



In the last 0.00002% of Earth's history, humanity has modified much of this planet's surface. The land cover, drainage, and vegetation of this landscape in China have all been changed dramatically due to human activity.

Chapter Objectives

By the end of this chapter you should know . . .

- why the Earth is a dynamic planet and ways that it can change.
- that some changes in the Earth System are unidirectional whereas others are cyclic and that some changes are gradual and some are catastrophic.
- during biogeochemical cycles, elements or compounds flow among various reservoirs.
- how the climate has changed significantly over geologic time, and how greenhouse gases play an important role in regulating the climate.
- how humans have significantly changed aspects of the Earth System.
- that addition of greenhouse gases during the past two centuries can cause warming.

*All we in one long caravan
are journeying since the world began,
we know not whither, we know . . . all must go.*

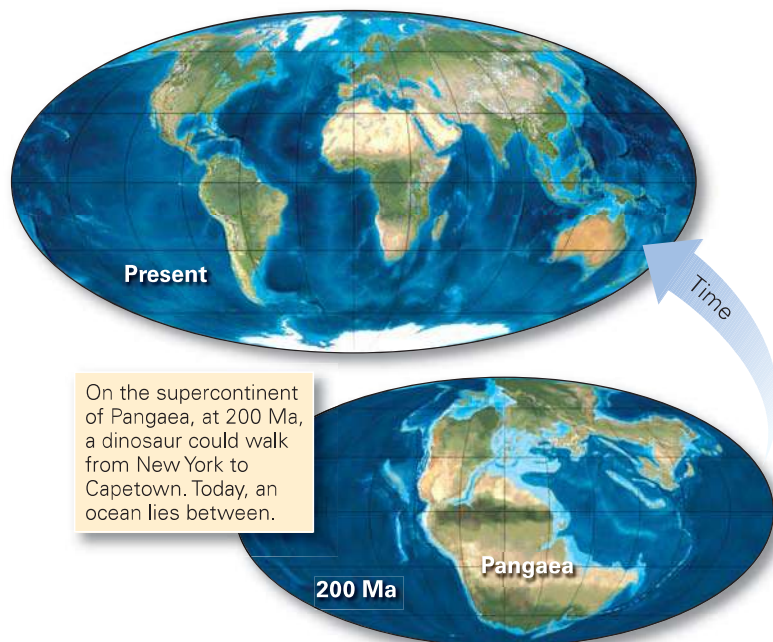
—Bhartrihari (Indian poet, ca. 500 C.E.)

19.1 Introduction

Did the Earth's surface look the same in the Jurassic Period as it does today? Definitely not! During the Jurassic, the North Atlantic Ocean was a narrow sea and the South Atlantic Ocean didn't exist at all, so most dry land connected to form a single vast continent (**Fig. 19.1**). Today, both parts of the Atlantic are wide oceans, and the Earth has seven separate continents. Moreover, during the Jurassic, the call of the wild rumbled from the throats of dinosaurs, whereas today, the largest land animals are mammals. In essence, what we see of the Earth today is just a snapshot, an instant in the life story of a constantly changing planet. This idea arguably stands as geology's greatest philosophical contribution to humanity's understanding of our Universe.

Why has the Earth changed so much over geologic time, and why can it continue to change? Ultimately, change happens both because the Earth's internal heat makes the asthenosphere weak enough to flow, and because the Sun's heat keeps most of the Earth's surface at temperatures above the freezing point of water. Flow in the asthenosphere permits plate

FIGURE 19.1 The map of Earth's surface changes over time because of plate motions.



tectonics, which in turn leads to continental drift, volcanism, and mountain building. Solar heat, along with gravity, keeps streams, glaciers, waves, and wind in motion, thereby causing erosion and deposition. Solar warmth plays an additional role by keeping the Earth's surface and near-surface regions at conditions appropriate for sustaining life. If the Earth did not have just the right mix of tectonic activity and solar heat, it would be a frozen dust bowl like Mars, a crater-pocked wasteland like the Moon, or a cloud-choked oven like Venus.

Many of the changes that take place on Earth reflect complex interactions among geologic and biological phenomena. For example, photosynthetic organisms affect the composition of the atmosphere by providing oxygen, and atmospheric composition in turn determines the nature of chemical weathering reactions that take place in rocks. We've referred to the global interconnecting web of physical and biological phenomena on Earth as the *Earth System* (see **Geology at a Glance**, pp. 548–549). We can now define **global change** as transformations or modifications of physical and biological components in the Earth System through time.

Geologists distinguish among different types of global change, on the basis of the rate or way in which change progresses with time. *Gradual* change takes place over long periods of geologic time (millions to billions of years). *Catastrophic* change takes place relatively rapidly in the context of geologic time (seconds to millennia). *Unidirectional* change involves transformations that never repeat. *Cyclic* change repeats the

same steps over and over, though not necessarily with the same results. Some types of cyclic change are periodic, in that the cycles happen with a definable frequency; others are not.

In this chapter, we begin by reviewing examples of global change involving phenomena discussed earlier in this book. Then we introduce the concept of a biogeochemical cycle, the exchange of chemicals among various living and nonliving reservoirs, for some kinds of global change reflect changes in the proportions of chemicals held in different reservoirs through time. Finally, we focus on global climate change, transformations or modifications in Earth's climate over time. We conclude this chapter, and this book, by considering hypotheses that describe the ultimate global change—the end of the Earth in the distant future.

19.2 Unidirectional Changes

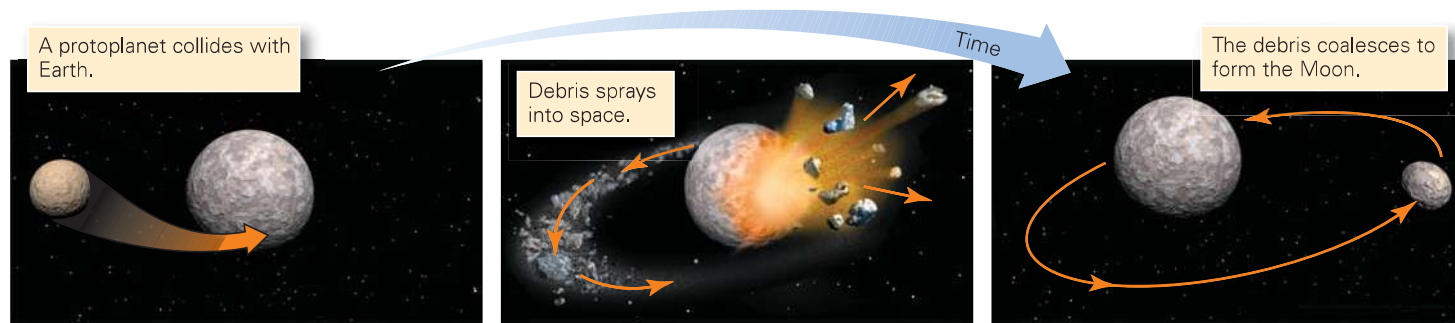
The Evolution of the Solid Earth

Recall from Chapter 1 that Earth began as a fairly homogeneous mass, formed by the coalescence of planetesimals. But the homogeneous proto-Earth did not last long—within about 100 million years of its birth, or even as it formed, the planet began to melt, yielding liquid iron alloy that sank rapidly to the center to form the core. This process of **differentiation** represents major unidirectional change: it produced a layered planet with an iron alloy core surrounded by a rocky mantle.

According to one supported model, a protoplanet appears to have collided with the rapidly spinning newborn Earth soon after differentiation. This collision caused a catastrophic change—a significant portion of the Earth and the colliding object fragmented and vaporized, creating a ring of debris that quickly coalesced to form the Moon (**Fig. 19.2**). After the collision, the Earth's mantle was probably partially molten, and the planet's surface became a sea of magma. The Earth endured intense bombardment by asteroids and comets between about 4.0 and 3.9 Ga, so any crust that had formed prior to 3.9 Ga was largely pulverized, melted, and recycled. Eventually, however, bombardment ceased and our planet gradually cooled, permitting a crust to stabilize at its surface and plate tectonics to begin operating. Over time, igneous activity produced lasting continental crust. Differentiation, Moon formation, and crust formation all represent major unidirectional changes that took place in the first 600 million or so years of Earth's history.

The Evolution of the Atmosphere and Oceans

Like its surface, the Earth's atmosphere has also changed unidirectionally over time. It initially formed from gases released by volcanic activity. More gases may have arrived when comets

FIGURE 19.2 The formation of the Moon is an example of a catastrophic unidirectional change.

collided with our new planet. Eventually, Earth accumulated an early atmosphere composed dominantly of carbon dioxide (CO_2) and water (H_2O). Other gases, such as nitrogen (N_2), composed only a minor proportion of the early atmosphere. When the

Did you ever wonder ...
has the Earth's atmosphere
always been breathable?

Earth's surface cooled, however, water condensed and fell as rain, collecting in low areas to form oceans. This may have happened before 4.0 Ga, but it had certainly happened by 3.8 Ga. Gradually, CO_2 dissolved in the oceans and was absorbed by chemical-weathering reactions on land, so its concentration in the atmosphere decreased. Nitrogen, which doesn't react with other chemicals, was left behind. Thus, the atmosphere's composition changed to become dominated by nitrogen. Photosynthetic organisms appeared early in the Archean. But it probably wasn't until between 2.5 and 2.0 Ga, the early Proterozoic, that oxygen (O_2) became a significant proportion of the atmosphere and it didn't reach breathable concentrations for another billion years.

The Evolution of Life

During most of the Hadean Eon, Earth's surface was probably lifeless, for carbon-based organisms could not survive the high temperatures of the time. The fossil record indicates that life had appeared at least by 3.8 billion years ago and has undergone unidirectional change (evolution) in fits and starts ever since (see Interlude E). Though simple organisms such as archaea and bacteria still exist, life evolution during the late Proterozoic and early Phanerozoic yielded multicellular plants and animals. Life now inhabits regions from a few kilometers below the surface to a few kilometers above, yielding a diverse and complex biosphere.

Take-Home Message

Since it first formed, the Earth has undergone major changes that are unidirectional, in that they will never repeat. Examples include internal differentiation (core formation), Moon formation, atmospheric evolution, ocean formation, and life evolution.

19.3 Physical Cycles

The Supercontinent Cycle

During Earth history, the map of the planet's surface has constantly changed. At times, almost all continental crust merged to form a single supercontinent, but usually the crust is distributed among several smaller continents. The process of change during which a supercontinent forms and later breaks apart is the **supercontinent cycle**. Geologists have found evidence that supercontinents existed at least three or four times during the past 3 billion years of Earth history—no two were alike. The most recent supercontinent, Pangaea, formed at the end of the Paleozoic Era.

