nations Environment Program to evaluate and make recommendations regarding the many aspects of global climate change.

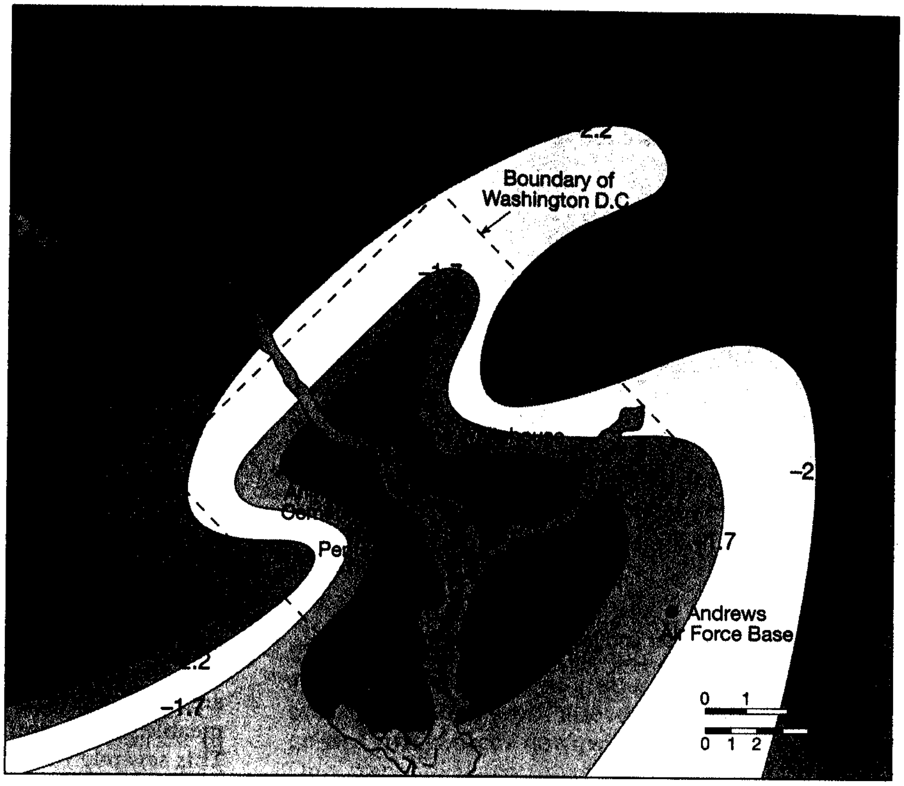

Figure 14–20 The heat island of Washington, D.C., as shown by the average minimum temperatures (°C) during the winter season (December through February). The city center had an average minimum that was nearly 4°C higher than some outlying areas. (After Clarence A. Woolum, "Notes from the Study of the Microclimatology of the Washington, D.C., Area for the Winter and Spring Seasons," *Weatherwise*, 17, no. 6 (1964), 264, 267)

or nearly 40 percent of Earth's population. The graph also projects rapid urban population growth. Much of it will be in the developing world.

As Table 14–1 illustrates, the climate changes produced by urbanization involve all major surface conditions. From Table 14–1 you can see that cities generally are cloudier, foggier, warmer, and wetter than the countryside. Some differences are obvious and relatively easy to measure. Others are more subtle and sometimes difficult to measure. The amount of change in any of these elements, at any time, depends on several variables, including the extent of the urban complex, the nature of industry, site factors such as topography and proximity to water bodies, time of day, season of the year, and existing weather conditions.

The Urban Heat Island

Certainly, the most studied and best-documented urban climate effect is the **urban heat island**. Temperatures within cities are generally higher than in rural areas, creating an "island" of warmer air. Within an urban complex, the intensity of the heat island is not uniform but varies considerably, as Figure 14–20 shows for Washington, D.C. As we might expect, the highest temperatures occur in zones where the greatest building density and industrialization exist.

