CHAPTER 20

The Atmosphere, Climate, and Global Warming

The years of the Medieval Warm Period, from about A.D. 950 to 1250, were good times for the people in Western Europe. Harvests were good, cultures flourished, the population expanded, and great cathedrals were built. In the southwestern United States, Mexico, and Central America, the same period brought persistent droughts that contributed to the collapse of some civilizations, including the Maya.

LEARNING OBJECTIVES

Earth's atmosphere—the layer of gases surrounding the Earth—is a complex, dynamic system that is changing continuously. After reading this chapter, you should understand . . .

- The basic composition and structure of the atmosphere;
- How the processes of atmospheric circulation and climate work;
- How the climate has changed over the Earth's history;
- What the term *greenhouse gas* means and what the major greenhouse gases are;
- What global warming is and what major kinds of evidence point to it;
- What effects global warming might have and how we can adjust to them.

CASE STUDY

What Does History Tell Us about Global Warming's Potential Consequences for People?

During an approximate 300-year period from A.D. 950 to 1250, Earth's surface was considerably warmer than what climatologists today call normal (meaning the average surface temperature during the past century or some shorter interval, such as 1960–1990). This warm time is known as the Medieval Warm Period (MWP). With all the concerns today about climate change, perhaps we can learn some lessons from that time. Since weather records were not kept then, we do not have a global picture of what it was like. What we do know is that parts of the world, in particular Western Europe and the Atlantic, may have been warmer some of the time than they were in the last decade of the 20th century. However on a global basis the MWP was not as warm as it is today.

In Western Europe, it was a time of flourishing culture and activity, as well as expansion of the population; a time when harvests were plentiful, people generally prospered, and many of Europe's grand cathedrals were constructed.[1, 2] Sea temperatures evidently were warmer, and there was less sea ice. Viking explorers from Scandinavia traveled widely in the Far North and established settlements in Iceland, Greenland, and even briefly in North America. Near the end of the 10th century, Erik the Red, the famous Viking explorer, arrived at Greenland with his ships and set up settlements that flourished for several hundred years. The settlers were able to raise domestic animals and grow a variety of crops that had never before been cultivated in Greenland (Figure 20.1). During the same warm period, Polynesian people in the Pacific, taking advantage of winds flowing throughout the Pacific, were able to sail to and colonize islands over vast areas of the Pacific, including Hawaii.[2]

While some prospered in Western Europe and the Pacific during the Medieval Warm Period, other cultures appear to have been less fortunate. Associated with the warming period were long, persistent droughts (think human-generational length) that appear to have been partially responsible for the collapse of sophisticated cultures in North and Central America. The collapses were not sudden but occurred over a period of many decades, and in some cases the people just moved away. These included the people living near Mono Lake on the eastern side of the Sierra Nevada in California, the Chacoan people in what is today Chaco Canyon in New Mexico, and the Mayan civilization in the Yucatán of southern Mexico and Central America.

FIGURE 20.1 Remains of a Viking settlement in Greenland from the Medieval Warm Period.

The Medieval Warm Period was followed by the Little Ice Age (LIA), which lasted from approximately mid-1400 to 1700. The cooling made life more difficult for people in Western Europe and North America. Crop failures occurred in Western Europe, and some mountain glaciers in the Swiss Alps advanced to the extent that they filled valleys and destroyed villages. Areas to the north that had enjoyed abundant crop production were under ice.[3] The population was devastated by the Black Plague, whose effects may have been exacerbated by poor nutrition as a result of crop failures and by the damp and cold that reached out across Europe and even to Iceland by about 1400.

Travel and trade became difficult in the Far North. Eventually, the Viking colonies in North America were abandoned and those in Greenland declined greatly. Part of the reason for the abandonment in North America, and particularly in Newfoundland, was that the Vikings may not have been able to adapt to the changing conditions, as did the Inuit peoples living there. As times became tough, the two cultures collided, and the Vikings, despite their fierce reputation, were less able than the Inuit to adapt to the cooling climate.

We do not know what caused the Medieval Warm Period, and the details about it are obscured by insufficient climate data to help us estimate temperatures during that period. We do know that it was relatively warm (in Western Europe). We can't associate the warming 1000 years ago with burning of fossil fuels. This suggests that more than one factor can cause warming. In this chapter we will explore climate dynamics so you can better understand what may be the causes of climate change and what might be the best estimates of how it could affect life on Earth and civilizations.[1–5]

20.1 Fundamental Global Warming Questions

The modern concern about global warming arose from two kinds of observations. The first, shown in Figure 20.2, is of the average surface temperature of the Earth from 1850 to the present. This graph shows an increase beginning in the 1930s and accelerating, especially after 1960, when the increase was about 0.2°C per decade.

The second kind of key observation is the measurement of carbon dioxide concentrations in the atmosphere. Of these, the best-known were made on Mauna Loa Mountain, Hawaii, by Charles Keeling and are now known as the Keeling Curve (Figure 20.3). Taken at 3,500 m (11,500 ft) on an island far from most human activities, these measurements provide an excellent estimate of the background condition of the atmosphere.

Here are the fundamental questions about global warming:

- What is the origin of known periods of rapid warming in the geologic record? This fundamental question is the subject of intense ongoing research and is not yet solved.
- Is the present rapid warming unprecedented or at least so rare that many living things will not be able to respond successfully to it?
- To what extent, have people caused it?
- What are likely to be the effects on people?
- What are likely to be the effects on all life on Earth?
- How can we make forecasts about it and other kinds of climate change?
- What can we do to minimize potential negative effects?

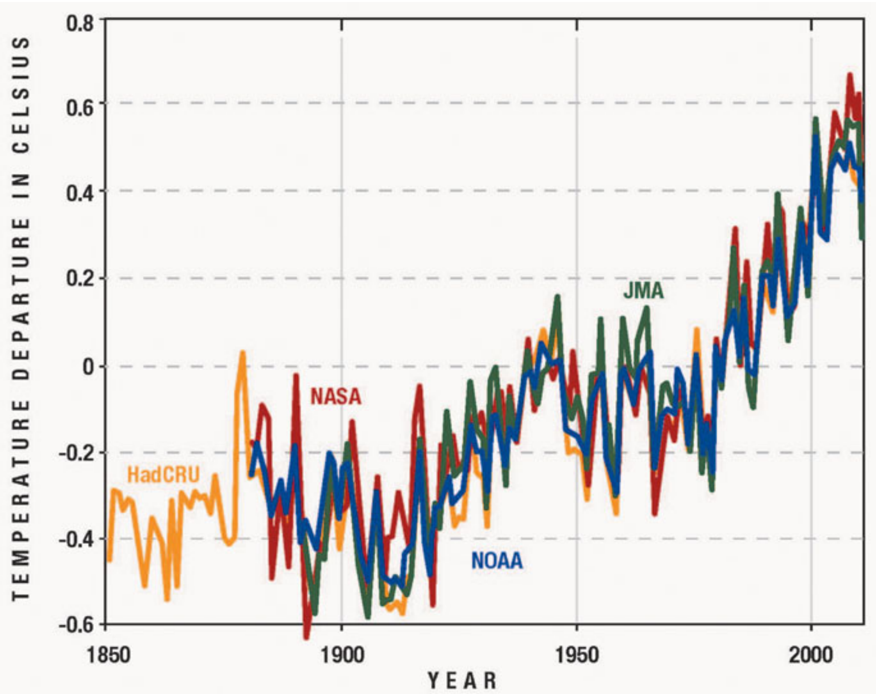
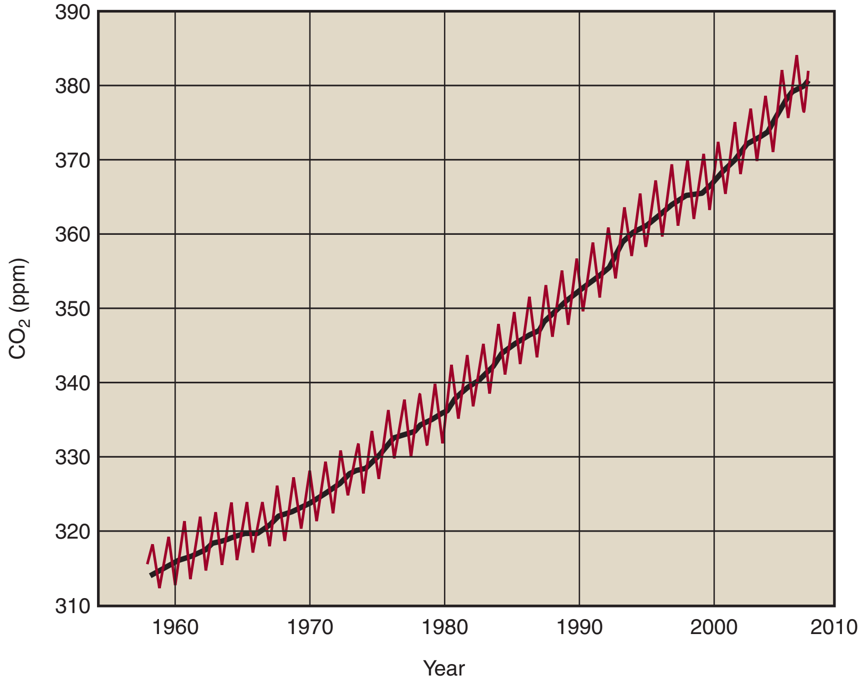


FIGURE 20.2 The temperature difference between the average at the end of the 19th century and the years between 1860 and today. This graph shows the difference between calculated world surface temperatures for each year and the average at the end of the 19th century. Temperature departure refers to changes in mean global temperature from some standard such as 1951–1980. Climatologists studying climate change prefer, in general, to look at the difference between temperatures at one time compared to another, rather than the actual temperature, for a variety of technical reasons. (*Source:* Hadley Meteorological Center, Great Britain.) http://www.metoffice.gov.uk/corporate/pressoffice/myths/2.html)



(a)

(b)

FIGURE 20.3 **(a)** Carbon dioxide concentrations in the air above Mauna Loa, Hawaii; **(b)** the NOAA Observatory on Mauna Loa, where these measurements were made. (*Sources:* **(a)** *Encyclopedia of Earth,* http://www.eoearth.org/article/Climate_change; taken from C.D. Keeling and T.P. Whorf, 2005. "Atmospheric CO_2 records from sites in the SIO air sampling network," in *Trends: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN).

20.2 Weather and Climate

Weather is what's happening now or over some short time period—this hour, today, this week—in the atmosphere near the ground: its temperature, pressure, cloudiness, precipitation, winds. **Climate** is the average weather and usually refers to average weather conditions over long periods, at least seasons, but more often years or decades. When we say it's hot and humid in New York today or raining in Seattle, we are speaking of weather. When we say Los Angeles has cool, wet winters and warm, dry summers, we are referring to the Los Angeles climate.

Since climates are characteristic of certain latitudes (and other factors that we will discuss later), they are classified mainly by latitude—tropical, subtropical, midlatitudinal (continental), sub-Arctic (continental), and Arctic—but also by wetness/dryness, such as humid continental, Mediterranean, monsoon, desert, and tropical wet–dry (Figure 20.4). Recall from the discussion of biogeography in Chapter 7 that similar climates produce similar kinds of ecosystems. Therefore, knowing the climate, we can make pretty good predictions about what kinds of life we will find there and what kinds could survive there if introduced.

The Climate Is Always Changing at a Variety of Time Scales

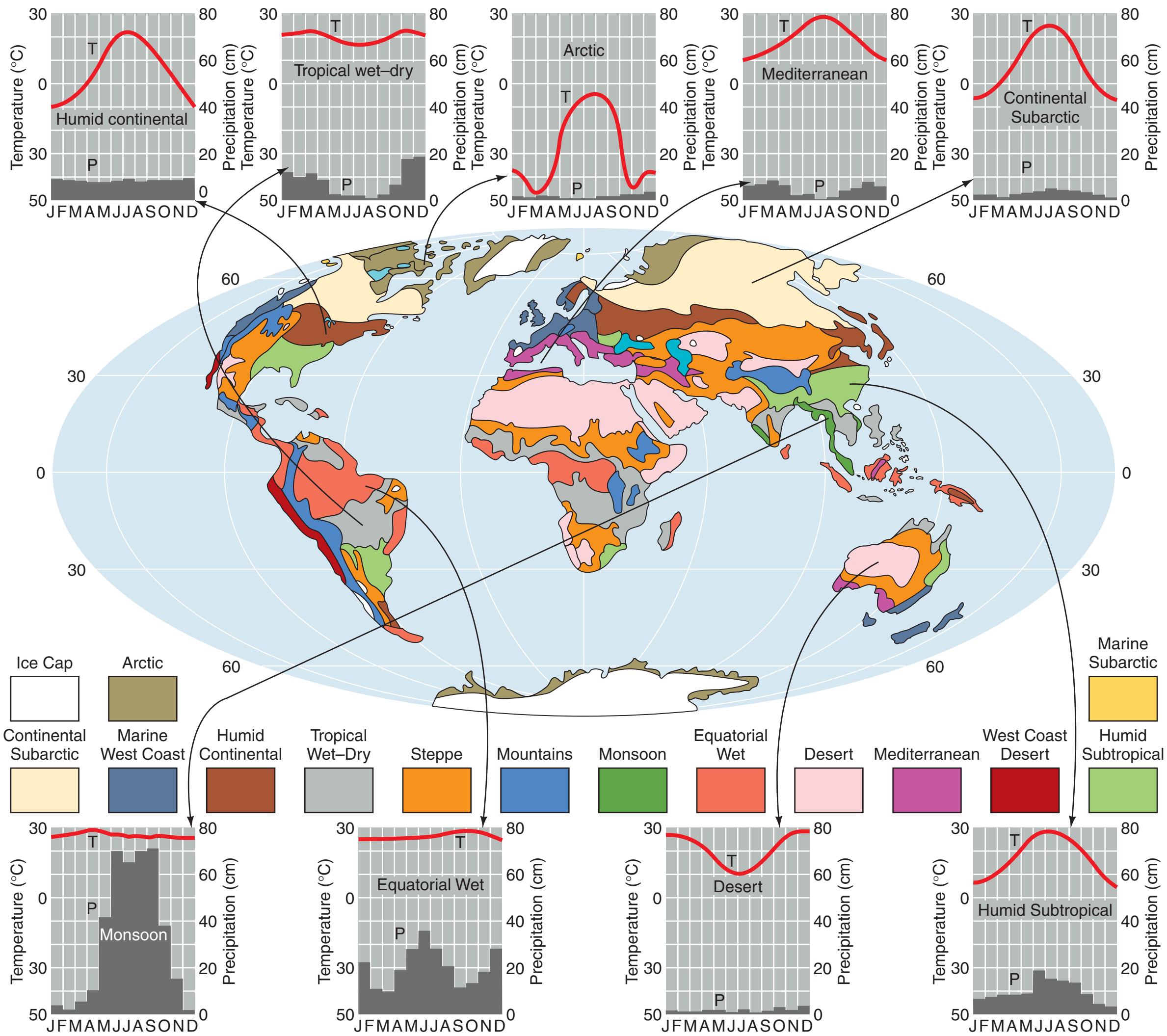
Answering questions about climate change is especially complicated because—and this is a key point about climate and life—the climate is always changing. This has been happening as far back in Earth's history as scientists have been able to study. The Precambrian Era, around 550 million years ago, averaged a relatively cool 12°C. Things warmed up to about 22°C in the Cambrian Period, got very cool in the Ordovician/Silurian transition, warmed again in the Devonian, cooled a lot again at the end of the Carboniferous, and warmed again in the Triassic. It's been quite a roller-coaster ride.

Climate changes have continued in more recent times—"recent" geologically speaking, that is. The mean annual temperature of Earth has swung up and down by several degrees Celsius over the past million years (Figure 20.5). Times of high temperature involve relatively ice-free periods (interglacial periods) over much of the planet; times of low temperature involve glacial events (Figure 20.5 a, b).[6-8]

Climate change over the last 18,000 years, during the last major time of continental glaciations, has greatly affected people. Continental glaciation ended about 12,500 years ago with a rapid warming, perhaps as brief as 100 years to a few decades.[7] This was followed by a global cooling about 11,000–13,000 years ago known as the Younger Diyas that occurred suddenly as Earth was warming (Figure 20.5c). The Younger Diyas was followed by the Medieval Warm Period, and then by the Little Ice Age, (Figure 12.5d) as discussed in the opening case study.

A warming trend began around 1850 and lasted until the 1940s, when temperatures began to cool again, followed by a leveling off in the 1950s and a further drop during the 1960s. After that, the average surface temperature rose (Figure 12.5e). The past two decades have been the warmest since global temperatures have been monitored.[6, 8]

FIGURE 20.4 The climates of the world and some of the major climate types in terms of characteristic precipitation and temperature conditions. (*Source:* Modified from W.M. Marsh and J. Dozier, *Landscape* [New York: John Wiley & Sons, 1981. Reprinted with permission of John Wiley & Sons, Inc.]).