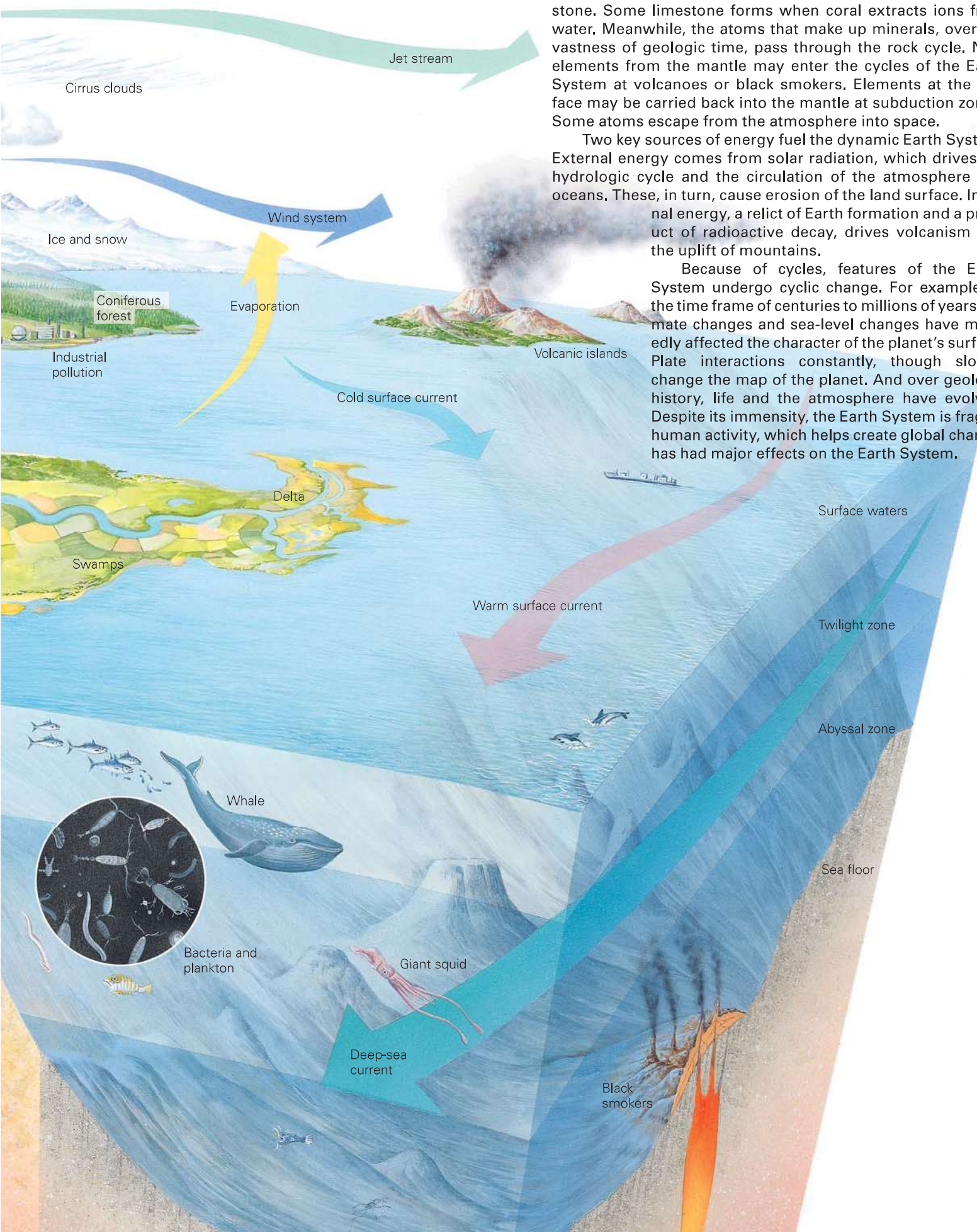
The Sea-Level Cycle

Global sea level rose and fell by as much as 300 m during the Phanerozoic, and likely did the same in the Precambrian. When sea level rises, the shoreline migrates inland, and low-lying plains in the continents become submerged. In fact, during periods of particularly high sea level, more than half of Earth's continental area can become covered by shallow seas; at such times, sediment buries continental regions. When sea level falls, the continents become dry again, and regional unconformities develop.

After studying sedimentary sequences around the world, geologists have pieced together a chart defining the succession of global transgressions and regressions during the Phanerozoic Eon. The global sedimentary cycle chart may largely reflect the cycles of *eustatic* (worldwide) sea-level change (Fig. 19.3). However, the chart probably does not give us an exact image of sea-level change, because the sedimentary record reflects other factors as well, such as changes in sediment supply, and remains controversial. Eustatic sea-level changes may be due to a variety of factors, including advances and retreats of continental glaciers, changes in the volume of mid-ocean ridge systems, and changes in continental elevation and area.

The Earth System



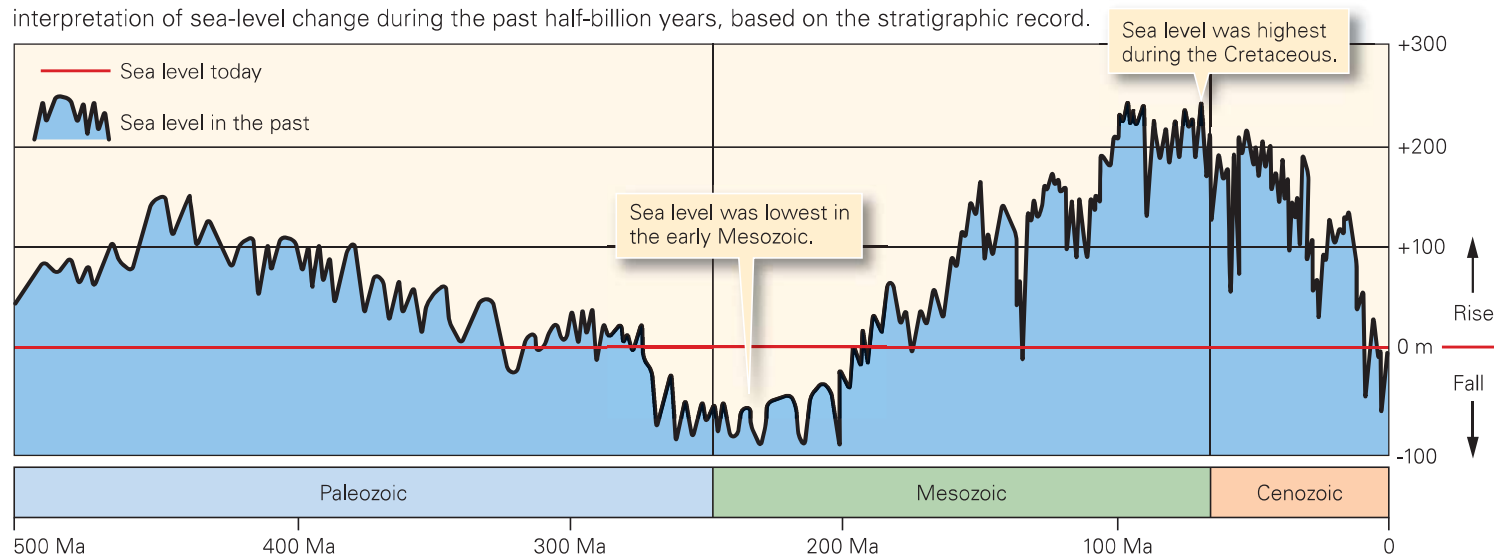


in the air, dissolved in water, or trapped in plants, coal, or limestone. Some limestone forms when coral extracts ions from water. Meanwhile, the atoms that make up minerals, over the vastness of geologic time, pass through the rock cycle. New elements from the mantle may enter the cycles of the Earth System at volcanoes or black smokers. Elements at the surface may be carried back into the mantle at subduction zones. Some atoms escape from the atmosphere into space.

Two key sources of energy fuel the dynamic Earth System. External energy comes from solar radiation, which drives the hydrologic cycle and the circulation of the atmosphere and oceans. These, in turn, cause erosion of the land surface. Internal energy, a relict of Earth formation and a product of radioactive decay, drives volcanism and the uplift of mountains.

Because of cycles, features of the Earth System undergo cyclic change. For example, in the time frame of centuries to millions of years, climate changes and sea-level changes have markedly affected the character of the planet's surface. Plate interactions constantly, though slowly, change the map of the planet. And over geologic history, life and the atmosphere have evolved. Despite its immensity, the Earth System is fragile; human activity, which helps create global change, has had major effects on the Earth System.

FIGURE 19.3 Sea-level change, and its manifestations, over geologic time. This chart provides one interpretation of sea-level change during the past half-billion years, based on the stratigraphic record.



The Rock Cycle

We learned early in this book that the crust of the Earth consists of three rock types: igneous, sedimentary, and metamorphic. Atoms making up the minerals of one rock type may later become part of another rock type. In effect, rocks are simply reservoirs of atoms, and the atoms can move from reservoir to reservoir over time. Each stage in the rock cycle changes the Earth by redistributing and modifying material.

Take-Home Message

Some changes in the Earth System are cyclic in that they have stages that may be repeated. Examples include the supercontinent cycle (accumulation of continents by collision, and then dispersal by rifting), the sea-level cycle (rise and fall of the sea), and the rock cycle.

19.4 Biogeochemical Cycles

A **biogeochemical cycle** involves the passage of a chemical among nonliving and living reservoirs in the Earth System, mostly on or near the planet's surface. Nonliving reservoirs include the atmosphere, the crust, and the ocean; living reservoirs include plants, animals, and microbes. Although a great variety of chemicals (water, carbon, oxygen, sulfur, ammonia, phosphorus, and nitrogen) participate in biogeochemical cycles, here we look at only two: water (H_2O) and carbon (C).

Some stages in a biogeochemical cycle may take only hours, some may take thousands of years, and others may take millions of years. The transfer of a chemical from reservoir to reservoir during these cycles doesn't really seem like a change in the Earth in the way that the movement of continents or

the metamorphism of rock seems like a change. In fact, for intervals of time, biogeochemical cycles attain a **steady-state condition**, meaning that the proportions of a chemical in different reservoirs remain fairly constant even though there is a constant flux (flow) of the chemical among reservoirs. When we speak of global change in a biogeochemical cycle, we mean a change in the relative proportions of a chemical held in different reservoirs at a given time—in other words, a change in the steady-state condition.