The heat island is clearly indicated when we examine statistical data. In Table 14–2 mean temperatures reveal the heat island's presence throughout the year. Table 14–3 uses less common statistics: the number of days on which the temperature equals or exceeds 32°C and the number of days on which it is lower than or equal to 0°C. The data in Table 14–3 show us not only that mean temperatures are higher in the city, but that these locales also have more hot

Table 14–2 Average temperatures (in °C) for Philadelphia airport and downtown Philadelphia (10-year averages)

	DOWNTOWN	AIRPORT
Annual mean	13.6°	12.8°
Mean June maximum	28.2°	27.8°
Mean December maximum	6.7°	6.4°
Mean June minimum	17.7°	16.5°
Mean December minimum	–0.4°	–2.1°

Source: Hans Neuberger and John Cahir, *Principles of Climatology* (New York: Holt, Rinehart, & Winston, Inc., 1969), p. 128.

Table 14–3 Average annual number of hot days (≥32°C) and cold days (≤0°C) at downtown and airport stations for five American cities

[illegible]	[illegible]	[illegible]
Philadelphia, Pa		
Downtown	73	32
Airport	89	25
Washington, D.C.		
Downtown	68	39
Airport	72	33
Indianapolis, Ind.		
Downtown	106	36
Airport	124	23
Baltimore, Md.		
Downtown	62	35
Airport	96	33
Pittsburgh, Pa.		
Downtown	96	19
Airport	124	9

Source: Hans Neuberger and John Cahir, *Principles of Climatology* (New York: Holt, Rinehart, & Winston, Inc., 1969), p. 128.

days and fewer cold days than do outlying areas. The magnitude of the temperature differences is probably even greater than these tables indicate because temperatures at suburban airports are usually higher than those in truly rural environments.

As is typical, the data for Philadelphia show that the heat island is most pronounced when minimum temperatures are examined. Although mean maximum temperatures are only 0.3 to 0.4°C higher in the city, minimums are from 1.2 to 1.7°C higher.

Figure 14–20 shows average minimum temperatures in the Washington, D.C., metropolitan area during winter over a five-year span. The pattern reveals a well-developed heat island. The warmest winter temperature occurred in the heart of the city, whereas the suburbs and surrounding countryside experienced average minimum temperatures that were as much as 3.3°C lower. Remember that these temperatures are averages, and that on many clear, calm nights the temperature difference between the city center and the countryside was considerably greater, often 11°C or more. Conversely, on many overcast or windy nights, the temperature differential approached 0°C. The same study revealed another interesting aspect of the heat-island effect: The last freeze of winter occurred 18 days earlier in the central part of the city than in outlying areas.

What Causes Urban Heat Islands?

There are four major causes of urban heat islands:

1. The rocklike materials from which the city is made have large thermal capacities (ability to store heat). They also create impervious surfaces that rapidly remove precipitation before it can evaporate, thus eliminating this major path of heat removal.
2. Industry, motor vehicles, and domestic heating release large quantities of heat.
3. Increased atmospheric pollution inhibits the loss of upward-directed radiation from the surface.
4. Tall buildings create a three-dimensional structure that alters the flow of air and creates a complex geometry for heat exchange.

The radical change in the surface that results when rural areas are transformed into cities is a significant cause of the urban heat island (Figure 14–21). The tall buildings and the concrete and asphalt of the city absorb and store greater quantities of solar radiation than do the vegetation and soil typical of rural areas. In addition, because the city surface is impermeable, the runoff of water following rain is rapid. This severely reduces the evaporation rate. Thus, heat that once would have been used to convert liquid water to a vapor instead goes to increase the surface temperature further. At night, although both city and countryside cool by radiation loss, the stonelike surface of the city gradually releases the additional heat accumulated during the day, keeping the urban air warmer than that of the outlying areas.

Part of the urban temperature rise is caused by waste heat from heating and air conditioning, power generation, industry, and transportation. Many studies have shown that the magnitude of human-made energy in metropolitan areas can be a significant fraction of the energy received from the Sun at the surface. For example, investigations in Sheffield, England, and Berlin, Germany, showed that their annual heat production equalled approximately one-third of that received from solar radiation. Another study of densely built-up Manhattan (New York City) revealed that during the winter, the heat produced from combustion alone was $2\frac{1}{2}$ times greater than the amount of solar energy reaching the ground. (In summer, the figure dropped to one-sixth.)