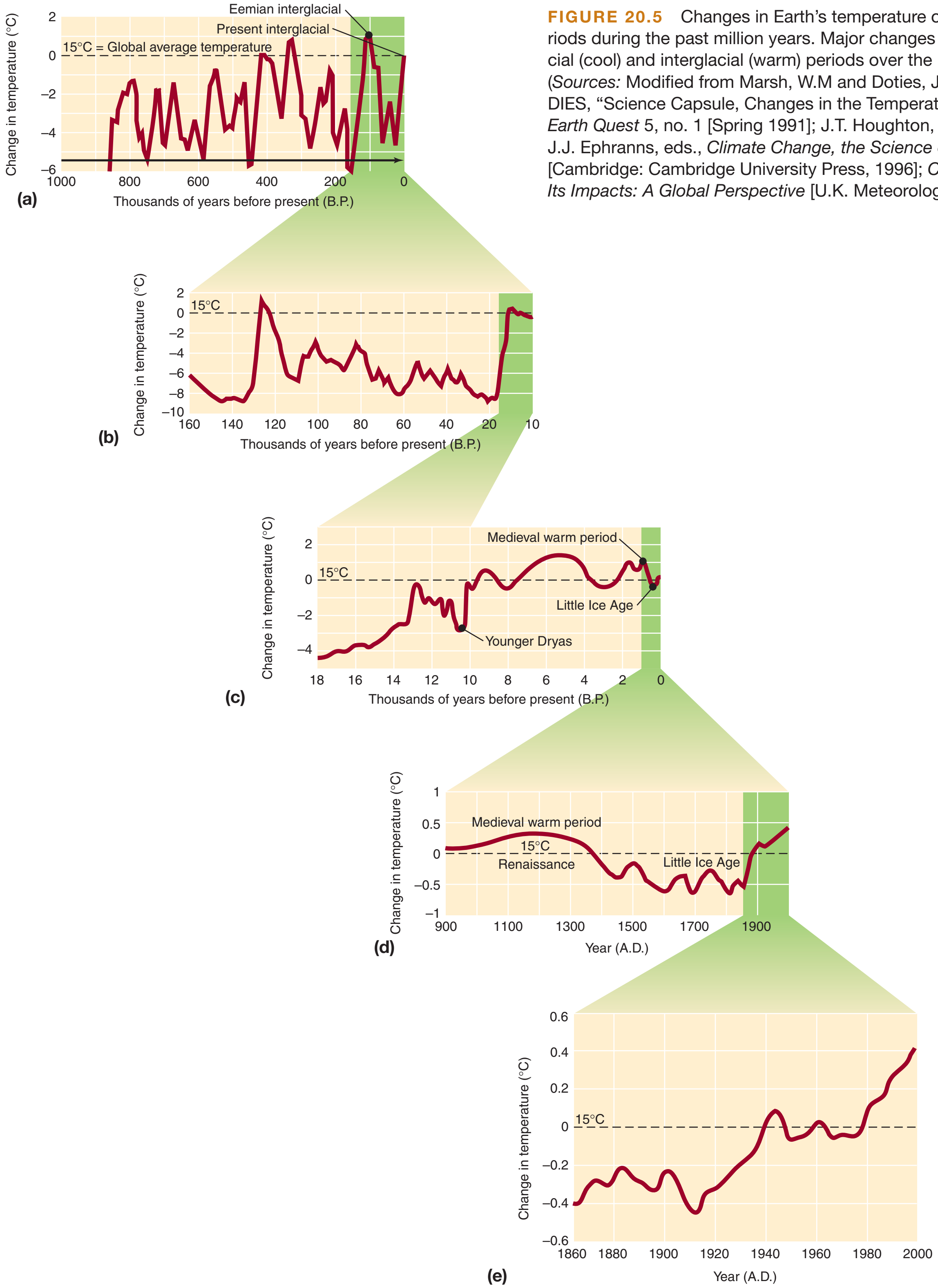


FIGURE 20.5 Changes in Earth's temperature over varying time periods during the past million years. Major changes correspond to glacial (cool) and interglacial (warm) periods over the past 800,000 years. (*Sources:* Modified from Marsh, W.M and Doties, J., 1981; and UCAR/DIES, "Science Capsule, Changes in the Temperature of the Earth," *Earth Quest* 5, no. 1 [Spring 1991]; J.T. Houghton, G.L. Jenkins, and J.J. Ephranns, eds., *Climate Change, the Science of Climate Change* [Cambridge: Cambridge University Press, 1996]; *Climate Change and Its Impacts: A Global Perspective* [U.K. Meteorological Office, 1997].

20.3 The Origin of the Global Warming Issue

That burning fossil fuels might enhance the levels of **greenhouse gases**—gases that warm the Earth's surface—was first proposed in the early 19th century, about half a century after the discovery of carbon dioxide, oxygen, and the other gases that make up the atmosphere. But well into the 20th century most scientists did not take the idea of global warming seriously. It just seemed impossible that people could be affecting the entire planet. For example, in 1938 the scientist Gary Stewart Callendar studied measurements of carbon dioxide concentration in the atmosphere taken in the 19th century and found that they were considerably lower than measurements made at his time.[9] He made some other calculations that suggested the difference could be accounted for by the amount of carbon dioxide added to the atmosphere from the burning of coal, oil, and natural gas since the beginning of the Industrial Revolution.

As it has today, the idea created a controversy. Callendar was attacked by his scientific colleagues, some of whom dismissed the notion simply on the grounds that 19th-century scientists could not have done as good a job as scientists in the 1930s, so the earlier measurements were likely inaccurate. It took modern measurement, monitoring, study of Earth's history, and new concepts to change the way scientists understood life and its environment at a global level. We turn now to that new understanding.

20.4 The Atmosphere

To understand and answer the fundamental global warming questions, we need a basic understanding of Earth's atmosphere. This atmosphere is the thin layer of gases that envelop Earth. These gases are almost always in motion, sometimes rising, sometimes falling, most of the time moving across Earth's surface. The atmosphere's gas molecules are held near to the Earth's surface by gravity and pushed upward by thermal energy—heating—of the molecules. Approximately 90% of the weight of the atmosphere is in the first 12 km above Earth's surface. Major gases in the atmosphere include nitrogen (78%), oxygen (21%), argon (0.9%), carbon dioxide (0.03%), and water vapor in varying concentrations in the lower few kilometers. The atmosphere also contains trace amounts of methane ozone, hydrogen sulfide, carbon monoxide, oxides of nitrogen and sulfur, and a number of small hydrocarbons, as well as synthetic chemicals, such as chlorofluorocarbons (CFCs). Methane at about 0.00017% of the atmosphere is emerging as an important gas that tracks closley with climate change (more so than CO_2).

Thus the atmosphere is a dynamic system, changing continuously. It is a vast, chemically active system, fueled by sunlight, affected by high-energy compounds emitted by living things (for example, oxygen, methane, and carbon dioxide) and by our industrial and agricultural activities. Many complex chemical reactions take place in the atmosphere, changing from day to night and with the chemical elements available.

Structure of the Atmosphere

You might think that the atmosphere is homogeneous, since it is a collection of gases that mix and move continuously. Actually, however, it has a surprisingly complicated structure. The **atmosphere** is made up of several vertical layers, beginning at the bottom with the **troposphere,** most familiar to us because we spend most of our lives in it. Above the troposphere is the **stratosphere,** which we visit occasionally when we travel by jet airplane, and then several other layers at higher altitudes, less familiar to us, each characterized by a range of temperatures and pressures (Figure 20.6).

The troposphere, which extends from the ground up to 10–20 km, is where weather occurs. Within the troposphere, the temperature decreases with elevation, from an average of about 17°C at the surface to –60°C at 12 km elevation. At the top of the troposphere is a boundary layer called the *tropopause,* which has a constant temperature of about –60°C and acts as a lid, or

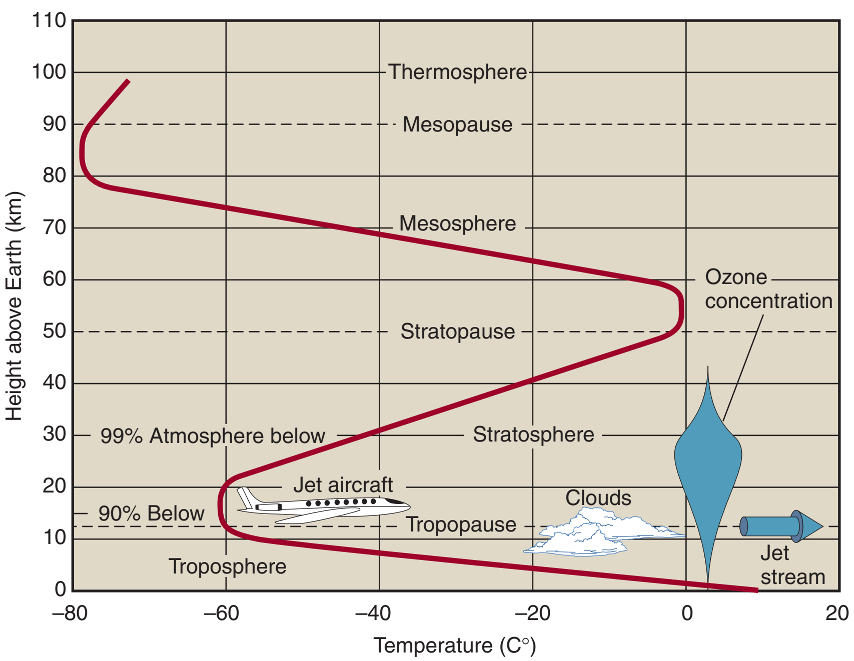


FIGURE 20.6 An idealized diagram of the structure of the atmosphere showing temperature profile and the ozone layer of the atmosphere to an altitude of 110 km. Note that 99% of the atmosphere (by weight) is below 30 km, the ozone layer is thickest at about 25–30 km, and the weather occurs below about 11 km—about the elevation of the jet stream. (*Source:* A.C. Duxbury and A.B. Duxbury, *An Introduction to the World's Oceans* [Dubuque, Iowa: Wm. C. Brown Publishers, 1997, 5th ed.].)

cold trap, on the troposphere because it is where almost all remaining water vapor condenses.

Another important layer for life is the *stratospheric ozone layer,* which extends from the tropopause to an elevation of approximately 40 km (25 mi), with a maximum concentration of ozone above the equator at about 25–30 km (16–19 mi) (Figure 20.6). Stratospheric ozone (O_3) protects life in the lower atmosphere from receiving harmful doses of ultraviolet radiation (see Chapter 21).

Atmospheric Processes: Temperature, Pressure, and Global Zones of High and Low Pressure

Two important qualities of the atmosphere are *pressure* and *temperature.* Pressure is force per unit area. Atmospheric pressure is caused by the weight of overlying atmospheric gases on those below and therefore decreases with altitude. At sea level, atmospheric pressure is 10^5 N/m^2 (newtons per square meter) (14.7 lb/in). We are familiar with this as **barometric pressure**, which the weatherman gives to us in units that are the height to which a column of mercury is raised by that pressure. We are also familiar with low- and high-pressure systems in the atmosphere. When the air pressure is low, air tends to rise, cooling as it rises and condensing its water vapor; it is therefore characterized by clouds and precipitation. When air pressure is high, it is moving downward, which warms the air, changing the condensed water drops in clouds to vapor; therefore high-pressure systems are clear and sunny.

Temperature, familiar to us as the relative warmth or coldness of materials, is a measure of thermal energy, which is the *kinetic* energy—the motion of atoms and molecules in a substance.

Water vapor content is another important characteristic of the lower atmosphere. It varies from less than 1% to about 4% by volume, depending on air temperature, air pressure, and availability of water vapor from the surface.

The atmosphere moves because of the Earth's rotation and differential heating of Earth's surface and atmosphere. These produce global patterns that include prevailing winds and latitudinal belts of low and high air pressure from the equator to the poles. Three cells of atmospheric circulation (Hadley cells) are present in

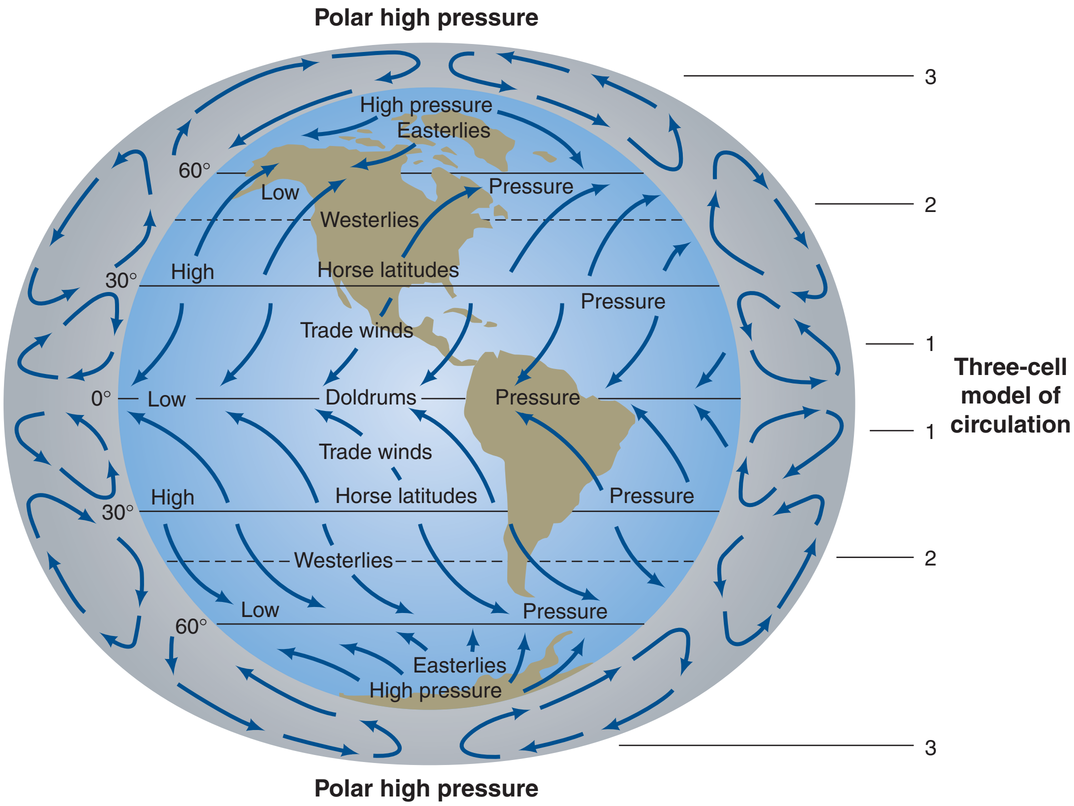


FIGURE 20.7 Generalized circulation of the atmosphere. The heating of the surface of the Earth is uneven, producing pressure differences (warm air is less dense than cooler air). There is rising warm air at the equator and sinking cool air at the poles. With rotation of Earth three cells of circulating air are formed in each hemisphere (called Hadley Cells after George Hadley who first proposed a model of atmospheric circulation in 1735). (*Source:* Samuel J. Williamson, *Fundamentals of Air Pollution*, Figure 5.5 [Reading, MS: Addison-Wesley, 1973]. Reprinted with permission of Addison-Wesley.)

each hemisphere (see Figure 20.7 for more details). In general belts of low air pressure develop at the equator where the air is warmed most of the time during the day by the sun. The heated air rises, creating an area of low pressure and a cloudy and rainy climate (cell 1 Figure 20.7). This air then moves to higher latitudes (toward the poles), and because it is cooler at higher elevations and because sunlight is less intense at the higher latitudes. By the time the air that was heated at the equator reaches about 30° latitude, it has cooled enough to become heavier, and it descends, creating a region of high pressure, with its characteristic sunny skies and low rainfall, forming a latitude belt where many of the world's deserts are found. Then the air that descended at 30° latitude moves poleward along the surface warms and rises again, creating another region of generally low pressure around 50° to 60° (cell 2, Figure 20.7) latitude and once again becoming a region of clouds and precipitation. Atmospheric orientation in cell 3 (Figure 20.7) moves air toward the poles at higher elevation and toward the equator along the surface. Sinking cool air at the poles produces the polar high-pressure zones at both poles. At the most basis level warm air rises at the equator moves toward the poles where it sinks after going through (cell 2) and return flow is along the surface of Earth toward the equator.

Of course, the exact locations of the areas of rising (low-pressure) and falling (high-pressure) air vary with the season, as the sun's position moves north and south relative to the Earth's surface. You can begin to understand that what would seem at first glance to be just a simple container of gases has complicated patterns of movement and that these change all the time for a variety of reasons.

The latitudinal belts (cells) just described have names, most of which came about during the days of sailing ships. Such names include the "doldrums," regions at the equator with little air movement; "trade winds," northeast and southeast winds important when clipper ships moved the world's goods; and "horse latitudes," two belts centered about 30° north and south of the equator with descending air and high pressure.

Energy and the Atmosphere: What Makes the Earth Warm

Almost all the energy the Earth receives is from the sun (a small amount comes from the interior of the Earth and an even smaller amount from frictional forces due to the moon revolving around the Earth). Sunlight comes in a wide range of electromagnetic radiation, from very long radio waves to much shorter infrared waves, then shorter wavelengths of visible light, even shorter wavelengths of ultraviolet, and then on to shorter and shorter wavelengths (Figure 20.8).