The Hydrologic Cycle

As we learned in Interlude F, the hydrologic cycle involves the movement of water from reservoir to reservoir on or near the surface of the Earth. The hydrologic cycle is an example of a biogeochemical cycle in that a chemical (H_2O) passes through both nonliving and living entities—the oceans, the atmosphere, surface water, groundwater, glaciers, soil, and living organisms. Global change in the hydrologic cycle occurs primarily when a change in global climate alters the ratio between the amount of water held in the ocean and the amount held in continental ice sheets. For example, during an ice age, water that had been stored in oceans moves into glacial reservoirs. Thus, the continents become covered with ice, and sea level drops. When the climate warms, water returns to the oceans, and sea level rises.

The Carbon Cycle

Most carbon in the near-surface realm of Earth originally bubbled out of the mantle in the form of CO_2 gas released by volcanoes (Fig. 19.4). Once it enters the atmosphere, it can be removed in various ways. Some dissolves in seawater to form bicarbonate (HCO_3^-) ions, whereas some is absorbed by photosynthetic organisms that convert it to sugar and other organic chemicals. This carbon enters the food chain and ultimately

makes up the flesh, fat, and sinew of animals. Some of the reactions that take place when rock undergoes chemical weathering incorporate atmospheric CO_2 and thus also remove carbon from the atmosphere.

Some carbon returns directly to the atmosphere through the respiration of animals (again as CO_2), by the flatulence of animals as methane (CH_4), or by the decay (oxidation) of dead organisms. But some can be stored for long periods of time in fossil fuels (oil and coal), in organic shale, in methane hydrates, or in limestone. These reservoirs contain most of the carbon in the near-surface realm of Earth and can hold on to it for long periods of time. But the carbon in these reservoirs can return to the atmosphere in the form of CO_2 due to the burning of fossil fuels and due to the metamorphism of rocks containing carbonate, or it can return to the sea after undergoing dissolution in river water or groundwater.

Take-Home Message

In the Earth System, chemicals—such as carbon and water—cycle through living and nonliving reservoirs. CO_2 gas in the atmosphere can dissolve in seawater to form bicarbonate ions, or be trapped in rock as calcite or as fossil fuel (oil, gas, and coal).

19.5 Global Climate Change

The **climate** is the average range of weather conditions (such as temperature, humidity, wind speed, and seasonality) for a given region. **Global climate change**, the transformation of

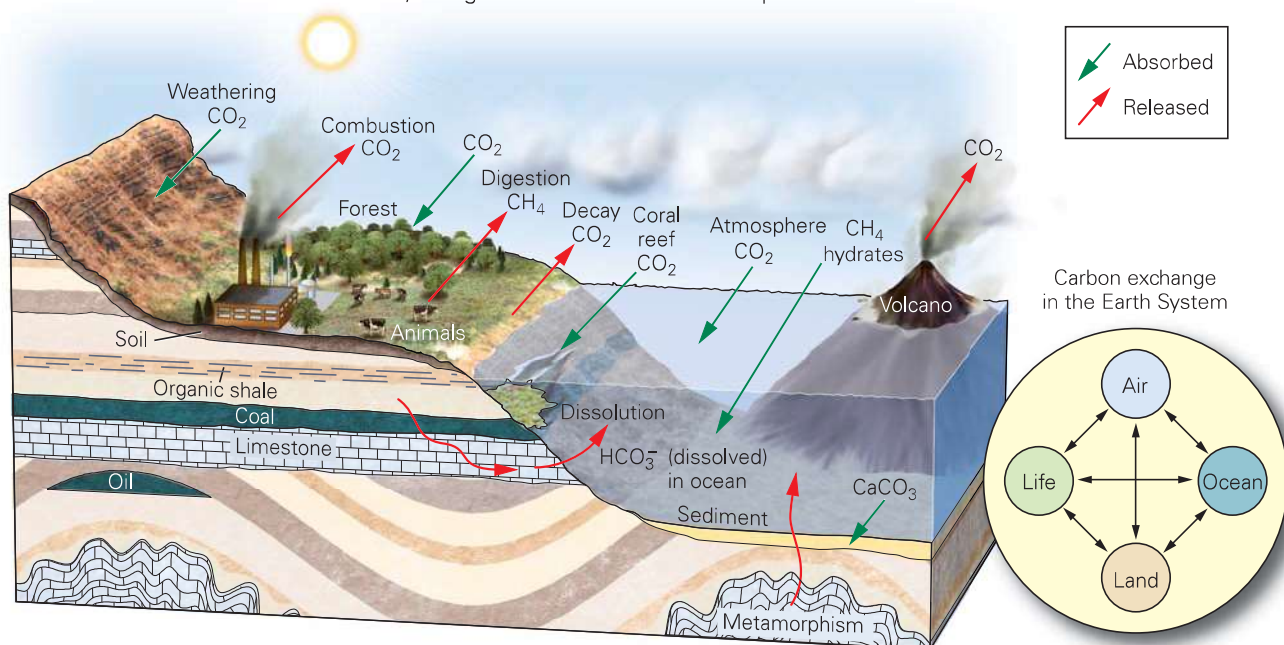
Earth's climate over time, has happened repeatedly throughout Earth's history for natural reasons. Measurements indicate that global climate change is now occurring, and that human activities may be a cause.

For purposes of discussion, we distinguish between *long-term climate change*, which takes place over millions to tens of millions of years, and *short-term climate change*, which takes place over tens to thousands of years. If the average atmospheric and sea-surface temperature rises, we have **global warming**, and if it falls, we have **global cooling**. Below, we discuss how researchers study climate change and how their observations characterize long-term and short-term changes.

Methods of Study

Geologists and climatologists are working hard to define the nature of climate change, the rates at which change can take place, and the effects that change may have on our planet. There are three basic approaches to studying global climate change: (1) researchers measure past climate change, as indicated by the stratigraphic record, to document the magnitude of changes that have happened, the rate at which such changes occurred, and the consequence of such changes; (2) researchers conduct experiments and calculations to see how changes in atmospheric components, such as CO_2 (Box 19.1) or dust, might affect climate; (3) researchers develop computer programs to calculate how factors such as atmospheric composition, topography, ocean currents, and Earth's orbit affect the circulation of the atmosphere and, therefore, the distribution of climate belts. They then use such **general circulation models (GCMs)** to develop computer-generated **climate-change models** in order to provide insight into when and

FIGURE 19.4 In the carbon cycle, carbon transfers among various reservoirs at or near the Earth's surface. Red arrows indicate release to the air, and green arrows indicate absorption from air.



The Role of Greenhouse Gases

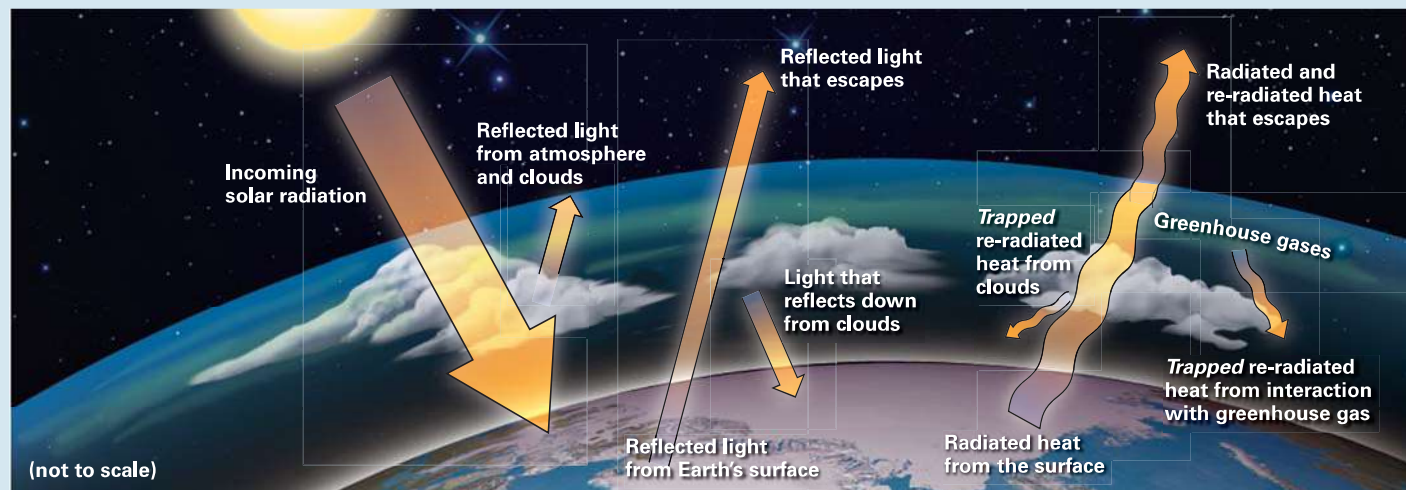
The Sun constantly bathes the Earth in visible light. Some of this energy reflects off the atmosphere and the Earth's surface, so that our planet shines when viewed from space. The Earth's surface absorbs the remainder of the incoming visible light, and then releases it in the form of thermal energy (infrared radiation) that heads back upward. If the Earth had no atmosphere, all of this thermal energy would escape back into space. But our planet does have an atmosphere, and certain gases in air absorb thermal radiation and re-radiate it. Some of

the re-radiated energy continues up into space, but some heads downward and warms the lower atmosphere (Fig. Bx 19.1). In effect, these gases trap infrared radiation and keep the lower atmosphere warm, somewhat like the way glass traps heat in a greenhouse. Thus, the overall trapping process is called the **greenhouse effect**, and the gases (such as H_2O , CO_2 , and CH_4) that cause it are called **greenhouse gases**.

Warming or cooling due to changes in the concentration of greenhouse gases can be amplified by positive or negative **feed-**

back mechanisms. Negative feedback slows a process down or even reverses it, whereas positive feedback enhances a process and amplifies its consequences. Let's consider an example of a feedback mechanism involving the greenhouse effect. Imagine that global average atmospheric temperature has increased due to an increase in CO_2 . This increase will, in turn, cause the oceans to warm and evaporate more, so more water transfers into the atmospheric reservoir globally, causing still more warming—this is a positive feedback.

FIGURE Bx19.1 The greenhouse effect shows how thermal energy can be trapped in the atmosphere.



why changes took place in the past, and to predict how rainfall, sea level, ice cover, and other physical phenomena may be influenced by the warming or cooling of the atmosphere.

Did you ever wonder . . . how do researchers study past climates on Earth?

Let's look first at how geologists study the **paleoclimate** (past climate), so as to document climate changes throughout Earth history. Any feature whose character depends on the climate and whose age can be determined can be a clue to defining paleoclimate.

➤ **The stratigraphic record:** The nature of sedimentary strata deposited at a certain location reflects the climate at that location. For example, a bed of coal represents deposits of a warm climate, whereas a bed of till represents deposits of a glacial climate.