Other causes of the urban heat island are less influential but worthy of mention. The "blanket" of pollutants over a city, including particulate matter, water vapor, and carbon dioxide, contributes to the heat island by absorbing a portion of the upward-directed longwave radiation emitted at the surface and

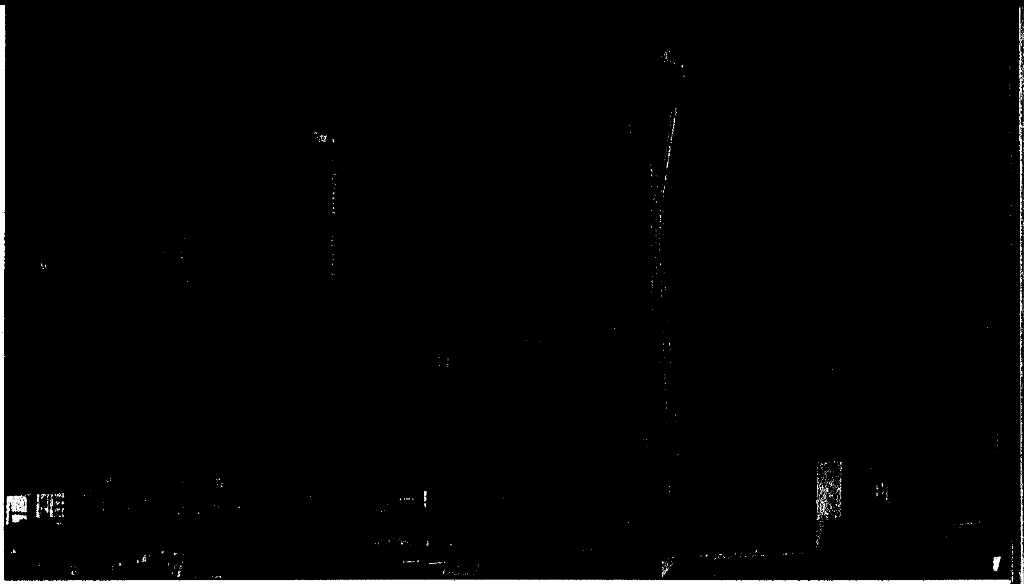

Figure 14–21 The heat island is the result of the city's rocklike materials, its three-dimensional structure, and the heat and pollution it generates. Skyline of Seattle, Washington. (Photo by Donald Johnson/The Stock Market)

reemitting some of it back toward the surface. A somewhat similar effect results from the three-dimensional structure of the city. The vertical walls of buildings do not allow radiation to escape as readily as in rural areas where surfaces are relatively flat. As the sides of these structures emit their stored heat, a portion is reradiated between buildings instead of upward and is therefore slowly dissipated.

In addition to retarding the loss of heat from the city, tall buildings also alter the flow of air. Because of the greater surface roughness, wind speeds within an urban area are reduced. Estimates suggest a decrease of about 25 percent from rural values. The slower wind speeds decrease the city's ventilation by inhibiting the movement of cooler outside air that, if allowed to penetrate, would reduce the higher temperatures of the city center. Conversely, when regional winds are strong, the heat island disappears. The necessary wind speed to dispel the heat island appears to be closely related to the size of the urban area. The larger the city, the greater the wind speed necessary to eliminate the heat island.

Urban-Induced Precipitation

Cities influence the occurrence and amount of precipitation in their vicinities. Several factors help to explain why an urban complex might be expected to increase precipitation.

1. The urban heat island creates thermally induced upward motions that act to increase the atmosphere's instability.
2. Clouds may be modified by the addition of condensation nuclei and freezing nuclei from industrial discharges.
3. The rougher city surface leads to low-level convergence and increased upward air motion. In addition, the rougher urban landscape impedes the progress of weather systems. Therefore, when rain-producing processes are taking place, they may linger over the urban area and increase the city's rainfall.

Several studies comparing urban and rural precipitation conclude that the amount of precipitation over a city is about 10 percent greater than over the nearby countryside. This work also demonstrated that even greater effects occur downwind from the city center. One comprehensive urban rain investigation in St. Louis clearly showed increases in precipitation at downwind locations that grew in magnitude over the years as industrial development expanded in the city. Further, if cities are really modifying precipitation, the effect should be greater on weekdays, when urban activities are most intense, than on weekends, when much of the activity ceases. This is indeed the case. The St. Louis study revealed a significantly greater frequency of rain per weekday than per weekend day in the affected downwind area. Figure 14–22 shows similar findings for Paris.