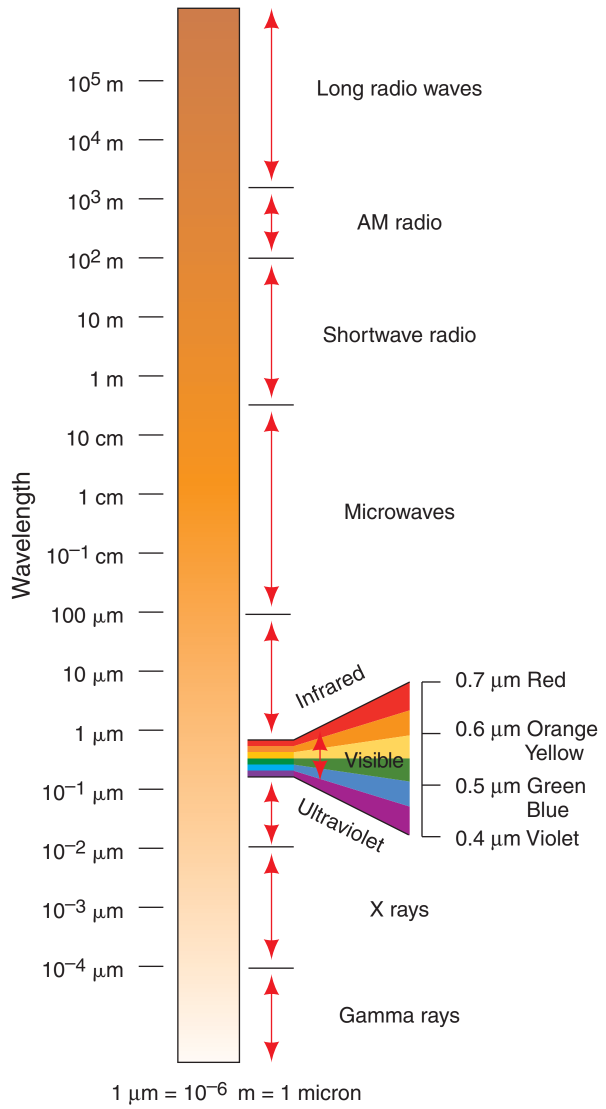
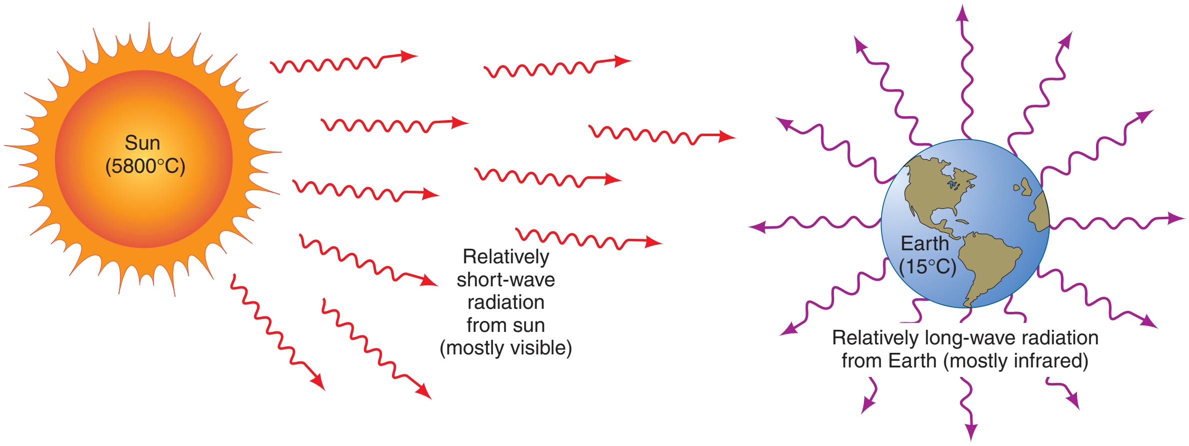


FIGURE 20.8 Kinds of electromagnetic radiation the Earth receives.

Most of the sun's radiation that reaches the Earth is in the visible and near infrared wavelengths (Figure 20.9), while the Earth, much cooler, radiates energy mostly in the far infrared, which has longer wavelengths. (The hotter the surface of any object, the shorter the dominant wavelengths. That's why a hot flame is blue and a cooler flame red.)

Under typical conditions, the Earth's atmosphere reflects about 30% of the electromagnetic (radiant) energy that comes in from the sun and absorbs about 25%. The remaining 45% gets to the surface (Figure 20.10). As the surface warms up, it radiates more energy back to the atmosphere, which absorbs some of it. The warmed atmosphere radiates some of its energy upward into outer space and some downward to the Earth's surface.



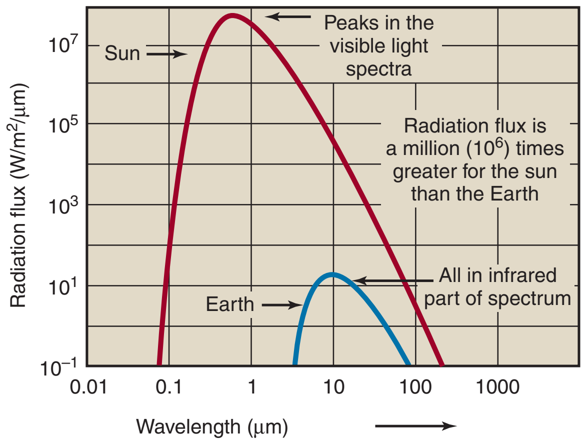


FIGURE 20.9 The sun, much hotter than the Earth, mostly emits energy in the visible and near infrared. The cooler Earth emits energy mostly in the far (longer-wavelength) infrared.

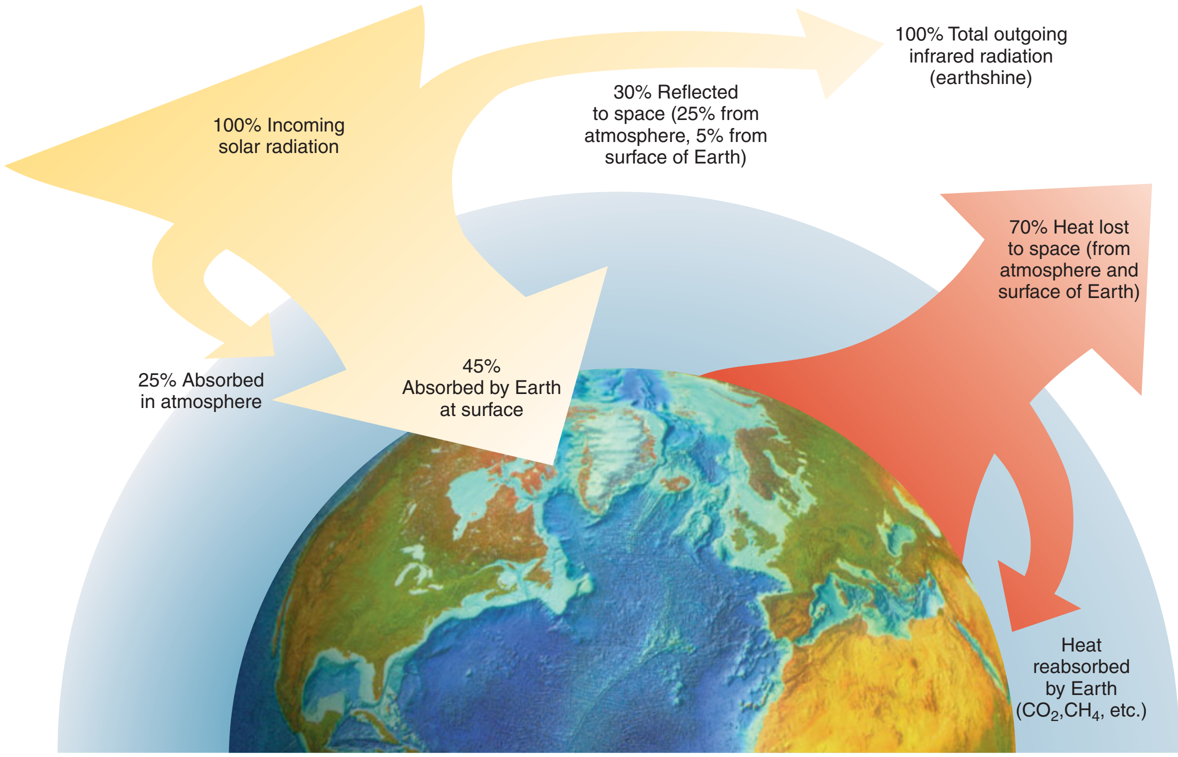


FIGURE 20.10 Earth's energy budget.

20.5 How We Study Climate

Data to document and understand climate change come from three main time periods grouped as the Instrumental Record; the Historical Record; and the Paleo-Proxy Record.[3, 10]

The Instrumental Record

The use of instruments to make climate measurements began around 1860. Since then, temperatures have been measured at various places on land and in the oceans. The average of these observations produces the graph shown earlier in Figure 20.2. In addition, the concentration of carbon dioxide in the atmosphere has been measured continuously since about 1957, and energy produced by the sun has been carefully measured over the past several decades. The problem in using these records to accurately estimate the global average is that few places have a complete record since 1850, and the places that do—such as London and Philadelphia, where people were especially interested in the weather and where scientists could readily make continual measurements—are not very representative of the global average. Until the advent of satellite remote sensing, air temperature over the oceans was measured only where ships traveled (which is not the kind of sampling that makes a statistician happy), and many of Earth's regions have never had good long-term, ground-based temperature measurements. As a result, when we want or need to know what the temperatures were like in the 19th century, before carbon dioxide concentrations began to rise from the burning of fossil fuels, experts seek ways to extrapolate, interpolate, and estimate.

Several groups have tried to reconstruct the average surface temperature of the Earth using available observations. For example, the Hadley Meteorological Center in Great Britain created a data set that divides Earth's surface into areas that are 5° longitude wide and 5° latitude high for every month of each year starting with 1850. Where historical records exist, these data are placed within the appropriate geographic rectangle. Where they are not, either the rectangle is left empty or various attempts are made to estimate what might be reasonable for that location and time. Recently, the extrapolation methods used to make these reconstructions have come under criticism, and today there is controversy over the reliability and usefulness of such attempts.

Temperature measurement has improved greatly in recent years thanks to such devices as ocean platforms with automatic weather-monitoring equipment, coordinated by the World Meteorological Organization. Thus, we have more accurate records since about 1960.

The Historical Record

A variety of documents are available from the historical records, which in some cases go back several centuries. Included here would be people's written recollections in books, newspapers, journal articles, personal journals, ships' logs, travelers' diaries, and farmers' logs, along with dates of wine harvests and small-grain harvests.[3, 10] Although these are mostly recorded as qualitative data, we can sometimes get quantitative information from them. For example, a painting of a mountain glacier in Switzerland can be used to determine the elevation to which the glacier had descended by the year it was painted. Then, as the climate cooled further, someone may have written that the same glacier reached farther down the mountain, eventually blocking a river in the valley, which flooded and destroyed a town, whose elevation is also known.

The Paleo-Proxy Record

The term *proxy data* refers to scientific data that are not strictly climatic in nature but can be correlated with climate data, such as temperature of the land or sea. Proxy data provides important insights into climate change. Information gathered as proxy data includes natural records of climate variability as indicated by tree rings, sediments, ice cores, fossil pollen, corals, and carbon-14 (^{14}C).[10]

Proxy Climate Records

Ice Cores

Polar ice caps and mountain glaciers have an accumulation record of snow that has been transformed into glacial ice over hundreds to thousands of years. Ice cores often contain small bubbles of air deposited at the time of the snow, and we can measure the atmospheric gases in these. Two important gases being measured in ice cores are carbon-dioxide (CO_2) and methane (CH_4). Of the two it appears methane most closely follows climate change determined from the geologic record over the past 1,000,000 years. As a result CO_2 and CH_4 are the most relevant proxy for climate change. The ice cores also contain a variety of chemicals and materials, such as volcanic ash and dust,

FIGURE 20.11 Scientist examining an ice core from a glacier. The core was stored in a freezer so that ice bubbles could be extracted from it to provide data about the atmosphere in the past (CO_2, dust, lead, etc.).

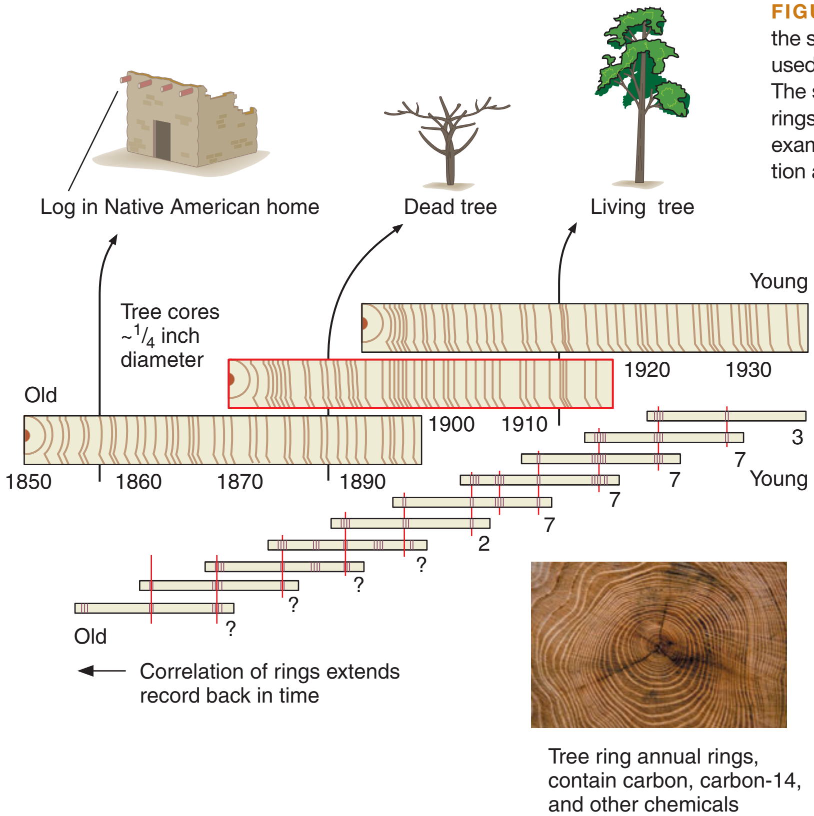


FIGURE 20.12 Dendrochronology, the study of tree growth rings, can be used as an indicator of past climate. The spacing (relative volume of wood) of rings and the isotopic content (^{14}C, for example) of wood can provide information about past rainfall and solar activity.

which may provide additional insights into possible causes of climate change. Ice cores are obtained by drilling into the ice (Figure 20.11). The age of glacial ice back to about 800,000 years is estimated by correlating ice accumulation rates linked to the geologic record of climate change from other proxy sources

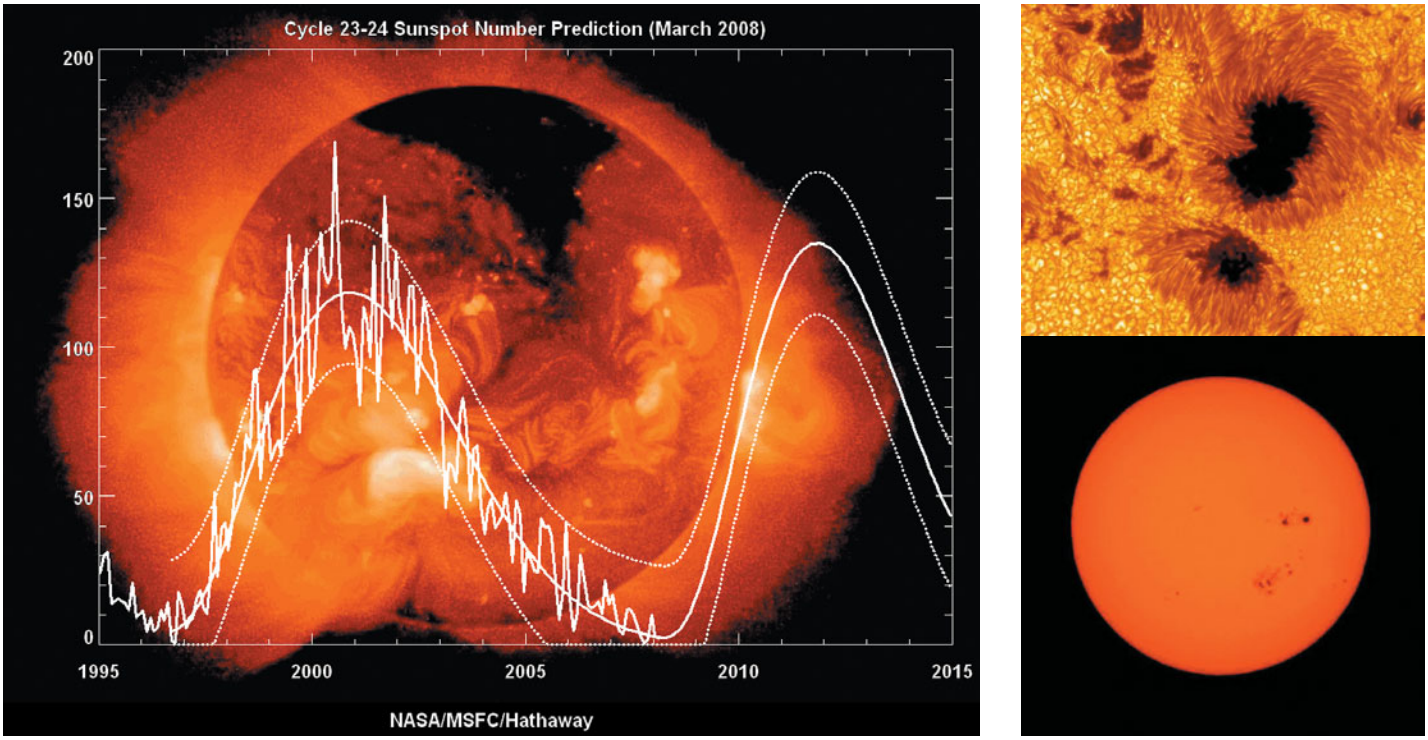
Tree Rings

The growth of trees is influenced by climate, both temperature and precipitation. Many trees put on one growth ring per year, and patterns in the tree rings—their width, density, and isotopic composition—tell us something about the variability of the climate. When conditions are good for growth, a ring is wide; when conditions are poor, the ring is narrow. Tree-ring chronology, known as dendrochronology, has produced a proxy record of climate that extends back over 10,000 years (Figure 20.12).