➤ **Paleontological evidence:** Different assemblages of species survive in different climatic belts. Thus, the succession of fossils in a sedimentary sequence provides clues to the changes in climate at that site. For example, a record of short-term climate change can be obtained by studying the succession of plankton fossils in sea-floor sediments, for cold-water species of plankton are different from warm-water species. Fossil plant pollen preserved in the mud of bogs also provides information about paleoclimate, because different plant species live in different climates (Fig. 19.5a). Pollen studies show, for example, that spruce forests, indicative of cool climates, have slowly migrated north since the last ice age (Fig. 19.5b).

➤ **Oxygen-isotope ratios:** Geologists have found that the ratio of ^{18}O to ^{16}O in glacial ice indicates the atmospheric temperature in which the snow that made up the ice formed: simplistically, the ratio is larger in snow that forms in warmer air,

but smaller in snow that forms in colder air. Because of this relationship, the isotope ratio of the oxygen in H_2O measured in a succession of ice layers in a glacier indicates temperature change over time. Researchers have now obtained ice cores down to a depth of almost 3 km in Antarctica and in Greenland; this record spans up to 720,000 years (Fig. 19.6a). For similar reasons, the $^{18}\text{O}/^{16}\text{O}$ ratio in the CaCO_3 making up plankton shells also gives geologists an indication of past temperatures. Thus, measurement of oxygen–isotope ratios in drill cores of marine sediment extends the record of temperature change back over millions of years (Fig. 19.6b, c).

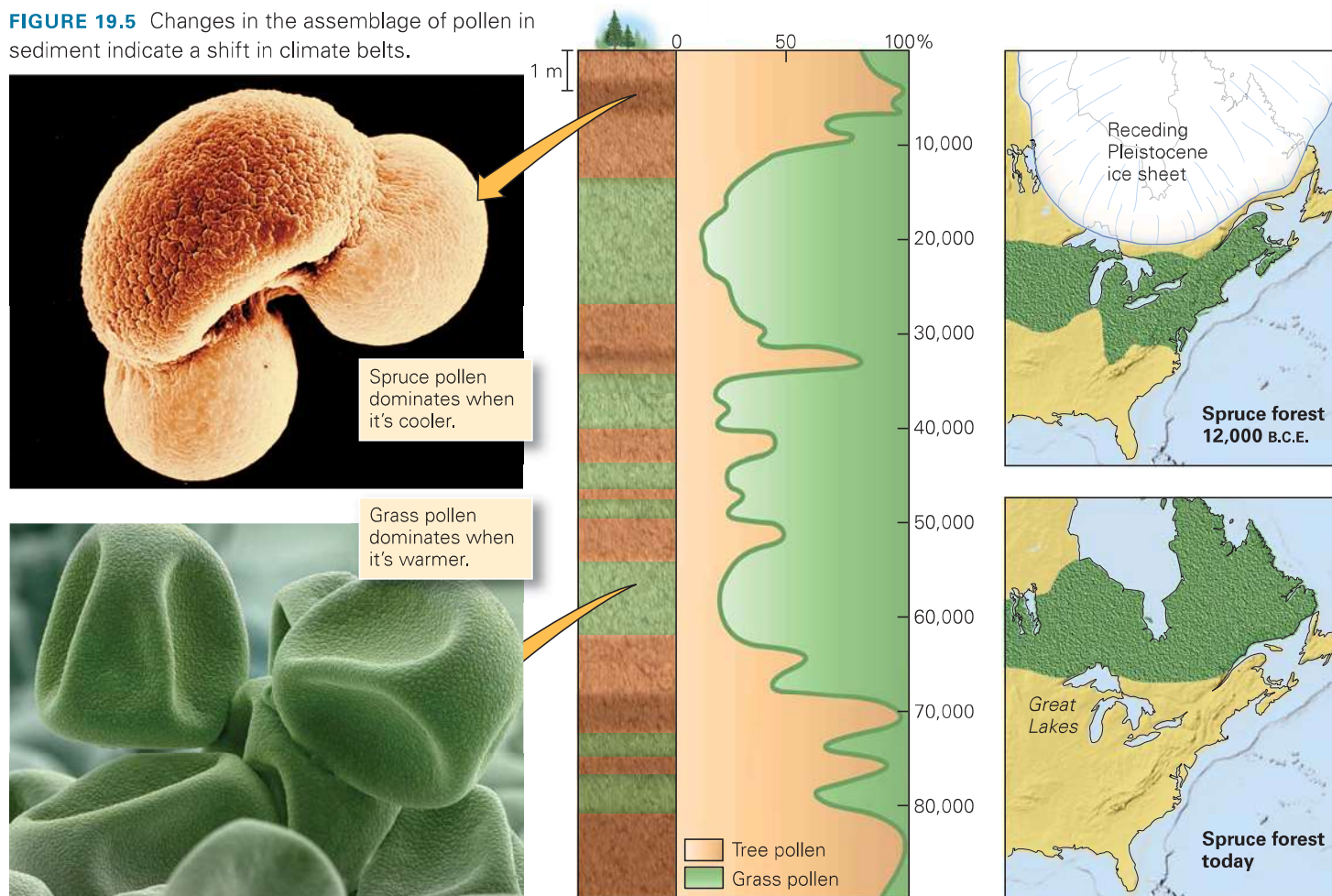
- **Growth rings:** If you've ever looked at a tree stump, you'll have noticed the concentric rings visible in the wood. Each ring represents one year of growth, and the thickness of the ring indicates the rate of growth in a given year. Trees grow faster during warmer, wetter years and more slowly during cold, dry years. Thus, the succession of ring widths provides a record of climate during the lifetime of the tree. Growth rings in corals and shells can provide similar information.
- **Human history:** Researchers have been able to make careful, direct measurements of climate changes only for the past few decades. This record is not long enough to document

long-term climate change. But history, both written and archaeological, contains important clues to climates at times in the past. Periods of unusual cold or drought leave an impression on people, who record them in paintings, stories, and records of crop success or failure.

Long-Term Climate Change

Using the variety of techniques described above, geologists have reconstructed an approximate record of global climate, represented by mean global temperature, for geologic time. The record shows that Earth's surface temperature has stayed between the freezing point of water and the boiling point of water since the beginning of the Archean. But at times in the past, the Earth's atmosphere was significantly warmer than it is today, whereas at other times, it was significantly cooler. The warmer periods have come to be known as **greenhouse periods** (or hothouse periods) and the colder ones as **icehouse periods**. (The more familiar term, *ice age*, refers to the times during an icehouse period when the Earth was cold enough for ice sheets to advance and cover substantial areas of the continents.) As the chart in Figure 19.7 shows, at least five major icehouse periods have occurred during geologic time.

FIGURE 19.5 Changes in the assemblage of pollen in sediment indicate a shift in climate belts.



(a) The proportion of tree pollen relative to grass pollen can change in a sedimentary sequence through time. Researchers plot changes in the proportion of pollen types over time by examining samples from a column of sediment. A higher proportion of grass pollen indicates warmer climate.

(b) Spruce forests (green) grew farther south 12,000 years ago than they do today.

What caused long-term global climate changes? The answer may lie in the complex relationships among the various solar, geologic, and biogeochemical components of the Earth System, as described earlier. For example:

- *Positions of continents:* Continental drift influences the climate by controlling the pattern of oceanic currents, which redistribute heat around the planet's surface. Drift also determines whether the land is at high or low latitudes (and thus how much solar radiation strikes it), whether or not there are large continental interior regions where extremely cold winter temperatures can develop, and/or whether there is a lot of rainfall that could cause weathering.
- *The uplift of land surfaces:* Tectonic events that lead to the long-term uplift of the land affect atmospheric CO_2 concentration, because such events expose land to weathering, and chemical-weathering reactions absorb CO_2 . Such uplift will also affect atmospheric circulation and rainfall rates.
- *The formation of coal and oil:* At various times during Earth history, environments suitable for coal and oil formation have been particularly widespread. Such formation removes CO_2 from the atmosphere and may result in global cooling.

The cooling that occurred in the late Paleozoic, a time when coal swamps were abundant, may be a manifestation of the process.

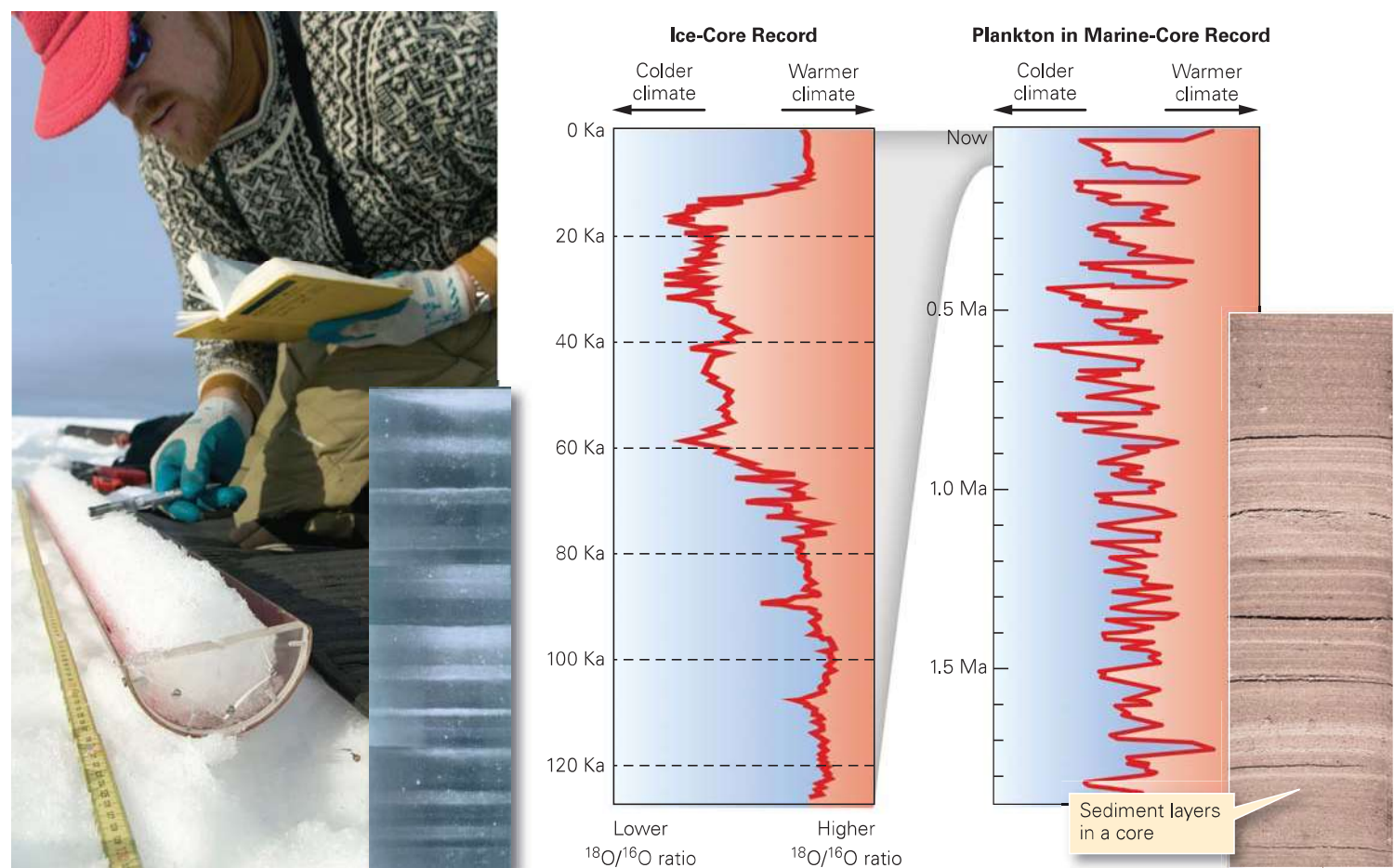
- *Life evolution:* The appearance or extinction of certain life forms may have affected climate significantly by removing or adding CO_2 from the atmosphere.