Other Urban Effects

Earlier, we saw that air pollution in cities contributes to the heat island by inhibiting the loss of longwave radiation at night. It also may have a "cloud-seeding" effect that increases precipitation in and downwind of cities. These influences, however, are not the only ways in which pollutants influence urban climates. The blanket of particulates over most large cities significantly reduces the amount of solar radiation reaching the surface. As Table 14–1 indicates, the overall reduction in the receipt of solar energy is 15 percent, whereas short-wavelength ultraviolet is decreased by up to 30 percent.

This weakening of solar radiation is, of course, variable. During air pollution episodes, the decrease will be much greater than for periods when ventilation

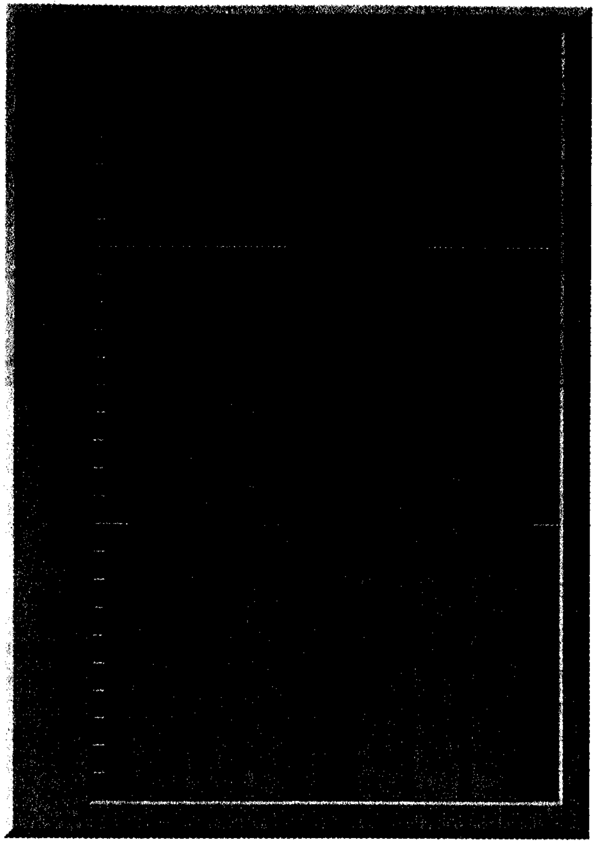

Figure 14–22 Average precipitation by day of the week in Paris for an 8-year period (1960–1967). Notice the gradual increase from Monday to Friday and the sharp drop in precipitation totals on Saturday and Sunday. The average for weekdays was 1.93 millimeters compared with only 1.47 on weekends, a difference of 24 percent. (After I. Dettwiller, in Helmut E. Landsberg, "Inadvertent Atmospheric Modification," in *Weather and Climate Modification*, edited by Wilmot N. Hess, p. 755. New York: John Wiley & Sons, Inc., 1974)

is good. Furthermore, particles are most effective in reducing solar radiation near the surface when the Sun angle is low, because the length of the path through the dust increases as the Sun angle drops. So, for a given quantity of particulate matter, solar energy will be reduced by the largest percentage at higher-latitude cities and during the winter.

Relative humidities are generally lower in cities, because temperatures are higher and evaporation is reduced (see Table 14–1). Nevertheless, the frequency of fogs and the amount of cloudiness are greater. It is likely that the large quantities of condensation nuclei produced by human activities in urban areas lead to this increase in cloudiness and fog. When hygroscopic (water-seeking) nuclei are plentiful, water vapor readily condenses on them, even when the air is not yet saturated.