Sediments

Biological material, including pollen from plants, is deposited on the land and stored for very long periods in lake, bog, and pond sediments and, once transported downstream to the coast, in the oceans. Samples may be taken of very small fossils and of chemicals in the sediments, and these may be interpreted to study past climates and extend our knowledge back hundreds of thousand years (Figure 20.13). Pollen is useful because (1) the quantity of pollen is an indicator of the relative abundance of each plant species; (2) the pollen can be dated, and since the grains are preserved in sedimentary layers that also might be dated, we can develop a chronology; and (3) based on the types of plants found at different times, we can construct a climatic history.

FIGURE 20.13 Scientist examining a sediment core taken by drilling into the seafloor.



(a) (b)

FIGURE 20.14 **(a)** Sunspot cycle with number of sunspots per year, from 1995 to 2009 and **(b)** photos of sunspots in 2003. The large sunspots are about 150,000 km across (for comparison, Earth's diameter is about 12,750 km). The sunspots are the dark areas, and each is surrounded by an orange ring and then a hot gold color. Notice the great variety in the number of sunspots from year to year in the 11-year cycle (over 150 in 2001 and very few in 2008 and 2009). (*Source:* NOAA Images.)

Sediments recovered by drilling in the bottom of the ocean basin provide some of the very strongest evidence of past climate change.

Corals

Corals have hard skeletons composed of calcium carbonate ($CaCO_3$), a mineral extracted by the corals from seawater. The carbonate contains isotopes of oxygen, as well as a variety of trace metals, which have been used to determine the temperature of the water in which the coral grew. The growth of corals has been dated directly with a variety of dating techniques over short time periods of coral growth thereby revealing the chronology of climate change over variable time periods.

Carbon-14

Radioactive carbon-14 (^{14}C) is produced in the upper atmosphere by the collision of cosmic rays and nitrogen-14 (^{14}N). Cosmic rays come from outer space; those the Earth receives are predominantly from the sun. The abundance of cosmic rays varies with the number of sunspots, so called because they appear as dark areas on the sun (Figure 20.14). The frequency of sunspots has been accurately measured for decades and observed by people for nearly 1,000 years. As sunspot activity increases, more energy from the sun reaches Earth. There is an associated solar wind, which produces ionized particles consisting mostly of protons and electrons, emanating from the sun. The radioactive ^{14}C is taken up by photosynthetic organisms—green plants, algae, and some bacteria—and stored in them. If these materials become part of sediments (see above), the year at which they were deposited can be estimated from the decay rate of the ^{14}C.

The record of ^{14}C in the atmosphere has been correlated with tree-ring chronology. Each ring of wood of known age contains carbon, and the amount of ^{14}C can be measured. Then, given the climatic record, it may be correlated with ^{14}C, and that correlation has been shown to be very strong.[10]

Thus, we can examine the output of the sun, going back thousands of years, by studying tree rings and the carbon-14 they contain. This connects to our opening case study about the Medieval Warm Period. Based on these records, it appears that the production of solar energy was slightly higher around A.D. 1000, during the Medieval Warm Period, and slightly lower during the Little Ice Age that followed several hundred years later and lasted from A.D. 1300 to 1850.

20.6 The Greenhouse Effect

Each gas in the atmosphere has its own absorption spectrum—which wavelengths it absorbs and which it transmits. Certain gases in Earth's atmosphere are especially strong absorbers in the infrared and therefore absorb radiation emitted by the warmed surfaces of the Earth. Warmed by this, the gases reemit this radiation. Some of it reaches back to the surface, making Earth warmer than it otherwise would be. The process by which the heat is trapped is not the same as in a greenhouse (air in a closed greenhouse has restricted circulation and will heat up). Still, in trapping heat this way, the gases act a little like the glass panes, which is why it is called the **greenhouse effect.** The major greenhouse gases are water vapor, carbon dioxide, methane, some oxides of nitrogen, and chlorofluorocarbons (CFCs). The greenhouse effect is a natural phenomenon that occurs on Earth and on other planets in our solar system. Most natural greenhouse warming is due to water in the atmosphere—water vapor and small particles of water in the atmosphere produce about 85% and 12%, respectively, of the total greenhouse warming.

How the Greenhouse Effect Works

Figure 20.15 is a highly idealized diagram of some important aspects of the greenhouse effect. The arrows labeled "energy input" represent the energy from the sun absorbed at or near Earth's surface. The arrows labeled "energy output" represent energy emitted from the upper atmosphere and Earth's surface, which balances input, consistent with Earth's energy balance. The highly contorted lines near the surface of the Earth represent the absorption of infrared radiation (IR) occurring there and producing the 15°C (59°F) near-surface temperature. Following many scatterings and absorptions and reemissions, the infrared radiation emitted from levels near the top of the atmosphere (troposphere) corresponds to a temperature of approximately 18°C (0°F). The one output arrow that goes directly through Earth's atmosphere represents radiation emitted through what is called the atmospheric window (Figure 20.16). The atmospheric window, centered on a wavelength of 10 m, is a region of wavelengths (8–12 m) where outgoing radiation from Earth is not absorbed well by natural greenhouse gases (water vapor and carbon dioxide). Anthropogenic CFCs do absorb in this region, however, and CFCs significantly contribute to the greenhouse effect in this way.

Let us look more closely at the relation of the greenhouse effect to Earth's energy balance, which was introduced in a simple way. The figure showed that, of the simple solar radiation, approximately 30% is reflected back to space from the atmosphere as shortwave solar radiation, while 70% is absorbed by Earth's surface and atmosphere. The 70% that is absorbed is eventually reemitted as infrared radiation into space. The sum of the reflected solar radiation and the outgoing infrared radiation balances with the energy arriving from the sun.

This simple balance becomes much more complicated when we consider exchanges of infrared radiation within the atmosphere and Earth surface. In some instances, these internal radiation fluxes (rates of transfer) may have magnitudes greater than the amount of energy entering Earth's atmospheric system from the sun, as shown in Figure 20.17. A major contributor to the fluxes is the greenhouse effect. At first glance, you might think it would be impossible to have internal radiation fluxes greater than the total amount of incoming solar radiation (shown as 100 units in Figure 20.17). It is possible because the infrared radiation is reabsorbed and readmitted many times in the

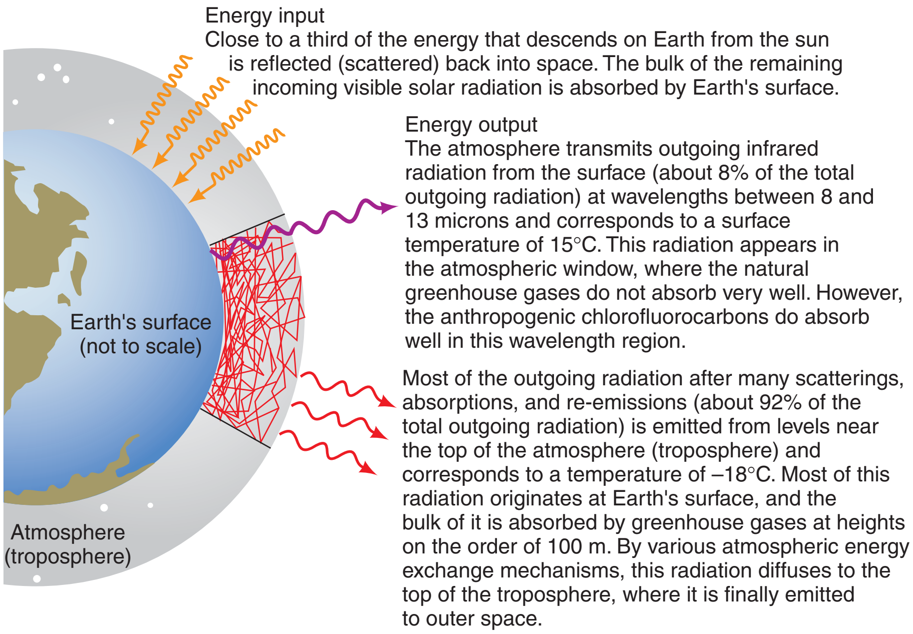


FIGURE 20.15 Idealized diagram showing the greenhouse effect. Incoming visible solar radiation is absorbed by Earth's surface, to be reemitted in the infrared region of the electromagnetic spectrum. Most of this reemitted infrared radiation is absorbed by the atmosphere, maintaining the greenhouse effect. (*Source*: Developed by M.S. Manalis and E.A. Keller, 1990.)

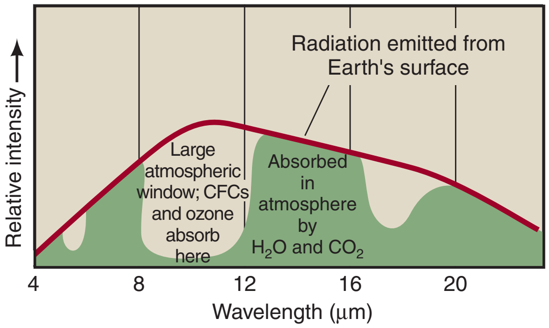


FIGURE 20.16 What the major greenhouse gases absorb in the Earth's atmosphere. Earth's surface radiates mostly in the infrared, which is the range of electromagnetic energy shown here. Water and carbon dioxide absorb heavily in some wavelengths within this range, making them major greenhouse gases. The other greenhouse gases, including methane, some oxides of nitrogen, CFCs, and ozone, absorb smaller amounts but in wavelengths not absorbed by water and carbon dioxide. (*Source*: Modified from T.G. Spiro and W.M. Stigliani, *Environmental Science in Perspective* [Albany: State University of New York Press, 1980].)

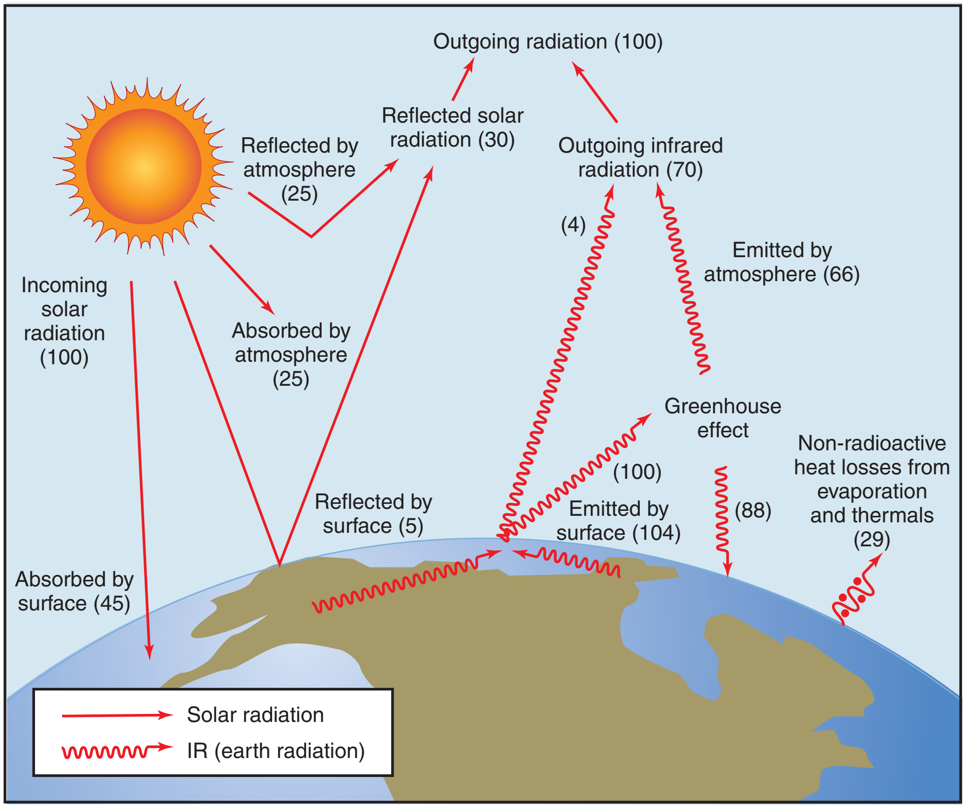


FIGURE 20.17 Idealized diagram showing Earth's energy balance and the greenhouse effect. Incoming solar radiation is arbitrarily set at 100 units, and this is balanced by outgoing radiation of 100 units. Notice that some of the fluxes (rates of transfer) of infrared radiation (IR) are greater than 100, reflecting the role of the greenhouse effect. Some of these fluxes are explained in the diagram. (*Source*: Modified from D.I. Hartmann, *Global Physical Climatology, International Geophysics Series*, vol. 56 [New York: Academic Press. 1994] and S. Schneider, "Climate Modeling," *Scientific American* 256 No. 5.)

- Total incoming solar radiation = 100 units
- Total absorbed by surface = 133 units
  - 45 from solar radiation (shortwave)
  - 88 from greenhouse effect IR (infrared)
- Total emitted by surface = 133 units
  - 104 IR (of this, only 4 units pass directly to space without being absorbed or re-emitted in greenhouse effect)
  - 29 from evaporation and thermals (non-radioactive heat loss)
- Total IR emitted by upper atmosphere to space = 70 units
  - 66 units emitted by atmosphere
  - 4 units emitted by surface
- The 25 units of solar radiation absorbed by atmosphere are eventually emitted as IR (part of the 66 units)
- Total outgoing radiation = 100 units
  - 70 IR
  - 30 reflected solar radiation

atmosphere, resulting in high internal fluxes. For example, in terms of the figure, the amount of IR absorbed at Earth's surface from the greenhouse effect is approximately 88 units, which is about twice the amount of shortwave solar radiation (45 units) absorbed by Earth's surface. Despite the large internal fluxes, the overall energy balance remains the same. At the top of the atmosphere, the net downward solar radiation (70 units, 45 units + 25 units) balances the outgoing IR from the top of the atmosphere (70 units).

The important point here is recognizing the strength of the greenhouse effect. For example, notice in the figure that of the 104 units of IR emitted by the surface of Earth, only 4 go directly to the upper atmosphere and are emitted. The rest is reabsorbed and reemitted by greenhouse gases. Of these, 88 units are directed downward to Earth and 66 units upward to the upper atmosphere.

All this may sound somewhat complicated, but if you read and study the points mentioned in Figures 20.15 to 20.17 carefully and work through the balances of the various parts of the energy fluxes, you will gain a deeper understanding of why the greenhouse effect is so important. The greenhouse effect keeps Earth's lower atmosphere approximately 33°C warmer than it would otherwise be and performs other important service functions as well. For example, without the strong downward emission of IR from the greenhouse effect, the land surface would cool much faster at night and warm much more quickly during the day. In sum, the greenhouse effect helps to limit temperature swings from day to night and maintain relatively comfortable surface temperatures. It is, then, not the greenhouse effect itself but the changes in greenhouse gases that are a concern.

20.7 The Major Greenhouse Gases

The major anthropogenic greenhouse gases are listed in Table 20.1. The table also lists the recent rate of increase for each gas and its relative contribution to the anthropogenic greenhouse effect.

Carbon Dioxide

Current estimates suggest that approximately 200 billion metric tons of carbon in the form of carbon dioxide (CO_2) enter and leave Earth's atmosphere each year as a result of a number of biological and physical processes: 50 to 60% of the anthropogenic greenhouse effect is attributed to this gas. Measurements of carbon dioxide trapped in air bubbles in the Antarctic ice sheet suggest that 160,000 years before the Industrial Revolution the atmospheric concentration of carbon dioxide varied from approximately 200 to 300 ppm.[12] The highest level or concentration of carbon dioxide in the atmosphere, other than today's, occurred during the major interglacial period about 125,000 years ago.