It is important to note the feedback among some of the above phenomena. For example, if global temperature rises due to an increase in CO_2 , then rates of evaporation and therefore amounts of rainfall increase. As a consequence, weathering rates (which absorb CO_2) increase, so the concentration of CO_2 may then go down (a negative feedback).

Natural Short-Term Climate Change

So far, we've emphasized how climate has changed over periods of tens to hundreds of millions of years. The geologic record of the past few million years provides enough detail to allow us to detect cycles of climate change that have durations of centuries to hundreds of thousands of years. Such short-term climate change events must be a consequence of factors that can operate quickly in the context of geologic time.

FIGURE 19.6 The proportion of isotopes transferred between reservoirs during evaporation or precipitation depends on temperature. The $^{18}\text{O}/^{16}\text{O}$ ratio can be studied in glacial ice (H_2O) and fossil shells (CaCO_3).



(a) A researcher examines an ice core in the field. Lab photos reveal annual layers.

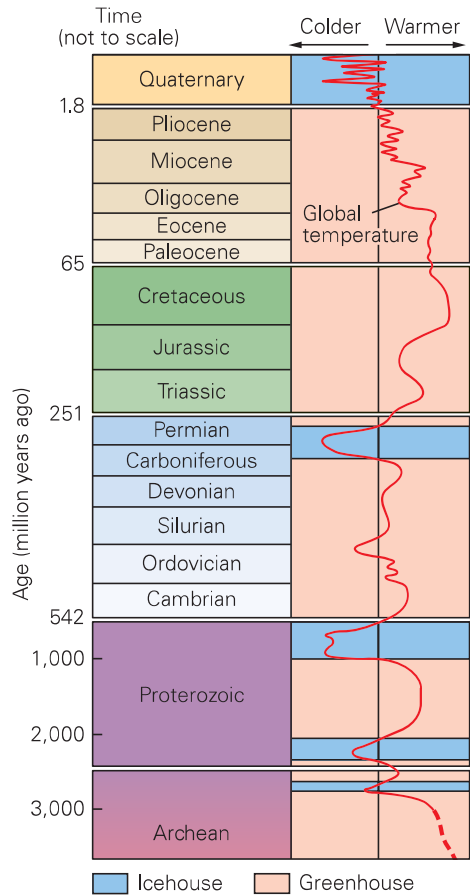
(b) The $^{18}\text{O}/^{16}\text{O}$ ratios in an ice core represent temperature changes.

(c) Studies of $^{18}\text{O}/^{16}\text{O}$ ratios in deep-sea cores also provide a climate record.

We can get a sense of short-term climate change events by considering the Pleistocene stratigraphic record. Changes in fossil assemblages, sediment composition, and isotopic ratios of minerals indicate that continental glaciers advanced and retreated about 20 to 30 times in the northern hemisphere. Each advance (glaciation) represents an interval of global cooling, and each retreat (interglacial) represents an interval of global warming. If we focus on the last 15,000 years, a period that includes all of the Holocene, we see trends of cooling or warming that last thousands of years, within which there are events whose duration lasts centuries or less (Fig. 19.8a).

Specifically, the time between about 15,000 and 10,500 B.C.E. was a warming period, during which the last ice-age glaciers retreated. This warming trend was followed by the Younger Dryas, an interval of cooler temperatures named for an Arctic flower that became widespread during the interval. Then, climate warmed again, reaching a peak at 5,000 to 6,000 years ago, a period called the Holocene maximum, when average temperatures were about 2°C above temperatures of today. This warming peak led to increased evaporation and therefore precipitation, making the Middle East unusually wet and fertile—conditions that may partially account for the rise of civilization in this part of the world.

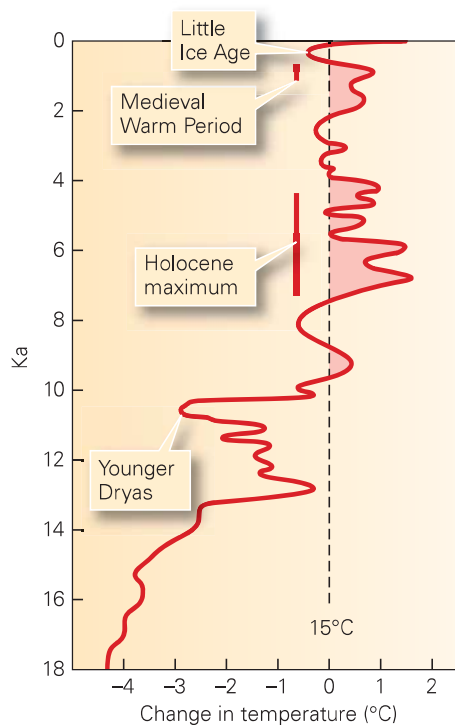
FIGURE 19.7 This chart shows the timing of icehouse and greenhouse phases at various times during Earth history.



The temperature dipped to a low about 3,000 years ago, before returning to a high during the Middle Ages, a time called the Medieval Warm Period. During this time, Vikings established self-supporting agricultural settlements along the coast of Greenland (Fig. 19.8b). The temperature dropped again from 1500 C.E. to about 1800 C.E., a period known as the Little Ice Age, when Alpine glaciers advanced and the canals of the Netherlands froze over in winter (Fig. 19.8c; see Fig. 18.29). Overall, the climate has warmed since the end of the Little Ice Age, and today it is as warm or warmer than it was during the Medieval Warm Period.

Geologists have focused on several factors to explain short-term climate change.

- *Fluctuations in solar radiation and cosmic rays:* The amount of energy produced by the Sun varies with the sunspot cycle. This cycle involves the appearance of large numbers of sunspots (black spots thought to be magnetic storms on the Sun's surface) about every 9 to 11.5 years. There may be longer-term cycles that have not yet been identified. Changes in the rate of influx of cosmic rays may affect climate, perhaps by generating clouds. Recent research suggests that cosmic rays striking the atmosphere produce clusters of ions that become condensation nuclei around which water molecules congregate, thus forming the mist droplets making up clouds.
- *Changes in Earth's orbit and tilt:* As Milanković first recognized in 1920, the change in the tilt of Earth's axis, the Earth's precession cycle, and changes in the eccentricity of its orbit together cause the amount of summer heat in high latitudes to vary. They also cause the overall amount of heat reaching Earth to vary (see Chapter 18). These changes correlate with observed ups and downs in atmospheric and oceanic temperature.
- *Changes in volcanic emissions:* Not all of the sunlight that reaches the Earth penetrates its atmosphere and warms the ground. Some is reflected by the atmosphere. The degree of reflectivity, or **albedo**, of the atmosphere increases if the concentration of volcanic aerosols in the atmosphere increases.
- *Changes in ocean currents:* Recent studies suggest that the configuration of currents can change quite quickly, and that this configuration affects the climate.
- *Changes in surface albedo:* Regional-scale changes in the nature of continental vegetation cover, and/or the proportion of snow and ice on the Earth's surface, and/or the sudden deposition of reflective volcanic ash affect our planet's albedo. Increasing surface albedo causes cooling, whereas decreasing albedo causes warming.
- *Abrupt changes in concentrations of greenhouse gases:* A sudden change in greenhouse gas concentration in the atmosphere could affect climate. One such change might happen if sea temperature warmed or sea level dropped, causing some of the methane hydrate that crystallized in sediment on the sea

FIGURE 19.8 Climate during the Holocene. Measurements suggest that temperature has varied significantly.**(a)** There have been several temperature highs and lows during the Holocene.

floor to melt and release CH_4 to the atmosphere. Melting of permafrost can have a similar effect, for the resulting rot of organic material preserved in the permafrost produces CH_4 . Algal blooms and reforestation (or deforestation) absorb CO_2 and cause cooling.

**(b)** During the Medieval Warm Period, Vikings settled in Greenland, where the climate was warm enough for agriculture.

At the end of the Little Ice Age, this tributary glacier in France reached the main valley floor.



Today, glaciers extend only part-way down the side valleys.

(c) Glaciers advanced in Europe during the Little Ice Age.

Catastrophic Climate Change and Mass-Extinction Events

Changes that happen on Earth almost instantaneously are called catastrophic changes. For example, a volcanic explosion, an earthquake, a tsunami, or a landslide can change a local landscape in seconds or minutes. But such events affect only relatively small areas. Can such catastrophes happen on a global scale? In the past decades, geoscientists have come to the conclusion that the answer is yes. The stratigraphic record shows that Earth history includes several **mass-extinction events**, during which large numbers of species abruptly vanished. Some of these events define boundaries between geologic periods. A mass-extinction event decreases the biodiversity (the number of different species that exist at a given time) of life on Earth. It takes millions of years after a mass-extinction event for biodiversity to increase again, and the

new species that appear differ from those that vanished, for evolution is unidirectional.