Finally, another urban-induced phenomenon is called the **country breeze**. As the name implies, this circulation pattern is characterized by a light wind blowing into the city from the surrounding countryside. It is best developed on relatively clear, calm nights—that is, on nights when the heat island is most pronounced. Heating in the city creates upward air motion, which, in turn, initiates the country-to-city flow (Figure 14–23). One investigation in Toronto showed that the heat island created a rural/city pressure difference that was sufficient to cause an inward and counterclockwise circulation centered on the downtown area. When this circulation pattern exists, pollutants emitted near the urban perimeter tend to drift in and concentrate near the city's center.

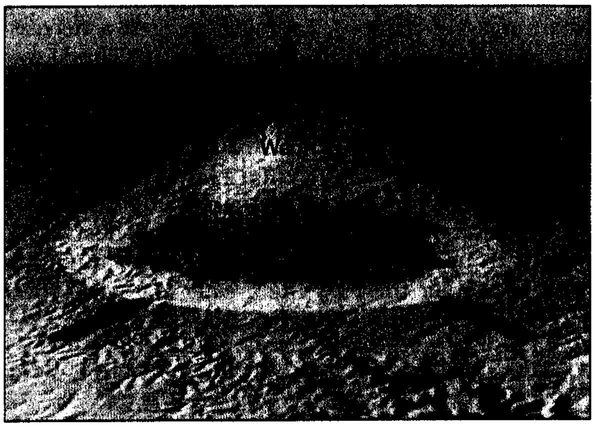

Figure 14–23 Idealized scheme of nighttime circulation above a city on a clear, calm night. The blue arrows represent the wind (country breeze). (After Helmut E. Landsberg, "Man-Made Climatic Changes," *Science*, 170 (1970), 1271. © 1970 by the American Association for the Advancement of Science)

Review

1. List the five parts of the climate system.
2. Planetary-scale atmospheric processes are so vast and complex that they cannot be reproduced in laboratory experiments. How do scientists study such processes?
3. List and describe some methods that scientists use to gain insight into the climates of the past.
4. How does plate tectonics theory help explain the previously "unexplainable" glacial features in present-day Africa, South America, and Australia?
5. Can plate tectonics account for short-term climate changes? Explain.
6. 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.
7. What geologic event was believed to be responsible for the "year without a summer"? (See Box 14–3.)
8. List and describe each of the three variables that link Earth's motions (Milankovitch cycles) and climate change.
9. Do recent studies of sea-floor sediments tend to confirm or refute the importance of Milankovitch cycles? What do these studies predict for the future?
10. List two examples of possible climate change linked to solar variability. Are these Sun–climate connections widely accepted?
11. Why has the carbon dioxide level of the atmosphere been rising for more than 130 years?
12. How are temperatures in the lower atmosphere likely to change as carbon dioxide levels continue to increase?
13. Aside from carbon dioxide, what other trace gases are contributing to a future global temperature change?
14. What are climate-feedback mechanisms? Give some examples.
15. List four possible consequences of a greenhouse warming.
16. In what setting do we find the most apparent human impact on climate?
17. Which temperature statistic (maximums, minimums, or means) reveals the greatest rural–urban temperature difference?
18. Compare a "typical" rural surface with a "typical" city surface. List two ways in which this adds to the urban heat island.
19. How do each of the following factors contribute to the urban heat island: heat production, the "blanket" of pollutants, and three-dimensional city structure?
20. During what season is heat production most important as a factor affecting the heat island?
21. List three factors that are the probable causes of greater precipitation in and downwind of cities.
22. A study of precipitation data in the St. Louis region led researchers to conclude that the urban–industrial complex caused precipitation totals to increase. List two lines of evidence that supported this conclusion.
23. Describe the reasons for the following urban climatic characteristics:
    a. reduced solar radiation
    b. reduced relative humidity
    c. increased fog and cloud frequency
    d. reduced wind speeds and more days when calms prevail
    e. fewer heating degree days
24. What is a "country breeze"? Describe its cause.

Vocabulary Review

climate system (p. 321)
climate-feedback mechanism (p. 337)
country breeze (p. 346)
eccentricity (p. 329)
Milankovitch cycles (p. 330)
negative-feedback mechanism (p. 339)
obliquity (p. 330)
oxygen isotope analysis (p. 322)
plate tectonics theory (p. 325)
positive-feedback mechanism (p. 339)
precession (p. 330)
sunspot (p. 332)
urban heat island (p. 342)