About 140 years ago, just before the major use of fossil fuels began as part of the Industrial Revolution, the atmospheric concentration of carbon dioxide was approximately 280 ppm.[13] Since then, and especially in the past few decades, the concentration of CO_2 in the atmosphere has grown rapidly. Today, the CO_2 concentration is about 392 ppm, and at its current rate of increase of about 0.5% per year, the level may rise to approximately 450 ppm by the year 2050—more than 1.5 times the preindustrial level.[13]

Table 20.1 MAJOR GREENHOUSE GASES

TRACE GASES	RELATIVE CONTRIBUTION (%)	GROWTH RATE (%/YR)
CFC	15[a]-25[b]	5
CH_4	12[a]-20[b]	0.4[c]
O_3(troposphere)	8[d]	0.5
N_2O	5[d]	0.2
Total	40–50	
Contribution of CO_2	50–60	0.3[e]–0.5[d,f]

[a]W. A. Nierenberg, "Atmospheric CO_2: Causes, Effects, and Options," *Chemical Engineering Progress* 85, no.8 (August 1989): 27

[b]J. Hansen, A. Lacis, and M. Prather, "Greenhouse Effect of Chlorofluorocarbons and Other Trace Gases," *Journal of Geophysical Research* 94 (November 20, 1989): 16, 417.

[c]Over the past 200 yrs.

[d]H. Rodha, "A Comparison of the Contribution of Various Gases to the Greenhouse Effect," *Science* 248 (1990): 1218, Table 2.

[e]W. W. Kellogg, "Economic and Political Implications of Climate Change," paper presented at Conference on Technology-based Confidence Building: Energy and Environment, University of California, Los Alamos National Laboratory, July 9–14, 1989.

[f]H. Abelson, "Uncertainties about Global Warming," *Science* 247 (March 30,1990): 1529.

Methane

The concentration of methane (CH_4) in the atmosphere more than doubled in the past 200 years and is thought to contribute approximately 12 to 20% of the anthropogenic greenhouse effect.[14, 15] Certain bacteria that can live only in oxygenless atmospheres produce methane and release it. These bacteria live in the guts of termites and the intestines of ruminant mammals, such as cows, which produce methane as they digest woody plants. These bacteria also live in oxygenless parts of freshwater wetlands, where they decompose vegetation, releasing methane as a decay product. Methane is also released with seepage from oil fields and seepage from methane hydrates (see Chapter 15).

Our activities also release methane. These activities include landfills (the major methane source in the United States), the burning of biofuels, production of coal and natural gas, and agriculture, such as raising cattle and cultivating rice. (Methane is also released by anaerobic activity in flooded lands where rice is grown.) As with carbon dioxide, there are important uncertainties in our understanding of the sources and sinks of methane in the atmosphere.

Chlorofluorocarbons

Chlorofluorocarbons (CFCs) are inert, stable compounds that have been used in spray cans as aerosol propellants and in refrigerators. The rate of increase of CFCs in the atmosphere in the recent past was about 5% per year, and it has been estimated that approximately 15 to 25% of the anthropogenic greenhouse effect may be related to CFCs. Because they affect the stratospheric ozone layer and also play a role in the greenhouse effect, the United States banned their use as propellants in 1978. In 1987, 24 countries signed the Montreal Protocol to reduce and eventually eliminate production of CFCs and accelerate the development of alternative chemicals. As a result of the treaty, production of CFCs was nearly phased out by 2000.

Potential global warming from CFCs is considerable because they absorb in the atmospheric window, as explained earlier, and each CFC molecule may absorb hundreds or even thousands of times more infrared radiation emitted from Earth than is absorbed by a molecule of carbon dioxide. Furthermore, because CFCs are highly stable, their residence time in the atmosphere is long. Even though their production was drastically reduced, their concentrations in the atmosphere will remain significant (although lower than today's) for many years, perhaps for as long as a century.[16, 17] (CFCs are discussed in Chapter 21, which examines stratospheric ozone depletion.)

Nitrous Oxide

Nitrous oxide (N_2O) is increasing in the atmosphere and probably contributes as much as 5% of the anthropogenic greenhouse effect.[18] Anthropogenic sources of nitrous oxide include agricultural application of fertilizers and the burning of fossil fuels. This gas, too, has a long residence time; even if emissions were stabilized or reduced, elevated concentrations of nitrous oxide would persist for at least several decades.

20.8 Climate Change and Feedback Loops

Part of the reason climate change is so complex is that there can be many positive and negative feedback loops. Only a few possible feedback loops of many are discussed here. Negative feedbacks are self-inhacing and help stabilize a system. Positive feedbacks are self-regulating, so a greater change now will result in an even greater change in the future. This is a simplistic statement about feedback and climate because some changes are associated with both positive and negative feedback. With this caveat stated, we will discuss positive and negative feedbacks with respect to climate change. We discussed feedback in Chapter 3; you may wish to review those concepts.

Here are some feedback loops that have been suggested for climate change.[19]

Possible Negative Feedback Loops for Climate Change

- As global warming occurs, the warmth and additional carbon dioxide could stimulate algae growth. This, in turn, could absorb carbon dioxide, reducing the concentration of CO_2 in the atmosphere and cooling Earth's climate.
- Increased CO_2 concentration with warming might similarly stimulate growth of land plants, leading to increased CO_2 absorption and reducing the greenhouse effect.
- If polar regions receive more precipitation from warmer air carrying more moisture, the increasing snowpack and ice buildup could reflect solar energy away from Earth's surface, causing cooling.
- Increases in water evaporation with warming from the ocean and the land could lead to cloudier conditions (the water vapor condenses), and the clouds would reflect more sunlight and cool the surface.

Possible Positive Feedback Loops for Climate Change

- The warming Earth increases water evaporation from the oceans, adding water vapor to the atmosphere. Water vapor is a major greenhouse gas that, as it increases, causes additional warming. If more clouds form from the increaced water vapor, and more solar radiation is reflected this would cause cooling as discussed with negative feedback above. Thus water vapor is associated with both positive and negative feedback. This makes study of clouds and global climate change complex.
- The warming Earth could melt a large amount of permafrost at high latitudes, which would in turn release the greenhouse gas methane, a by-product of decomposition of organic material in the melted permafrost layer. This would cause additional warming.
- Replacing some of the summer snowpack or glacial ice with darker vegetation and soil surfaces decreases the albedo (reflectivity) increasing the absorption of solar energy, further warming surface. This is a powerful positive feedback explaining, in part, why the Arctic is warming faster than at lower latitudes.
- In warming climates, people use more air-conditioning and thus more fossil fuels. The resulting increase in carbon dioxide could lead to additional global warming.

Since negative and positive feedback can occur simultaneously in the atmosphere, the dynamics of climate change are all the more complex. Research is ongoing to better understand negative feedback processes associated with clouds and their water vapor.

20.9 Causes of Climate Change

Not until the 19th century did scientists begin to understand that climate changed greatly over long periods and included times of continental glaciations. The realization that there had been glacial and interglacial episodes began in 1815 when a Swiss peasant, Jean-Paul Perraudin, suggested to a Swiss civil engineer, Ignaz Venetz-Sitten, that some features of mountain valleys, including the boulders and soil debris, were due to glaciers that in a previous time had extended down the slopes beyond their present limits. Impressed with these observations, Venetz-Sitten spoke before a natural history society at Lucerne in 1821 and suggested that the glaciers had at some previous time extended considerably beyond their present range.

At first, he wasn't taken seriously—in fact, the famous 19th-century geologist Louis Agassiz traveled to the Alps to refute these ideas. But once Agassiz saw the evidence, he changed his mind and formulated a theory of continental glaciation. The evidence was debris—rocks and soils—at the edges of existing mountain glaciers and the same kinds of deposits at lower elevations. Agassiz realized that only glaciers could have produced the kinds of debris now far below the ice. It was soon recognized that glaciers had covered vast areas in Great Britain, mainland Europe, and North America.[20]

This began the search for an answer to a puzzling question: Why does the climate change, and change so drastically? One of the most important insights was achieved in the 1920s by Milutin Milankovitch, a Serbian astronomer who looked at long-term climate records and began to think about what might correlate with these records. Look at Figure 20.18 and you will see that cycles of about 100,000 years are apparent; these seem to be divided as well into shorter cycles of about 20,000 to 40,000 years.

Milankovitch Cycles

Milankovitch realized that the explanation might have to do with the way the Earth revolved on its axis and rotated around the sun. Our spinning Earth is like a wobbling top following an elliptical orbit around the sun. Three kinds of changes occur.

First, the wobble means that the Earth is unable to keep its poles at a constant angle in relation to the sun (Figure 20.18a). Right now, the North Pole points to Polaris, the North Star, but this changes as the planet wobbles. The wobble makes a complete cycle in 26,000 years.

Second, the tilt of Earth's axis varies over a period of 41,000 years (Figure 20.18b).

Third, the elliptical orbit around the sun also changes. Sometimes it is a more extreme ellipse; at other times it is closer to a circle (Figure 20.18c), and this occurs over 100,000 years.

The combination of these changes leads to periodic changes in the amount and distribution of sunlight reaching the Earth. Sometimes the wobble causes the Northern Hemisphere to be tilted toward the sun (Northern Hemisphere summertime) when the Earth is closest to the sun. At other times, the opposite occurs—the Northern Hemisphere is tipped away from the sun (northern wintertime) when the Earth is closest to the sun. Milankovitch showed that these variations correlated with the major glacial and interglacial periods (Figure 20.18). They are now called Milankovitch cycles.[21]

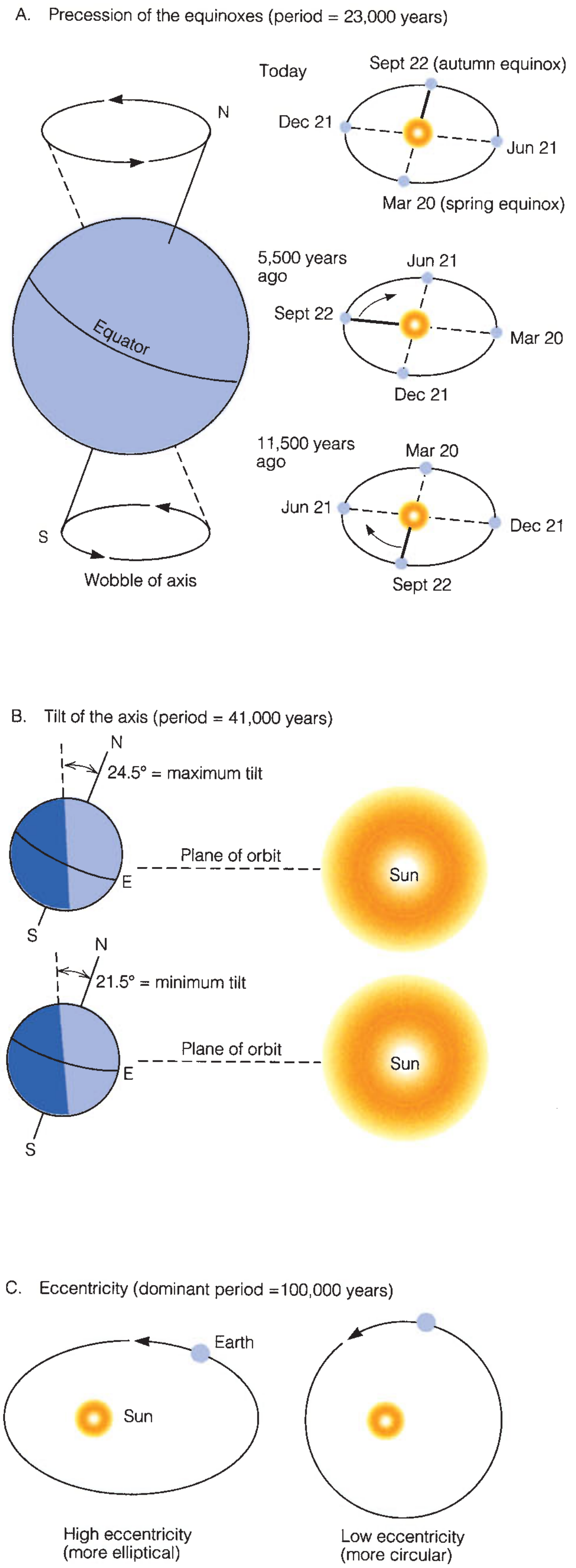


FIGURE 20.18 The Earth wobbles, changes its tilt, and has an elliptical orbit that changes as well. (*Source:* Skinner, Porter, and Botkin, *The Blue Planet* [John Wiley], 2nd edition, p. 335.)

Milankovich attempted explain ice ages through changes in solar radiation reaching Earth. His contribution is very significant. While Milankovitch cycles are consistent with the timing of variations in glacial and inter glacial change, they were not intented to not account for all the large-scale climatic variations in the geologic record. It is perhaps best to think of these cycles as response of climate to orbital variations.

Once Earth receives energy from the sun, Earth's surface features affect the climate. These earthly factors that affect, and are in turn affected by, regional and global temperature changes include warmer ice-sheet temperatures; changes in vegetation; changes in atmospheric gases, such as carbon dioxide, methane, and nitrous oxide; and particulates and aerosols. Volcanoes inject aerosols into the upper atmosphere, where they reflect sunlight and cool the Earth's surface.

Solar Cycles

As we discussed earlier, the sun goes through cycles too, sometimes growing hotter, sometimes colder. Today, solar intensity is observed directly with telescopes and other instruments. Variations in the sun's intensity in the past can be determined because hotter and cooler sun periods emit different amounts of **radionuclides**—atoms with unstable nuclei that undergo radioactive decay (such as beryllium-10 and carbon-14), which are trapped in glacial ice and can then be measured. As we mentioned earlier, evaluation of these radionuclides in ice cores from glaciers reveals that during the Medieval Warm Period, from approximately A.D. 950 to 1250, the amount of solar energy reaching Earth was relatively high, and that minimum solar activity occurred during the 14th century, coincident with the beginning of the Little Ice Age. Thus, it appears that the variability of solar energy input explains a small part of the Earth's climatic variability.[22, 23] Since about 1880 solar input has increased about 0.5% while CO_2 has increased about 33%. Solar input in the Arctic has closely followed annual surface temperature. Since 1960, CO_2 increase in the atmosphere has been about 25% in close agreement with Arctic surface temperature increase. Thus in the past 50 years CO_2 appears to be a dominant factor in increasing surface temperature in the Arctic as well as the entire Earth.[24] That is recent warming cannot be explained by solar activity.

Atmospheric Transparency Affects Climate and Weather

How transparent the atmosphere is to the radiation coming to it, from both the sun and Earth's surface, affects the temperature of the Earth. Dust and aerosols absorb light, cooling the Earth's surfaces. Volcanoes and large forest fires put dust into the atmosphere, as do various human activities, such as plowing large areas. Each gas compound has its own absorption spectrum (the electromagnetic radiation that is absorbed by a gas as it passes through the atmosphere). Thus the chemical and physical composition of the atmosphere can make things warmer or cooler.

The Surface of Earth and Albedo (reflectivity) Affects

Albedo is the reflectivity of an object that is measured as the percentage of incoming radiation that is reflected. For examples the approximate albedos are: Earth (as a whole) is 30%, clouds depending on type and thickness are 40–90%, fresh snow is 85%, glacial ice depending on soil rock cover is 20–40%, a pine forest is 10% dark rock is 5–15%, dry sand is 40%, and a grass-covered meadow is 15%.

A dark rock surface exposed near the North Pole absorbs more of the sunlight it receives than it reflects in the summer, warming the surface and the air passing over it. When a glacier spreads out and covers that rock, it reflects more of the incoming sunlight than the darker rock cooling both the surface and the air that comes in contact with it.

Vegetation also affects the climate and weather in the same way. If vegetation is a darker color than the soil, it warms the surface. If it is a lighter color than the soil, it cools the surface. Now you know why if you walk barefoot on dark asphalt on a hot day you feel the heat radiating from the surface (you may burn the bottom of your feet).

Roughness of the Earth's Surface Affects the Atmosphere

Above a completely smooth surface, air flows smoothly—a flow called "laminar." A rough surface causes air to become turbulent—to spin, rotate, reverse, and so forth. Turbulent air gives up some of the energy in its motion (its kinetic energy), and that energy is turned into heat. This affects the weather above. Forests are a much rougher surface than smooth rock or glaciers, so in this way, too, vegetation affects weather and climate.

The Chemistry of Life Affects the Atmosphere

The emission and uptake of chemicals by living things affect the weather and climate, as we will discuss in detail in the next section. Thus, a planet with water vapor, liquid water, frozen water, and living things has a much more complex energy-exchange system than a lifeless, waterless planet. This is one reason (of many) why it is difficult to forecast climate change.