Geologists speculate that some mass-extinction events reflect a catastrophic change in the planet's climate, brought about by unusually voluminous volcanic eruptions or by the impact of a comet or an asteroid with the Earth. Either of these events could eject enough debris into the atmosphere to block sunlight. Without the warmth of the Sun, winter-like or night-like conditions would last for weeks to years, long enough to disrupt the food chain. In addition, either event could eject aerosols that would turn into global acid rain, scatter hot debris that would ignite forest fires, or give off chemicals that, when dissolved in the ocean, would make the ocean either toxic, killing marine life, or so nutritious that oxygen-consuming algae could thrive. At present, many geologists favor the hypothesis that the Permian-Triassic extinction was due to the eruption

of 3 million cubic km of basalt in Siberia, and that the Cretaceous-Tertiary extinction was due to a giant meteorite impact near the Yucatán peninsula in Mexico.

Take-Home Message

Geologic study shows that past climate alternates between greenhouse and icehouse conditions. Factors including life evolution, continental drift, and orbital change cause long- and short-term change. Volcanoes and meteorites can cause catastrophic change.

19.6 Human Impact on the Earth System

According to some researchers, perhaps only 20,000 people lived on Earth after the catastrophic eruption of the Toba volcano about 70,000 years ago. By the dawn of civilization, 4000 B.C.E., the population was still, at most, a few tens of millions. But by the beginning of the 19th century, revolutions in industrial methods, agriculture, medicine, and hygiene had substantially lowered death rates and raised living standards, so that the human population began to grow at accelerating rates and reached 1 billion in 1850. It took only 80 years for the population to double, reaching 2 billion in 1930. Now the doubling time is only 44 years, and the population passed the 6 billion mark just before the year 2000 (Fig. 19.9). Global population surpassed 7 billion during 2012.

As the population grows and the standard of living improves, per capita usage of resources increases. We use land for agriculture and grazing, forests for wood, rock and dirt for construction, oil and coal for energy or plastics, and ores for metals (see Chapter 12). Without a doubt, our usage of resources has affected the Earth System profoundly, and thus humanity has become a major agent of global change. Here, we examine some of these anthropogenic (human-induced) impacts.

The Modification of Landscapes

Every time we pick up a shovel and move a pile of rock or soil, we redistribute a portion of the Earth's crust. In the last century, the pace of Earth movement has accelerated, for now we have shovels in coal mines that can move 300 cubic meters of rock in a single scoop, trucks that can carry 200 tons of ore in a single load, and tankers that can transport 500 million liters (~3 million barrels) of oil during a single journey. In North America, human activity now moves more sediment each year than the continent's rivers do. The extraction of rock during mining, the building of levees and dams along rivers or of sea walls along the coast, and the construction of highways and cities

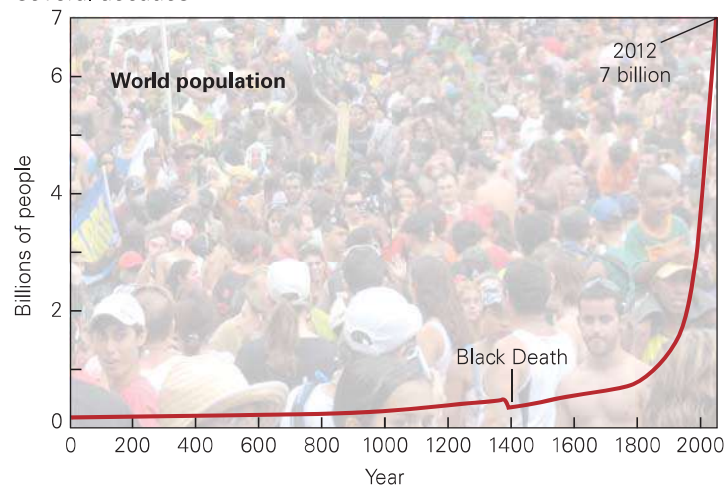
all involve the redistribution of Earth materials (Fig. 19.10). In addition, people clear and plow fields, drain and fill wetlands, and pave over the land surface. All these activities change the landscape, the water table, and the supply of sediment.

The Modification of Ecosystems

In an undisturbed area, the **ecosystem** (an interconnected network of organisms and the physical environment in which they live) of a region is the product of evolution for an extended period of time. The ecosystem's flora and fauna include species that have adapted to living together in a particular climate and on the substrate available. Human-caused deforestation, overgrazing, agriculture, and urbanization disrupt ecosystems and lead to a decrease in biodiversity.

Archaeological studies have found that the earliest example of human modification of an ecosystem occurred in the Stone Age, when hunters played a major role in causing the mass extinction of many species of large mammals (mammoth, giant sloths, giant bears). Today, less than 5% of Europe retains its original habitats. The same number can be applied to the eastern United States, which lost its original forest and prairie. Tropical rain forests cover less than about half the area worldwide that they covered before the dawn of civilization, and they are disappearing at a rate of about 1.8% per year (Fig. 19.11a, b). Much of this loss comes from slash-and-burn agriculture, in which farmers and ranchers destroy forest to make open land for farming and grazing (Fig. 19.11c). Unfortunately, the heavy rainfall of tropical regions removes nutrients from the soil, making the soil useless in just a few years. Overgrazing by domesticated animals can remove vegetation so completely that some grasslands have undergone desertification. And urbanization replaces the natural land surface with concrete or asphalt, a process that completely destroys an ecosystem and radically changes the amount of rain that infiltrates the land surface to become groundwater.

FIGURE 19.9 Population now doubles about every 44 years. The Black Death pandemic caused an abrupt drop that lasted for several decades.



Pollution

The environment has always contained contaminants such as soot, dust, and the by-products of organisms. But when human populations grew, urbanization, industrial and agricultural activity, the production of electricity, and modern modes of transportation greatly increased both the quantity and diversity of contaminants that entered the air, surface water, and groundwater. These contaminants, or **pollution**, include both natural and synthetic materials in liquid, solid, and gaseous form. They have become a problem because they are produced too fast for the Earth System to naturally absorb or modify. For example, small quantities of sewage can be absorbed by clay minerals in the soil or destroyed by bacterial metabolism, but large quantities overwhelm natural controls and can accumulate in destructive concentrations. Pollution of the Earth System is a type of global change because it is a redistribution and reformulation of materials. Some key problems associated with this change include the following:

- **Smog:** The term was originally coined to refer to the dank, dark air that resulted when smoke from the burning of coal mixed with fog in London and other industrial cities. Another kind of smog, called photochemical smog, is the ozone-rich brown haze that blankets cities when exhaust from cars and trucks reacts with air in the presence of sunlight.
- **Water contamination:** We dump a great variety of chemicals into surface water and groundwater. Examples include gasoline, other organic chemicals, radioactive waste, acids, fertilizers—the list could go on for pages. These chemicals affect biodiversity.
- **Acid runoff:** Dissolution of sulfide-containing minerals in ores or coal by groundwater or stream water makes the water acidic.
- **Acid rain:** When rain passes through air that contains sulfur-containing aerosols (emitted from power plants), the water dissolves the sulfur and creates sulfuric acid, or **acid rain**.

Wind can carry aerosols far from a power plant, so acid rain can damage a broad region.

- **Radioactive materials:** Nuclear weapons, nuclear energy, and medical waste transfer radioactive materials from rock to Earth's surface environment.
- **Ozone depletion:** When emitted into the atmosphere, human-produced chemicals, most notably chlorofluorocarbons (CFCs), react with ozone in the stratosphere. This reaction, which happens most rapidly on the surfaces of tiny ice crystals in polar stratospheric clouds, destroys ozone molecules, thus creating an **ozone hole** over high-latitude regions, particularly during the spring (**Fig. 19.12**). Note that the “hole” is not an area where no ozone is present, but rather is a region where atmospheric ozone has been reduced substantially. Ozone holes have dangerous consequences, for they affect the ability of the atmosphere to shield the Earth's surface from harmful ultraviolet radiation.

Recent Global Warming

We've seen that greenhouse gases, most notably CO_2 and CH_4 , play a major role in the regulation of the Earth's surface temperatures—without these gases, the Earth could not be a home for life. Both CO_2 and CH_4 cycle through various biogeochemical reservoirs of the Earth System, and the fluxes between reservoirs determine the amount in any given reservoir at any given time. For most of geologic time, the concentration of these gases in the atmosphere was governed by natural processes—volcanic eruptions, life evolution events (appearance of new genera or extinction of existing ones), forest fires, orogenic uplift and related weathering, warming and cooling due to the Milanković cycle, changes in solar activity or cosmic-ray flux, and even meteor impact. But beginning around 8,000 years ago, human society began to modify the environment significantly, first with the invention of agriculture and then, during the past two centuries, with the advent of major industrialization.

FIGURE 19.10 Excavation, agriculture, and construction modify topography, drainage, infiltration, and ecology.



Humans move vast amounts of rock.



Agriculture eliminates diverse ecosystems.

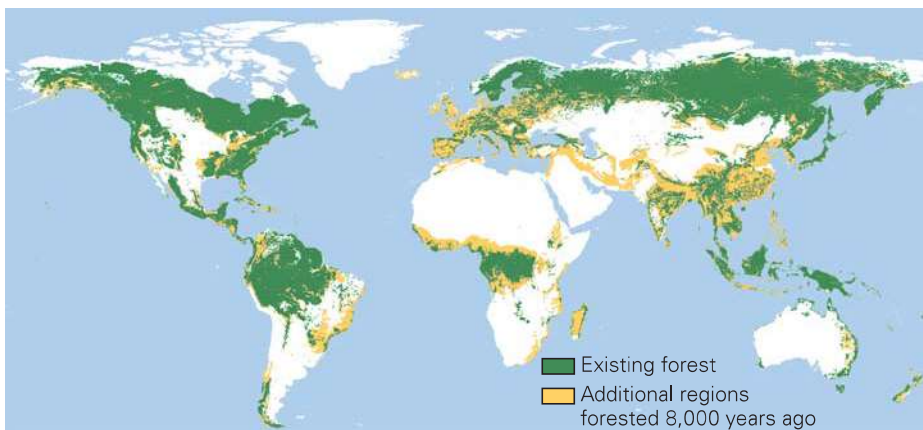


Urbanization changes the water table.

Both industry and agriculture produce greenhouse gases that transfer carbon from underground reservoirs or biomass reservoirs into the atmospheric reservoir. For example: the burning of fossil fuels oxidizes vast quantities of carbon that had previously been held in oil, gas, or coal underground to produce CO_2 that mixes into the atmosphere; the heating of calcite (CaCO_3) to produce the lime (CaO) of cement takes carbon that had been locked in limestone and produces CO_2 that also mixes into the air; the clear-cutting of forests to make way for grazing land or fields replaces high-biomass vegetation (trees) with low-biomass vegetation (grasses or crops) thereby leaving CO_2 in the atmosphere; and the decay of organic material in soggy rice paddies, as well as the flatulence of cattle herds, produces significant quantities of CH_4 that would otherwise remain locked in biomass.

About 85% of the CO_2 that we send into the atmosphere comes from burning fossil fuels and producing cement, while about 15% is a consequence of deforestation. How does the rate of production of CO_2 by humanity compare to the rate of production by volcanic eruptions? Researchers estimate that in

FIGURE 19.11 The area of the Earth covered by forests has been shrinking.



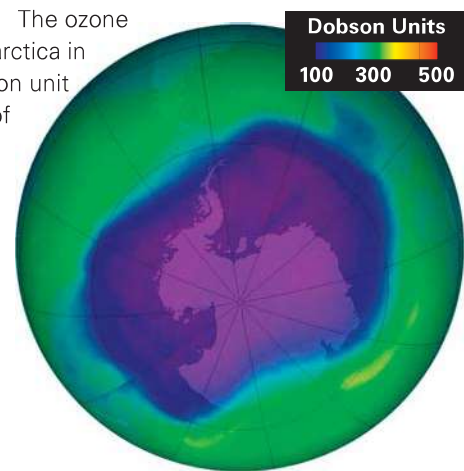
(a) Comparison of existing forest area (green) to precivilization forest area (gold and green together) emphasizes changes in Earth's forest cover. Tropical rainforest areas are shrinking rapidly.

(c) Slash-and-burn agriculture.



(b) Satellite images of a region in the Amazon show the increase in cleared areas (light).

FIGURE 19.12 The ozone hole over Antarctica in 2006. A Dobson unit is a measure of the amount of ozone in the atmosphere; red is more, purple is less.



a year all volcanic eruptions together (including both submarine and subaerial eruptions) emit about 0.15 to 0.26 gigatons of CO_2 . By comparison, activities of humanity emit about 35 gigatons of CO_2 every year, or at least 135 times as much. Significantly, not all of the greenhouse gases that society sends into the atmosphere stay there. In the case of CO_2 , some dissolves in the ocean, some reacts with minerals in rocks during chemical weathering, and some is utilized by plants during photosynthesis. But calculations and isotopic studies suggest that only 43% of the CO_2 that society produces (what researchers refer to as anthropogenic CO_2) returns into the Earth in biogeochemical cycles—the remaining 57% stays in the atmosphere.

In the early 1960s, a chemist named Charles Keeling wondered whether changes in atmospheric CO_2 concentration could be detected, and he set out to measure the concentration of CO_2 in the atmosphere using the most accurate methods available. To avoid areas with urban pollution, he decided to analyze air samples collected every month at the summit of Mauna Kea volcano in Hawaii. After completing many years of measurements, Keeling showed not only that distinct seasonal variations occurred (CO_2 concentration goes down in the warm summer when rates of photosynthesis increase, and it goes up in the winter when organic matter dies and decays), but also that the *average annual concentration* of CO_2 was steadily rising (**Fig. 19.13a**)! The average yearly CO_2 concentration was 320 ppm in 1965, and it reached 360 ppm in 1995. Charles Keeling died in 2005, but measurements at Mauna Kea have continued, and in 2012, the average yearly CO_2 concentration there reached 394 ppm.

Using records in ice cores, researchers extended the record of CO_2 concentration further back in time and have found that in 1750, CO_2 concentration was only 280 ppm (Fig. 19.13b). Thus, atmospheric CO_2 concentration has increased by about 40% since the beginning of the industrial revolution. Ice cores from the Antarctic ice sheet now provide a CO_2 record back through the last 800,000 years, and they demonstrate that during the alternating glacial and interglacial periods of the Late Pleistocene, CO_2 concentration varied between about 180 and 300 ppm (Fig. 19.13c). Thus, the increases that have happened since the beginning of the industrial revolution appear to be beyond the range of natural fluctuations that occurred during the last 800,000 years. Have CO_2 concentrations ever been higher than they are today? Probably. For example, a recent study suggests that CO_2 concentration during the Eocene climate optimum (49 to 56 Ma) was over 1,000 ppm, about three times what it is today. CH_4 concentrations have also demonstrably increased over the past two centuries (Fig. 19.13d).

The fundamental principles of the greenhouse effect require that an increase in CO_2 concentration cause warming. But has warming taken place during the past 200 years? During the past 30 years, researchers have published thousands of observations suggesting that it has. For example:

- Large ice shelves, such as the Larsen B Ice Shelf, along the Antarctic Peninsula, and the Ayles Ice Shelf, along Ellesmere Island in northernmost Canada, are breaking up (Fig. 19.14a).
- The area covered by sea ice in the Arctic Ocean has decreased substantially in recent decades. Some estimates place the rate of ice-cover loss at about 3% per decade. This observation leads to the prediction that it may be possible to sail across the Arctic Ocean within decades (Fig. 19.14b).
- The Greenland ice sheet is melting at an accelerating pace. Studies suggest that the rate of ice loss has increased from 90 to 220 cubic km per year in the last 10 years and that, in places, the sheet is thinning by about 1 m per year. In addition, the annual melt zone along the margins of the ice sheet has widened dramatically because the elevation of the equilibrium line (see Chapter 18) has risen (Fig. 19.14c). Valley glaciers draining the ice sheet flowed 50% faster in 2003 than they did in 1992.
- Valley glaciers worldwide, with few exceptions, have been retreating rapidly, so that areas that were once ice covered are now bare. The change is truly dramatic in many locations (Fig. 19.14d).
- Worldwide, glacial volumes have been diminishing. About 400 km³ of ice disappears every year.
- Biological phenomena that are sensitive to climate are being disrupted. For example, the time at which sap in the maple trees of the northeastern United States starts to flow has changed, and the mosquito line (the elevation at which mosquitoes can survive) has risen substantially. Plant hardiness zones in North America have migrated northward

FIGURE 19.13 Changes in carbon dioxide (CO_2) and methane (CH_4) concentrations over time.

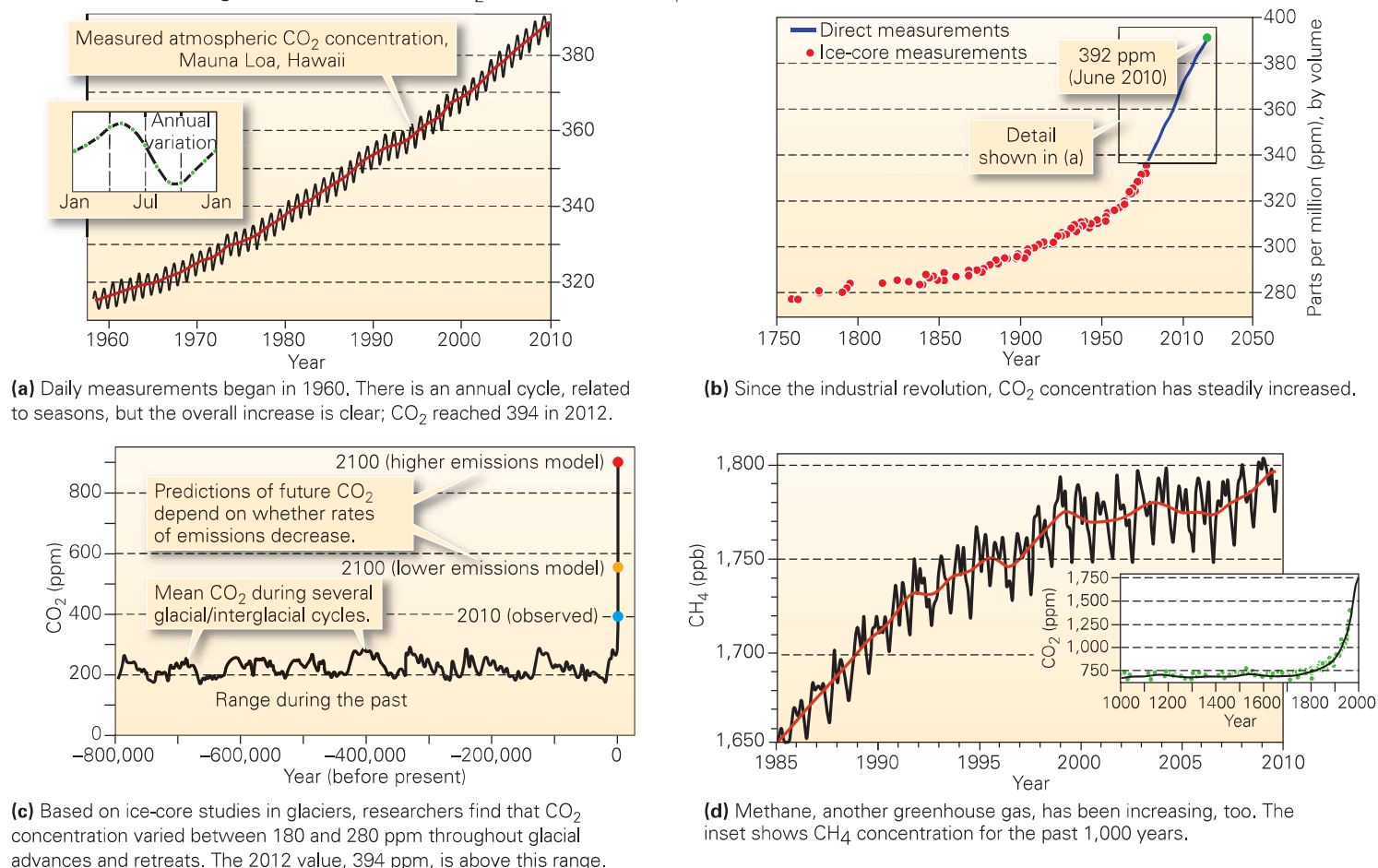
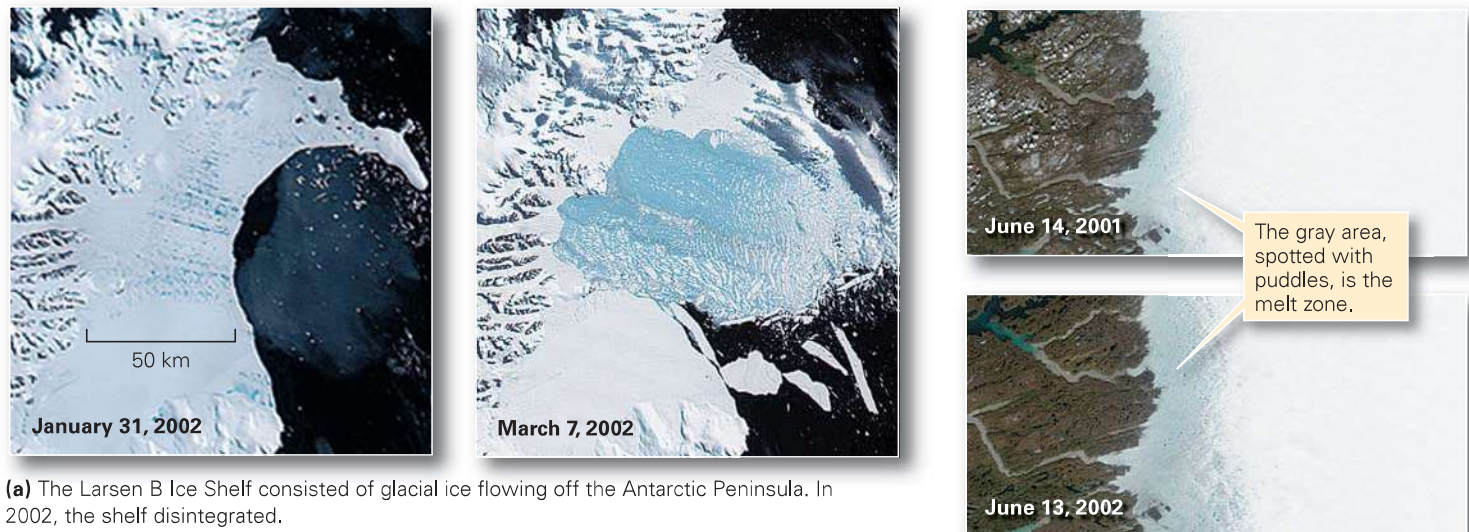
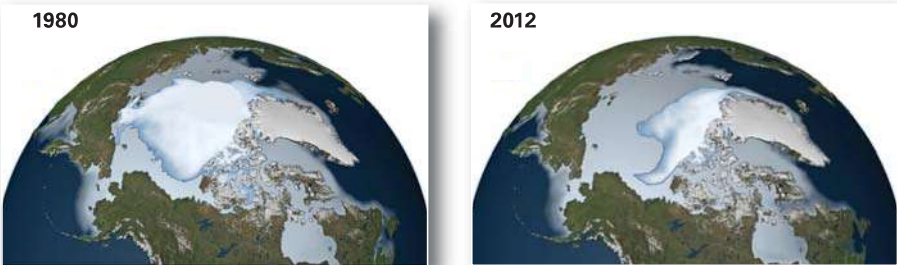