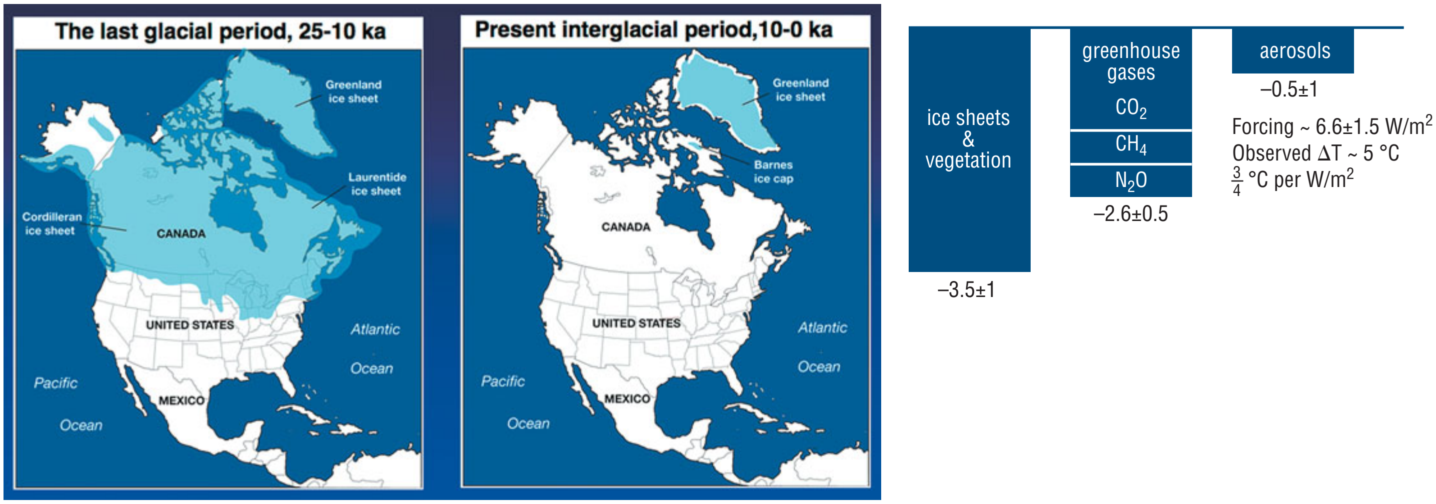
Climate Forcing

It can be helpful to view climate change in terms of ***climate forcing***—defined as an imposed perturbation of Earth's energy balance.[8] The major forcings associated with the glaciations are shown in Figure 20.19a. Factors that affect and are in turn affected by regional global temperature changes include higher ice-sheet temperatures; changes in vegetation; changes in atmospheric gases, such as carbon dioxide, methane, and nitrous oxide; and changes in sunlight intensity. Aerosols, such as those ejected by a volcano into the upper atmosphere, reflect sunlight and cool the Earth's surface. Changes in sunlight intensity are caused both by variations in sunlight brightness and by changes in Earth's orbit. Total energy forcing of the Last Glacial Maximum (LGM), around 22,000 years ago, when glaciers were at their thickest and sea levels their lowest, is calculated to have been about 6.6 ± 1.5 W/m^2. Thus, the average 5°C lowering equates to 3/4°C per W/m^2. The units are power per unit area.

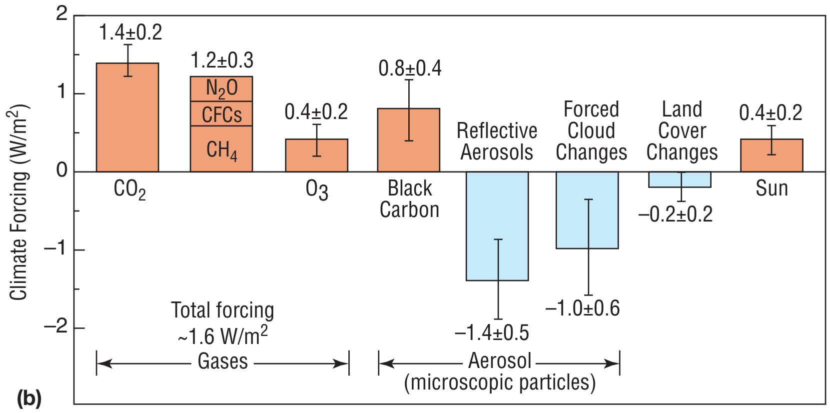
Climate forcing during the industrial age is shown on Figure 20-19b. Positive forcings cause warm and negative forcings cause cooling. In recent decades human caused forcings have dominated over natural forcings. Total forcing is 1.6 ± 0.1 W/m^2, consistent with the observed rise in global surface air temperature over the past few decades.

Forcings operate by changing the properties of both the atmosphere and the surface that feed back into climate. As ice sheets grow, they reflect more incoming solar radiation, which enhances cooling. Changes in the amount of area covered by vegetation and the kinds of vegetation change reflectivity and absorption of solar energy and the uptake and release of atmospheric gases. Atmospheric gases, such as carbon dioxide, methane, and nitrous oxide, also play important roles. For now, it is more important to recognize that climate forcing is related to Earth's energy balance and as such is an important quantitative tool with which to evaluate global change in the geologic past, as well as global warming, which refers to the more recent rise in global surface air temperatures over the past few decades.[25]

As a way to visualize forcing, consider a checking account that you are free to use but earns no interest use. Assume you initially deposit $1,000, and each year you deposit $500 and write checks for $500. You do this for many years, and at the end of that time you still have $1,000 in your account. The point is that for any system, when input equals output for some material (in this case, dollars), the amount in the system remains constant. In our bank account example, if we increased the total amount in the account by only $3 per year (a 0.3% increase per year), it would double to $2,000 over a period of about 233 years. In short, a small imbalance over many years can cause significant change.



(a)



(b)

- Increases of greenhouse gases (except O_3) are known from observations and bubbles of air trapped in ice sheels. The increase of CO_2 from 285 parts per million (ppm) in 1850 to 392 in 2010 is accurate to about 5 ppm. The conversion of this gas change to a climate forcing (1.4 W/m^2), from calculation of the infrared opacity, adds about 10% to the uncertainty.
- Increase of CH_4 since 1850, including its effect on stratospheric H_2O and tropospheric O_3, causes a climate forcing about half as large as that by CO_2. Main sources of CH_4 include landfills, coal mining, leaky natural gas lines, increasing ruminant (cow) population, rice cultivation, and waste management. Growth rate of CH_4 has slowed in recent years.
- Tropospheric O_3 is increasing. The U.S. and Europe have reduced O_3 precursor emissions (hydrocarbons) in recent years, but increased emissions are occurring in the developing world.
- Block carbon ("soot"), a product of incomplete combustion, is visible in the exhaust of diesel trucks. It is also produced by biofuels and outdoor biomass burning. Black carbon aerosols are not well measured, and their climate forcing is estimated from measurements of total aerosol absorption. The forcing includes the effect of soot in reducing the reflectance of snow and ice.
- Human-made reflective aerosols include sulfates, nitrates, organic carbon, and soil dust. Sources include burning fossil fuel and agricultural activities. Uncertainty in the forcing by reflective aerosols is at least 35%.
- Indirect effects of aerosols on cloud properties are difficult to compute, but satellite measurements of the correlation of aerosol and cloud properties are consistent with the estimated net forcing of –1 W/m^2, with uncertainty of at least 50%.

FIGURE 20.19 **(a)** Climate forcing during the last major glaciations about 22,000 years ago was 6.6 ± 1.5 W/m^2, which produced a drop in global lower atmospheric temperature **(b)** climate forcing during industrial age. (*Source*: **(a)** USGS and NASA **(b)** modified from Hansen, J. 2003. *Can we defuse the global warming time bomb*? Edited version of the presentation to the Council on Environmental Quality. June 12. Washington DC, also *Natural Science* http://www.naturalscience.com)

20.10 The Oceans and Climate Change

The oceans play an important role in climate because two-thirds of the Earth is covered by water. Moreover, water has the highest heat-storage capacity of any compound, so a very large amount of heat energy can be stored in the world's oceans. There is a complex, dynamic, and ongoing relationship between the oceans and the atmosphere. If carbon dioxide increases in the atmosphere, it will also increase in the oceans, and, over time the oceans can absorb a very large quantity of CO_2. This can cause seawater to become more acidic ($H_2O + CO_2 \rightarrow H_2CO_3$) as carbonic acid increases.

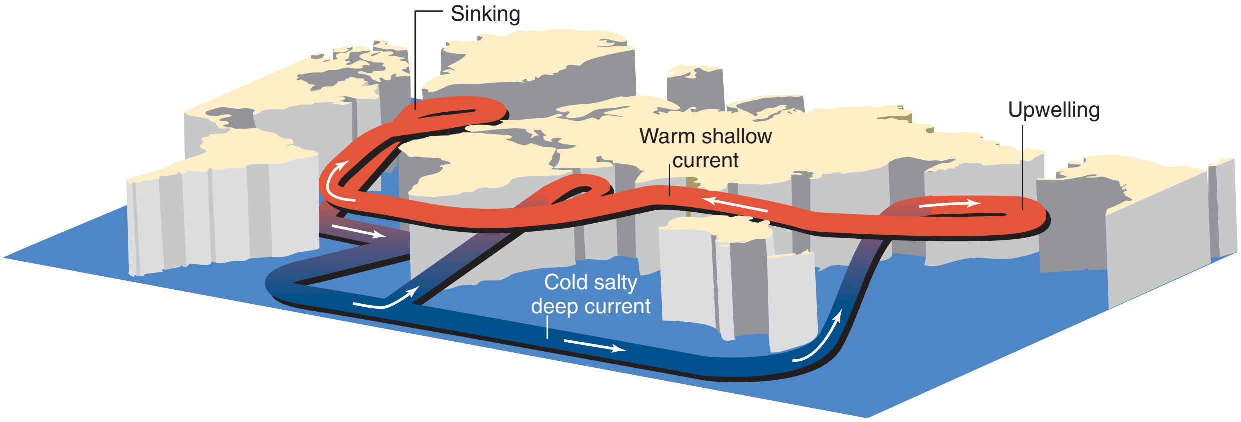


FIGURE 20.20 Idealized diagram of the oceanic conveyor belt. The actual system is more complex, but in general the warm surface water (red) is transported westward and northward (increasing in salinity because of evaporation) to near Greenland, where it cools from contact with cold Canadian air. As the surface water becomes denser, it sinks to the bottom and flows south, then east to the Pacific, then north, where upwelling occurs in the North Pacific. The masses of sinking and upwelling waters balance, and the total flow rate is about 20 million m^3/sec. The heat released to the atmosphere from the warm water keeps Northern Europe 5°C—10°C warmer than if the oceanic conveyor belt were not present. (*Source*: Modified from W. Broker, "Will Our Ride into the Greenhouse Future Be a Smooth One?" *Geology Today* 7, no. 5 [1997]:2–6.)

Part of what may drive the climate system and its changes is the "ocean conveyor belt"—a global circulation of ocean waters characterized by strong northward movement of upper warm waters of the Gulf Stream in the Atlantic Ocean. The temperature of these waters is approximately 12°–13°C when they arrive near Greenland, and they are cooled in the North Atlantic to a temperature of 2°–4°C (Figure 20.20).[25] As the water cools, it becomes saltier and denser, causing it to sink to the bottom. The cold, deep current flows southward, then eastward, and finally northward in the Pacific Ocean. Upwelling in the North Pacific starts the warm, shallow current again. The flow in this conveyor-belt current is huge—20 million m^3/sec, about equal to 100 Amazon rivers.

If the ocean conveyor belt were to shut down, some major changes might occur in the climates of some regions. Western Europe would cool but probably not experience extreme cold or icebound conditions.[26]

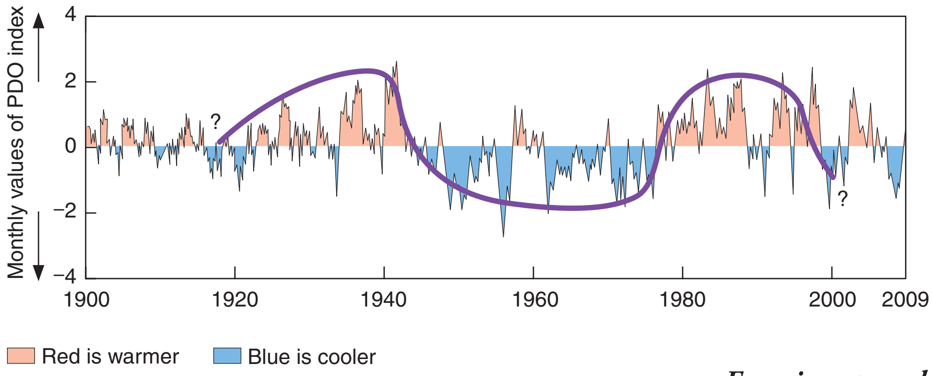
The ocean currents of the world have oscillations related to changes in water temperature, air pressure, storms, and weather over periods of a year or so to decades. They occur in the North Pacific, South Pacific, Indian, and North Atlantic oceans and can influence the climate. The Pacific Decadal Oscillation (PDO) for the North Pacific from 1900 to about 2010 is shown in Figure 20.21a. Natural oscillations of the ocean linked to the atmosphere can produce warmer or cooler periods of a few years to a decade or so. The effect of the oscillations can be ten times as strong (in a given year) as long-term warming that we have observed over the past century—larger, over a period of a few decades, than human-induced climate change. By comparison, the annual increase in warming due mostly to human activity is about two-hundredths of a degree Celsius per year.[27] Some scientists attribute the cool winter of 2009–2010 to natural ocean–atmosphere oscillations, and also suggest that these caused a cool year in 1911 that froze Niagara Falls. The more famous El Niño oscillations that occur in the Pacific Ocean are connected to large-scale but short-term changes in weather.

El Niño and Climate

A curious and historically important climate change linked to variations in ocean currents is the Southern Oscillation, known informally as El Niño. From the time of early Spanish settlement of the west coast of South America, people observed a strange event that occurred about every seven years. Usually starting around Christmas (hence the Spanish name El Niño, referring to the little Christ Child), the ocean waters would warm up, fishing would become poor, and seabirds would disappear.

Under normal conditions, there are strong vertical, rising currents, called upwelling, off the shore of Peru. These are caused by prevailing winds coming westward off the South American Continent, which move the surface water away from the shore and allow cold water to rise from the depths, along with important nutrients that promote the growth of algae (the base of the food chain) and thus produce lots of fish. Seabirds feed on those fish and live in great numbers, nesting on small islands just offshore.

El Niño occurs when those cold upwellings weaken or stop rising altogether. As a result, nutrients decline, algae grow poorly, and so do the fish, which either die, fail to reproduce, or move away. The seabirds, too, either leave or die. Because rainfall follows warm water eastward during El Niño years, there are high rates of precipitation and flooding in Peru, while droughts and fires are common in Australia and Indonesia. Because warm ocean water provides an atmospheric heat source, El Niño changes global atmospheric circulation, which causes changes in weather in regions that are far removed from the tropical Pacific.[28]



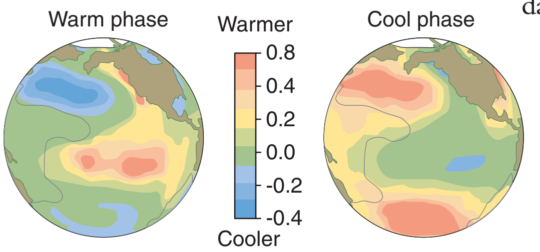


FIGURE 20.21 **(a)** The Pacific Decadal Oscillation (PDO) from 1900 to 2009. Three oscillations are clear (heavy line); **(b)** PDO warm and cool phases with characteristic changes in water temperature (°C) in the North Pacific and along the coast of the Pacific Northwest. (*Source*: Modified after http://jisao.washington.edu. Accessed March 26, 2010.)

20.11 Forecasting Climate Change

Concerns about global warming have to do with the future of the climate. This presents a problem because predicting the future has always been difficult and because people who make predictions have often been wrong. For climate and its effects on living things, there are two approaches to forecasting the future: empirical and theoretical.

Past Observations and Laboratory Research

Past Observations

We discussed this first kind of empirical approach in Section 20.5 in terms of how past climates are reconstructed. The use of empirical records is based on the idea of **uniformitarianism**—the idea that processes occurring in the past occur today and that processes occurring today occurred in the past. Therefore, the past is the key to the present and future. This leads to an "if–then" way of thinking about the future: *If* climate change in the past correlated with change of a certain factor, *then* perhaps a change in that factor will lead to a similar climate change in the future. The argument that human actions are leading to global warming is heavily based on this kind of empirical evidence, in particular measurements from the past 150 years and proxy evidence over the past few hundred years that suggest relationships between Earth's average surface temperature with both the concentations of carbon dioxide and methane in the atmosphere.[15]

Experiments and Laboratory Research

Laboratory research has taught scientists some fundamental things about the cause and effect of climate change. For example, the understanding that carbon dioxide absorbs in specific infrared wavelengths that are different from those of the other gases in the atmosphere comes from a long history of laboratory studies of the air around us, beginning with the work of one of the first modern chemical scientists, the Englishman Joseph Priestley (1733–1804). In the 1770s he did experiments with plants, mice, and candles that were in closed glass containers. He found that if a mouse was kept in a jar by itself, it soon died; but if there was a plant in the jar, the mouse lived. He also found that a plant grew better in a jar in which a mouse had died than it did when by itself. He put a mint plant and a lighted candle in a glass jar, closed the jar, and the candle soon went out. He left the closed jar for a month, and when he came back he lit the candle without opening the jar (focusing sunlight on the candle's wick) and it burned again. Obviously, the mint plant had somehow changed the air in the jar, as had the mouse.

In this way, Priestley discovered that animals and plants change the atmosphere. It wasn't long afterward that oxygen (given off, of course by the green plant) and carbon dioxide (given off by the mouse and the candle) were identified and their light-absorption spectra were determined. Without this kind of study, we wouldn't know that there were such things as greenhouse gases.[29]

Computer Simulations

Scientists have been trying to use mathematics to predict the weather since the beginning of the 20th century. They began by trying to forecast the weather a day in advance, using the formal theory of how the atmosphere functioned. The first person to try this eventually went off to fight in World War I and never completed the forecast. By the early 1970s, computers had gotten fast enough and models sophisticated enough to forecast the next day's weather in two days—not much help in practice, but a start. At least they knew whether their forecast of yesterday's weather had been right!

Computers are much faster today, and the major theoretical method used today to forecast climate change is a group of computer models called **general circulation**

models (GCMs). Mathematically, these are deterministic differential equation models. The dominant computer models of Earth's climate are all based on the general idea shown in Figure 20.22. The atmosphere is divided into rectangular solids, each a few kilometers high and several kilometers north and south. For each of these, the flux of energy and matter is calculated for each of the adjacent cells. Since there are many cells, and each cell has six sides, a huge number of calculations have to be made. Determining how well these GCMs work is a major challenge because the real test is what the future brings.

Many such computer simulations are in use around the world, but all are very similar mathematically. They all use deterministic differential equations to calculate the rate of exchange of energy and matter among the atmospheric cells. They are all steady-state models, meaning that for any given set of input information about the climate at the beginning, the result will always be the same—there is no chance or randomness involved. These models assume that the climate is in a steady state except for specific perturbations, especially those belived to be caused by human activities. Thus an assumption of these models, and a necessary outcome, is that the climate, if left to itself, will be in balance, in a steady state. This is unlike the real world's global environmental systems, which are inherently non-steady-state—always changing, as we saw at the beginning of this chapter.

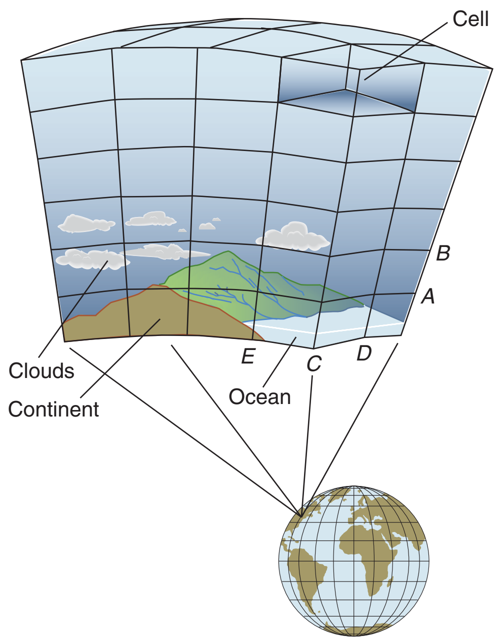


FIGURE 20.22 Idealized diagram of how the huge, general circulation models (models of the entire Earth's climate) are viewed by the computers that run the programs. The atmosphere is divided into hundreds of rectangular cells, and the flow of energy and material is calculated for the transfer between each boundary of every cell to its adjacent cells.

20.12 Potential Rates of Global Climate Change

The global average temperature since 1900 has risen by about 0.8° C (1.5°F).[31] Global surface temperature has risen about 0.2 °C (0.36° F) per decade in the past 30 years.[8] The warmest year since direct surface air temperature has been measured was 2005 (but 2005 will likely be surpassed by 2010 when all data is in). Virtually tied for second were 2002, 2003, 2006, 2007 and 2009. The decade 2001–2010 will be the warmest on record.

According to current GCMs, if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, warming of about 0.1° C per decade would be expected.[30, 31] Based on current and expected rates of CO_2 release by human activities, it is estimated that by 2030 the concentration of carbon dioxide in the atmosphere will be double the pre–Industrial Revolution level. If so, the GCMs forecast that the average global temperature will rise approximately 1°–2°C (2°–4°F), with greater increases toward the poles.[31]

In recent decades, the surface air temperature has risen more in some polar regions, in part because of positive feedback. As snow and ice melt, solar energy that used to be reflected outward by ice and snow is now absorbed by vegetation and water, resulting in enhanced warming. This is termed **polar amplification**.

20.13 Potential Environmental, Ecological, and Human Effects of Global Warming

Changes in River Flow

With a continuation of global warming, melting of glacial ice and reductions in snow cover are anticipated to accelerate throughout the twenty-first century. This is also projected to reduce water availability and hydropower potential, and change the seasonality of flows in regions supplied by meltwater from major mountain ranges (e.g., Hindu-Kush, Himalaya, Andes), where more than one-sixth of the world population currently lives.[31, 32]

California, which depends on snowmelt from the Sierra Nevada for water to irrigate one of the richest agriculture regions in the world, will have problems storing water in reservoirs if these forecasts became true. Rainfall will likely increase, but there will be less snowpack with warming. Runoff, will be more rapid than if snow slowly melts. As a result, reservoirs will fill sooner and more water will escape to the Pacific Ocean. Lower runoff is projected for much of Mexico, South America, southern Europe, India, southern Africa, and Australia.

Rise in Sea Level

The sea level reached a minimum during the most recent glacial maximum. Since then, the sea level has risen slowly. Sea level rises from two causes: (1) Liquid water expands as it warms; and (2) ice sheets on land that melt increase the amount of water in the oceans. Since the end of the last ice age, the sea level has risen approximately 23 cm (about 1 foot) per century. Climatologists forecast that global warming could about double that rate. Various models predict that the sea level may rise anywhere from 20 cm to approximately 2 m (8–80 in) in the next century; the most likely rise is probably 20–40 cm (8–16 in).[31]

About half the people on Earth live in a coastal zone, and about 50 million people each year experience flooding due to storm surges. As the sea level rises and the population increases, more and more people become vulnerable to coastal flooding. The rising sea level particularly threatens island nations (Figure 20.23) and could worsen coastal erosion on open beaches, making structures more vulnerable to damage from waves. This could lead to further investments to protect cities in the coastal zone by constructing seawalls, dikes, and other structures to control erosion. Groundwater supplies for coastal communities could also be threatened by saltwater intrusion (see Chapter 19). In short, coastal erosion is a difficult problem that is very expensive to deal with. In many cases, it is best to allow erosion to take place naturally where feasible and defend against coastal erosion only where absolutely necessary.

Glaciers and Sea Ice

The amount of ice on the Earth's surface changes in complicated ways. A major concern is whether global warming will lead to a great decline in the volume of water stored as ice, especially because melting of glacial ice raises the mean sea level and because mountain glaciers are often significant sources of water for lower-elevation ecosystems. At present, many more glaciers in North America, Europe, and other areas are retreating, than are advancing (Figure 20.24). In the Cascades of the Pacific Northwest and the Alps in Switzerland and Italy, retreats are accelerating. For example, on Mt. Baker in the Northern Cascades of Washington, all eight glaciers on the mountain were advancing in 1976. Today all eight are retreating.[32] If present trends continue, all glaciers in Glacier National Park in Montana could be gone by 2030 and most glaciers in the European Alps could be gone by the end of the century.[33]

Not all melting of glacial ice is due to global warming. For example, the study of decrease in the glacier ice on Mt. Kilimanjaro in Africa shows that the primary cause of the ice loss is not melting. The glaciers of Kilimanjaro formed during African Humid Period about 4,000 to 11,000 years ago. Although there have been wet periods since then—notably in the nineteenth century, which appears to have led to a secondary increase in ice—condition have generally been drier.[34]

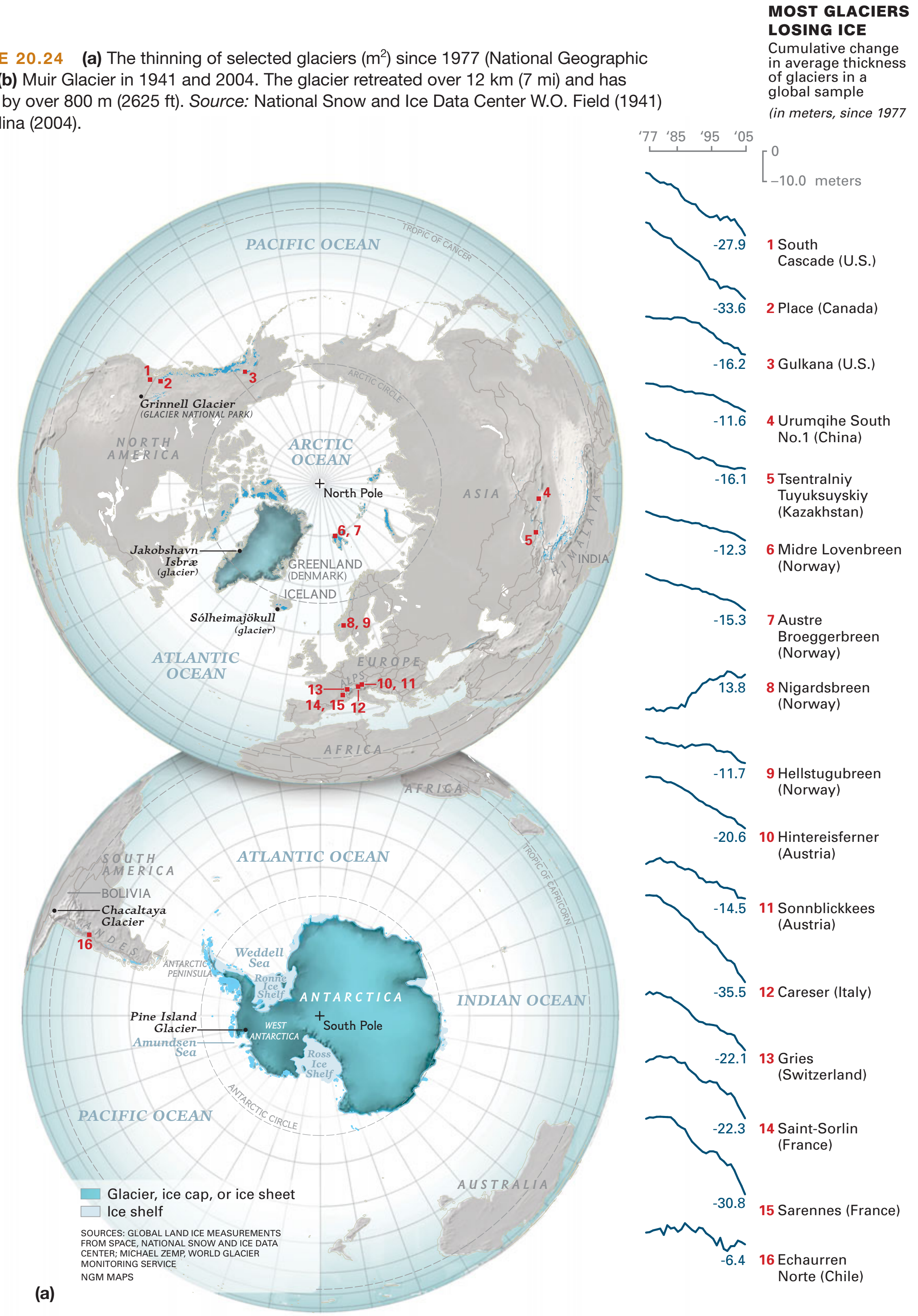
Since they were first observed in 1912, the glaciers of Kilimanjaro have decreased in area by about 80%. The ice is disappearing not from warmer temperatures at the top of the mountain, which are almost always below freezing, but because less snowfall is occurring and ice is being depleted by solar radiation and sublimation (ice is transformed from solid state to water vapor without melting). More arid conditions in the past century led to air that contained less moisture and thus favored sublimation. This may be due to land use changes from native vegetation to agriculture. Much of the ice depletion had occurred by the mid-1950s.[34]

In addition to many glaciers melting back, the Northern Hemisphere sea ice coverage in September, the time of the ice minimum, has declined an average of 10.7% per decade since satellite remote sensing became possible in the 1970s (Figure 20.25). If present trends were to continue, the Arctic Ocean might be seasonally

(a) (b)

FIGURE 20.23 The world's smallest nation, Tuvalu, may succumb to sea-level rise. Tuvalu consists of nine coral islands in the South Pacific, with a total area smaller than Manhattan, and its highest elevation above sea level is 4.5 meters. Sea levels have been rising since the end of the last ice age, a natural response. But global warming could accelerate this rise, making the 12,000 citizens of Tuvalu the world's first sea-level-rise refugees.

FIGURE 20.24 **(a)** The thinning of selected glaciers (m^2) since 1977 (National Geographic Maps); **(b)** Muir Glacier in 1941 and 2004. The glacier retreated over 12 km (7 mi) and has thinned by over 800 m (2625 ft). *Source:* National Snow and Ice Data Center W.O. Field (1941) and Molina (2004).



(a)

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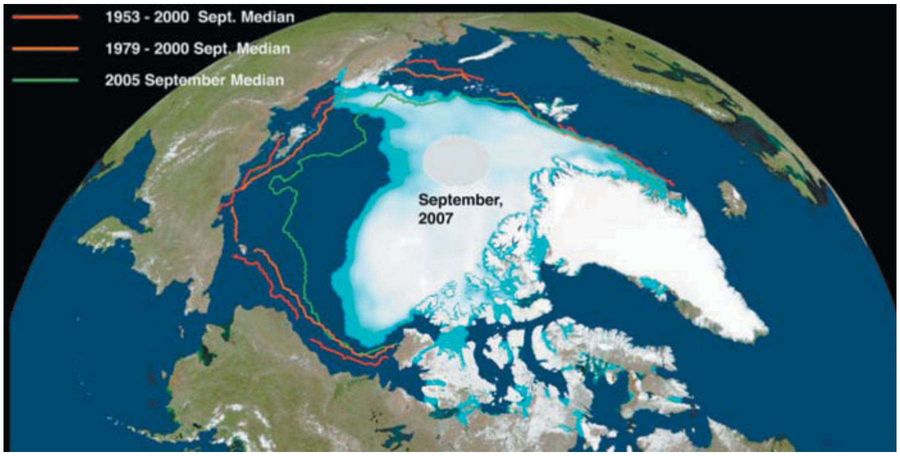

FIGURE 20.25 Satellite observations, which began in 1977, show that Arctic sea ice reached a minimum in September 2007 and has increased since then. The sea ice coverage varies greatly between summer and winter, with July marking the summer minimum. The rapid decline in 2007 was partly due to atmospheric circulation that favored melting. (*Source*: Modified after Stroever et al., 2008. EOS 89 [2] 13–14.)

A CLOSER LOOK 20.1

Some Animals and Plants in Great Britain Are Adjusting to Global Warming

Two of the longest studies of animals and plants in Great Britain show that at least some are adjusting to recent and rapid climate change. The first is a 47-year study of the bird *Parus major*. This study, one of the longest for any bird species, shows that these birds are responding behaviorally to rapid climate change. It's the case of the early bird gets the worm. A species of caterpillar that is one of the main foods of this bird during egg laying has been emerging earlier as the climate has warmed. In response, females of this bird species are laying their eggs an average of two weeks earlier (Figure 20.26). Both birds and caterpillars are doing okay so far.[39]

The second study, one of the longest experiments about how vegetation responds to temperature and rainfall, shows that long-lived small grasses and sedges are highly resistant to climate change. The authors report that changes in temperature and rainfall during the past 13 years "have had little effect on vegetation structure and physiognomy".[40]

These studies demonstrate what ecologists have known for a long time and has been one focus of their studies, as described in Chapters 5, 6, and 7: Individuals, populations, and species have evolved with, are adapted to, and adjust to environmental change, including climate change. However, as we learned from the niche concept, each species persists within a certain range of each environmental condition, so there are limits to the adjustment any one species can make over a short time. Larger changes require biological evolution, which for long-lived animals and plants can take a long time. Whether most species will be able to adjust fast enough to global warming is a hotly debated topic.

FIGURE 20.26 This pretty bird, *Parus major*, a native of Great Britain, is adjusting to rapid climate change.

ice-free by 2030.[35] On the other hand, the central ice cap on Antarctica has grown during the same time. Satellite measurement from 1992 to 2003 suggests the East Antarctica ice sheet increased in mass by about 50 billion tons per year during the period of measurement.[36] As Earth warms, more snow falls on Antarctica.

Changes in sea ice involve more than total area; also involved is the depth of the ice and the age of the ice. The newer the ice, the thinner it is, and therefore the smaller amount of water that is frozen.

The rate of melting of the Greenland ice sheet has doubled since about 1998. As melting produces surface water, it flows into the interior to the base of the ice sheet, causing the ice to flow faster, further destabilizing the ice sheet.[33] It is clear that the polar regions are complex regions on Earth. Changing patterns of ocean and atmosphere circulation in the Arctic and Antarctic regions influence everything from snowfall to melting of glacial and sea ice and movement of glacial ice.[36, 37]

Satellite observations of sea ice became possible in the 1970s . Since then, Northern Hemisphere sea ice reached an observed minimum area covered in September 2007 (Figure 20.25). However, Arctic sea ice has increased since 2007,[19] and so has the central ice cap on Antarctica. Satellite measurement from 1992 to 2003 suggests the East Antarctica ice sheet increased in mass by about 50 billion tons per year during the period of measurement.[36] Changes in sea ice involve more than total area; also involved are the depth of the ice and the age of the ice. The newer the ice, the thinner it is, and therefore the smaller amount of water that is frozen.

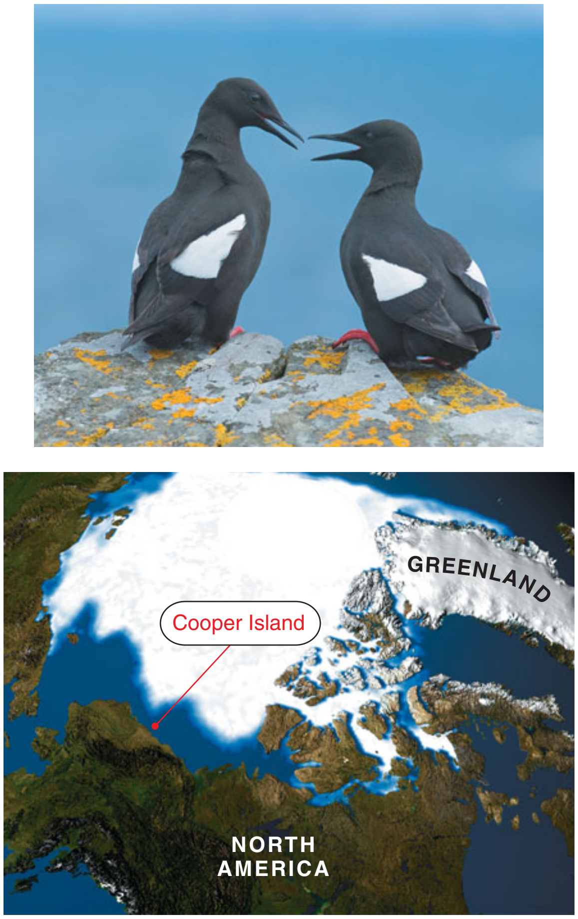

FIGURE 20.27 Black guillemots, medium-size birds also called sea pigeons, nest in the Far North (blue in the map above), including Cooper Island, Alaska.

Changes in Biological Diversity

Some of the greatest uncertainties about the consequence of global warming have to do with changes in biodiversity. This is because organisms are complex and so their responses to change can be complex. Warming is one change, but others—such as availability of nutrients, relations with other organisms (predator and prey), and competition for habitat and niches in ecosystems—also affect biodiversity. Because we lack adequate theoretical models to link specific climate changes to specific changes in overall biodiversity, our best insights come from empirical evidence. Surprisingly few species went extinct as a result of climate change during the past 2.5 million years, even though the amount of changes was about the same as that forecast for today and the next few decades.[38] Warming will certainly change some areas, and plants and animals will experience stress. Many will adapt, as apparently occurred during the Medieval Warm Period (see A Closer Look 20.1). For example, polar bears were undoubtedly stressed during this period but did not become extinct.

On the other hand, black guillemots, birds that nest on Cooper Island, Alaska, illustrate the concerns some scientists have about global warming and certain species (Figure 20.27). The abundance of this species has declined since ternperature increases in the 1990s caused the sea ice to recede farther from Cooper Island each spring. The parent birds feed on Arctic cod found under the sea ice and must then return to the nest to feed their chicks, who are not yet mature enough to survive on their own. For the parents to do this, the distance from feeding grounds to nest must be less than about 30 km, but in recent years the ice in the spring has been receding as much as 250 km from the island. As a result, the black guillemots on the island have lost an important source of food. The future of black guillemots on Cooper Island depends on future springtime weather. Too warm and the birds may disappear; Too cold and there may be too few snow-free days for breeding, in which case they also will disappear.

Agricultural Productivity

Globally, agricultural production will likely increase in some regions and decline in others.[19] In the Northern Hemisphere, some of the more northern areas, such as Canada and Russia, may become more productive. Although global warming might move North America's prime farming climate north from the Midwestern United States to the region of Saskatchewan, Canada, the U.S. loss would not simply be translated into a gain for Canada. Saskatchewan would have the optimum climate for growing, but Canadian soils are thinner and less fertile than the prairie-formed soils of the U.S. Midwest. Therefore, a climate shift could have serious negative effects on midlatitude food production. Meanwhile, lands in the southern part of the Northern Hemisphere may become more arid. Prolonged drought as a result of future warming as evidently occurred during the Medieval warming period (see opening case study) with loss of agricultural productivity could be one of the serious impacts of global warming.

Human Health Effects

Like other biological and ecological responses, the effects of global warrning on human health are difficult to forecast. The IPCC *Climate Change 2007: Synthesis Report* is cautious about these possible effects, stating only that one needs to be thinking about "some aspects of human health, such as excess heat-related mortality in Europe, changes in infectious disease vectors in parts of Europe, and earlier onset of and increases in seasonal production of allergenic pollen in Northern Hemisphere high and mid-latitudes."[31] Some have suggested that global warming might increase the incidence of malaria. However, this has been shown not to be the case in past and present circumstances because temperature alone is not a good correlate for malaria.[41] The same has been found for tick-borne encephalitis, another disease that some thought might increase from global warming.[42]

20.14 Adjusting to Potential Global Warming

People can adjust to the threat of global warming in two ways:

- ***Adapt***: Learn to live with future global climate change over the next 20 years because there is warming in the pipeline from greenhouse gases already emitted.
- ***Mitigate***: Work to reduce the emissions of greenhouse gases and take actions to reduce the undesirable effects of a global warming.

How can carbon dioxide emissions be reduced? Increasing energy conservation and efficiency, along with the use of alternative energy sources, can reduce emissions of carbon dioxide. Rebalancing our use of fossil fuels so that we burn more natural gas would also be helpful because natural gas releases 28% less carbon per unit of energy than does oil and 50% less than coal.[43, 44] Conservation strategies to reduce CO_2 emissions include greater use of mass transit and less use of automobiles; providing larger economic incentives to energy-efficient technology; setting higher fuel-economy standards for cars, trucks, and buses; and establishing higher standards of energy efficiency.

Because clearing forests for agriculture reduces storage of carbon dioxide, protecting the world's forests would help reduce the threat of global warming, as would reforestation.[45]

Geologic (rock) sequestration is another way to reduce the amount of carbon dioxide that would otherwise enter the atmosphere. The idea is to capture carbon dioxide from power plants and industrial smokestacks and inject it into deep subsurface geologic reservoirs. Geologic environments suitable for carbon sequestration are sedimentary rocks that contain saltwater, and sedimentary rocks at the sites of depleted oil and gas fields. To significantly mitigate the adverse effects of CO_2 emissions that result in global warming, we need to sequester approximately 2 gigatons of CO_2 per year.[46]

The process of carbon sequestration involves compressing carbon dioxide and changing it to a mixture of both liquid and gas, then injecting it deep underground. Individual injection projects can sequester approximately 1 million tons of CO_2 per year. A carbon-sequestration project is under way in Norway beneath the North Sea. The carbon dioxide from a large natural-gas production facility is injected approximately 1 km into sedimentary rocks below a natural-gas field. The project, begun in 1996, injects about 1 million tons of CO_2 every year, and it is estimated that the entire reservoir can hold up to about 600 billion tons of CO_2—about as much as is likely to be produced from all of Europe's fossil-fuel plants in the next several hundred years. Sequestering carbon dioxide beneath the North Sea is expensive, but it saves the company from paying carbon dioxide taxes for emissions into the atmosphere.

Pilot projects to demonstrate the potential of sequestering CO_2 in sedimentary rocks have been initiated in Texas beneath depleted oil fields. The storage potential at sites in Texas and Louisiana is immense: One estimate is that 200–250 billion tons of CO_2 could be sequestered in this region.[47]

International Agreements to Mitigate Global Warming

There are several approaches to seeking international agreements to limit greenhouse-gas emissions. One major approach is the international agreement in which each nation agrees to some specific limit on emissions. Another major approach is carbon trading in which a nation agrees to cap its carbon emissions at a certain total amount and then issues emission permits to its corporations and other entities, allowing each to emit a certain quantity. These permits can be traded: For example, a power company that wants to build a new fossil-fuel power plant might trade permits with a company that does reforestation, based on estimates of the amount of CO_2 the power plant would release and of an area of forest that could take up that amount. One of the most important programs of this kind is the European Climate Exchange. Carbon trading in the U.S. has come under criticism from both sides of the debate of what to do about potential global warming. That is should we use "cap and trade or not"? Those in favor argue we need to control CO_2 emissions to be proactive and reduce potential adverse inputs at global warming. Those opposed to cap and trade say the economic impact of reducing emissions and changing energy policy is too expensive and will result in economic disaster.

Attempts to establish international treaties limiting greenhouse-gas emissions began in 1988 at a major scientific conference on global warming held in Toronto, Canada. Scientists recommended a 20% reduction in carbon dioxide emissions by 2005. The meeting was a catalyst for scientists to work with politicians to initiate international agreements for reducing emissions of greenhouse gases.

In 1992, at the Earth Summit in Rio de Janeiro, Brazil, a general blueprint for reducing global emissions was suggested. Some in the United States, however, objected that the reductions in CO_2 emissions would be too costly. Agreements from the Earth Summit did not include legally binding limits. After the meetings in Rio de Janeiro, governments worked to strengthen a climate-control treaty that included specific limits on the amounts of greenhouse gases that each industrialized country could emit into the atmosphere.

Legally binding emission limits were discussed in Kyoto, Japan, in December 1997, but specific aspects of the agreement divided the delegates. The United States eventually agreed to cut emissions to about 7% below 1990 levels, but that was far short of the reductions suggested by leading global warmng scientists, who recommended reductions of 60–80% below 1990 levels. A "Kyoto Protocol" resulted from this meeting, was signed by 166 nations, and became a formal international treaty in February 2006.

In July 2008, the leaders of the G-8 nations, meeting in Japan, agreed to "consider and adopt" reductions of at least 50% in greenhouse gas emissions as part of a new U.N. treaty to be discussed in Copenhagen in 2009. This was the first time the United States agreed in principle to such a reduction (in practice, the United States has not gone along with it).

The United States, with 5% of the world's population, emits about 20% of the world's atmospheric carbon dioxide. The fast-growing economies of China and India are rapidly increasing their CO_2 emissions and are not bound by the Kyoto Protocol. California, which by itself is twelfth in the world in CO_2 emissions, passed legislation in 2006 to reduce emissions by 25% by 2020. Some have labeled the action a "job killer" but environmentalists point out that the legislation will bring opportunity and new jobs to the state. California is often a leader, and other states are considering how to control greenhouse gases. The U.S. (as a mid 2010) had not agreed to any international agreements to address climate change. New energy bills to reduce greenhouse gas emissions and turn to alternative energy to reduce our dependency on fossil fuels have been stopped in Congress. Failure to address global change will compromise our ability to be proactive and require our response to be reactive as change occurs. This is not effective environmental planning.

CRITICAL THINKING ISSUE

What Is Valid Science in the Global Warming Debate?

Modern concerns about global warming began in the 1960s with a scientific inquiry into the possibility that human activities might be able to affect the Earth's climate. But the issue touched on so many aspects of civilization, as well as the activities of individuals, that by 1990 global warming had become an intensely debated political and ideological subject

In November 2009, 1,000 e-mails and 3,000 other documents from computers at the University of East Anglia's Climatic Research Unit were hacked and released to the public. Some people claimed that the e-mails revealed efforts by IPCC scientists to exclude views of others, to withhold scientific data, and to tamper with data (a claim now refuted). In response, some defenders of the IPCC made a request to the U.S. government, under the Freedom of Information Act, to gain access to the e-mails of scientists who were said to oppose global warming. The overall result was to further transform what should have been a scientific inquiry into an even more highly politicized and ideological debate.

In Chapter 2 we discussed the scientific method. It may have seemed somewhat academic at the beginning of this book, but with the current chapter's topic you can see that understanding what is and what is not legitimate science—and what are and are not legitimate scientific findings—can affect many aspects of our lives, from international economics and trade to individual choices about how to travel. Therefore, it is important to think about the scientific method within the context of global warming. If you have the interest, you can investigate this topic broadly, but for our purposes consider the following:

A 2007 IPCC report stated that Himalayan glaciers were in danger of melting as soon as 2035. This report quickly gained wide acceptance. Some glaciers in the central Himalayas are in fact melting fast. The western larger glaciers, however, are growing, as warming has increased snowfall. In 2009, the IPCC withdrew the assertion after it was revealed that the source turned out not to be a peer-reviewed scientific article but a report of the World Wildlife Fund, which in turn was based on an article in a popular magazine in India, whose author later disavowed his offhand speculation.[48]

Scientific study suggest that the huge Himalayan ice fields would take more than 300 years to melt if global warming occurred over the next century as currently forecast by general circulation models. Others that feed water to places like India are melting faster and could impact water resources in less than 100 years.

Critical Thinking Questions

1. If you were in charge of IPCC, overseeing the report writing of many scientists, what precautions would you take to ensure that only the best scientific information got into the publications?
2. Give a general description of the kinds of data and other scientific analysis that could be used to determine the rate at which huge areas of mountain glaciers could melt. (You don't have to learn all about glaciers to answer this question, just consider the information in this chapter about what affects the Earth's climate.)
3. In what ways could laboratory research help you study how fast or how slowly glaciers might melt?
4. Why do you think so much of the climate change debate has moved from the scientific arena to the political arena? What are implications of this shift?

SUMMARY

- The atmosphere, a layer of gases that envelops Earth, is a dynamic system that is constantly changing. A great number of complex chemical reactions take place in the atmosphere, and atmospheric circulation takes place on a variety of scales, producing the world's weather and climates.
- Nearly all the compounds found in the atmosphere either are produced primarily by biological activity or are greatly affected by life.
- Major climate changes have occurred throughout the Earth's history. Of special interest to us is that periodic glacial and interglacial episodes have characterized the Earth since the evolution of our species.
- During the past 1,000 years, several warming and cooling trends have affected civilizations.
- During the past 100 years, the mean global surface air temperature has risen by about 0.8°C. About 0.5°C of this increase has occurred since about 1960.
- Water vapor, carbon dioxide, methane, some oxides of nitrogen, and CFCs are the major greenhouse gases. The vast majority of the greenhouse effect is produced by water vapor, a natural constituent of the atmosphere. Carbon dioxide and other greenhouse gases also occur naturally in the atmosphere. However, especially since the Industrial Revolution, human activity has added substantial amounts of carbon dioxide to the atmosphere, along with such greenhouse gases as methane and CFCs.
- Climate models suggest that a doubling of carbon dioxide concentration in the atmosphere could raise the mean global temperature 1°–2°C in the next few decades and 1.5°C–4.5°C by the end of this century.
- Many complex positive feedback and negative feedback cycles affect the atmosphere. Natural cycles, solar forcing, aerosol forcing, particulate forcing from volcanic eruptions, and El Niño events also affect the temperature of Earth.
- There are concerns based on scientific evidence that global warming is leading to changes in climate patterns, rise in sea level, melting of glaciers, and changes in the biosphere. A potential threat from future warming, as in the Medieval Warm Period, is the occurrence of prolonged drought that would compromise our food supply.
- Adjusting to global warming includes learning to live with the changes and attempting to mitigate warming by reducing emissions of greenhouse gases.

REEXAMINING THEMES AND ISSUES

Human Population

Burning of fossil fuels and trees has increased emissions of carbon dioxide into the atmosphere. As the human population increases and standards of living rise, the demand for energy increases; and, as long as fossil fuels are used, greenhouse gases will also increase.

Sustainability

Through our emissions of greenhouse gases, we are conducting global experiments, the final results of which are difficult to predict. As a result, achieving sustainability in the future will be more difficult. If we do not know in detail what the consequences or magnitude of human-induced climate change will be, then it is difficult to predict how we might achieve sustainable development for future generations.

Global Perspective

Global warming is a global problem.

Urban World

If sea levels rise as climate models forecast coastal cities will be affected by higher storm surges. Rising air temperatures can accentuate urban heat-island effects, making life in cities more unpleasant in the summer. If global warming reduces the availability of freshwater, cities will feel the impact.

People and Nature

Our ancestors adapted to natural climate change over the past million years. During that period, Earth experienced glacial and interglacial periods that were colder and warmer than today. Burning fossil fuels has led to human-induced climate changes different in scope from past human effects.

Science and Values

Responding to global warming requires choices based on value judgments. Scientific information, especially geologic data and the instrumental (historic) record along with modern computer simulations, is providing a solid foundation for the belief that global warming is happening. The extent to which scientific information of this kind is accepted involves value decisions.

KEY TERMS

atmosphere **434**
barometric pressure **435**
climate **431**
climate forcing **447**
general circulation models (GCMs) **451**
greenhouse effect **441**
greenhouse gases **433**
polar amplification **451**
radionuclides **446**
stratosphere **434**
troposphere **434**
uniformitarianism **450**
weather **431**

STUDY QUESTIONS

1. Summarize the scientific data that global warming as a result of human activity is occuring.
2. What is the composition of Earth's atmosphere, and how has life affected the atmosphere during the past several billion years?
3. What is the greenhouse effect? What is its importance to global climate?
4. What is an anthropogenic greenhouse gas? Discuss the various anthropogenic greenhouse gases in terms of their potential to cause global warming.
5. What are some of the major negative feedback cycles and positive feedback cycles that might increase or decrease global warming?
6. In terms of the effects of global warming, do you think that a change in climate patterns and storm frequency and intensity is likely to be more serious than a global rise in sea level? Illustrate your answer with specific problems and areas where the problems are likely to occur.
7. How would you refute or defend the statement that the best adjustment to global warming is to do little or nothing and learn to live with change?

FURTHER READING

Fay, J. A., and D. Golumb, *Energy and the Environment* (New York: Oxford University Press, 2002). See Chapter 10 on global warming.

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