FIGURE 19.14 Visible examples of large-scale changes in Earth’s ice cover.

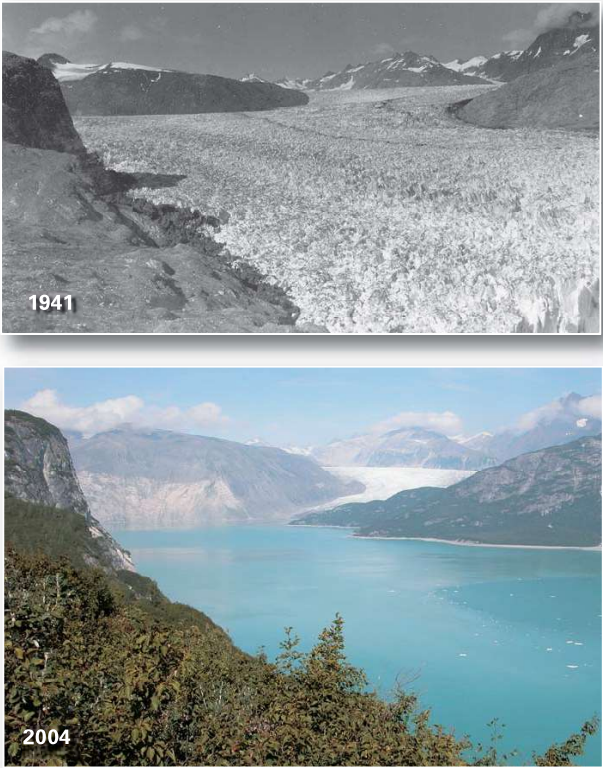


(a) The Larsen B Ice Shelf consisted of glacial ice flowing off the Antarctic Peninsula. In 2002, the shelf disintegrated.

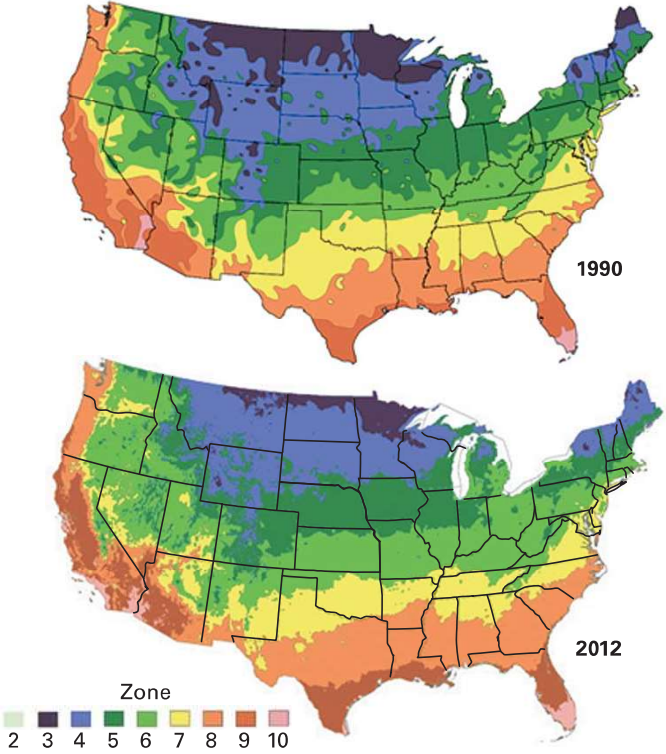


(b) The northern polar ice cap shrank significantly between 1980 and 2012.

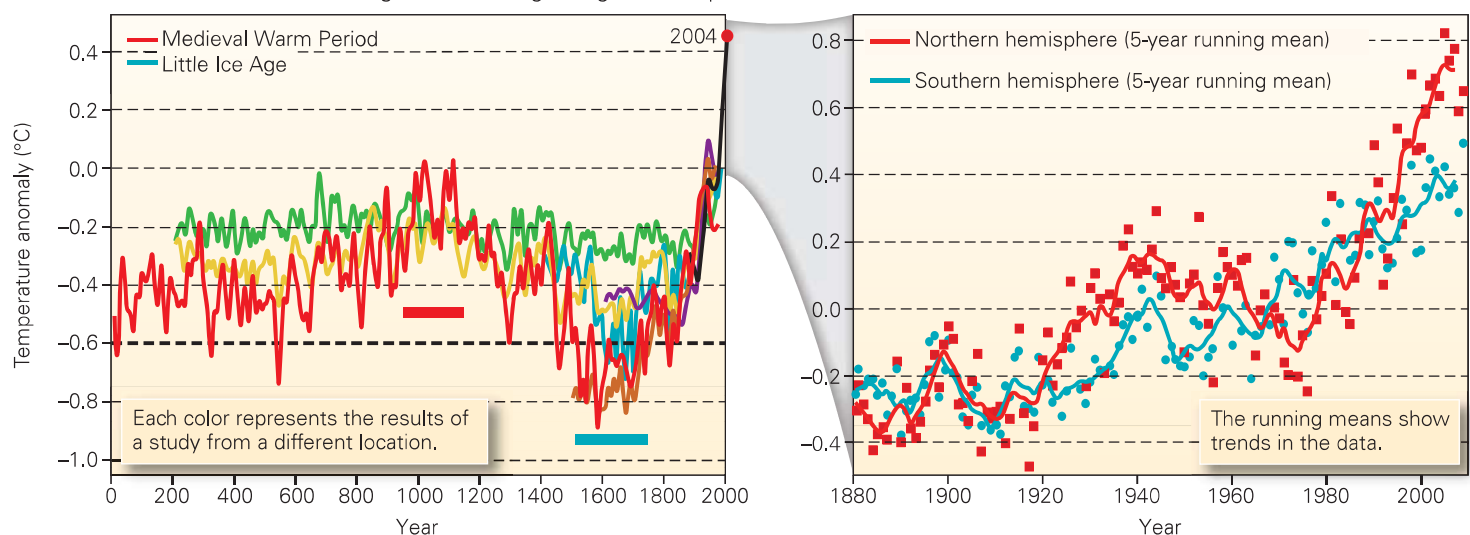
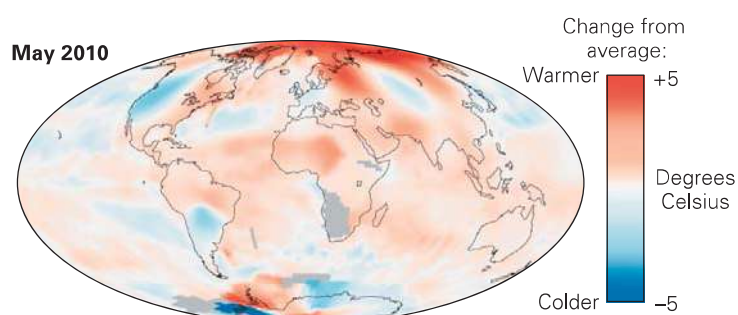
(c) The summer melt line has risen along the edge of Greenland’s ice sheet. Each photo shows the same area.



(d) The Muir Glacier, Alaska, retreated 12 km between 1941 and 2004.



(e) Plant hardiness is an indication of the earliest date in a year when crops can be planted. The zones are moving north.

FIGURE 19.15 Measurements of global warming and global temperature anomalies.**(a)** Reconstructions of temperature during the past 2000 years. The black line is the average of direct measurements.**(b)** The change in global average temperature from 1880 to 2008, relative to a reference value. Both hemispheres show a temperature increase.**(c)** Colors represent differences relative to the average temperature of the period from 1951 to 1980. Redder areas are warmer than the 1951–1980 average.

(Fig. 19.14c). Also, the average weight of polar bears has been decreasing, because the bears can no longer walk over pack ice to reach their hunting grounds in the sea.

- The area of permafrost in high latitudes has substantially decreased, and melt ponds have replaced frozen land.
- Water vapor in the atmosphere has been increasing due to evaporation of warmer seas, possibly leading to more severe hurricanes.
- Measured values of *average* global surface atmospheric temperature are rising, a phenomenon widely referred to as global warming (Fig. 19.15a–c). Specifically, global mean atmospheric temperature has risen by about 1°C during the last century. Although such a change may seem small, the magnitude of temperature change between the last ice age and now, by comparison, was only 3° to 5°C. A small change in average temperature may have major consequences.
- Measured values of near-surface ocean-water temperatures are rising. Studies of global averages of temperatures in the

sea indicate that overall, the oceans have been warming over the past century and a half (Fig. 19.16).

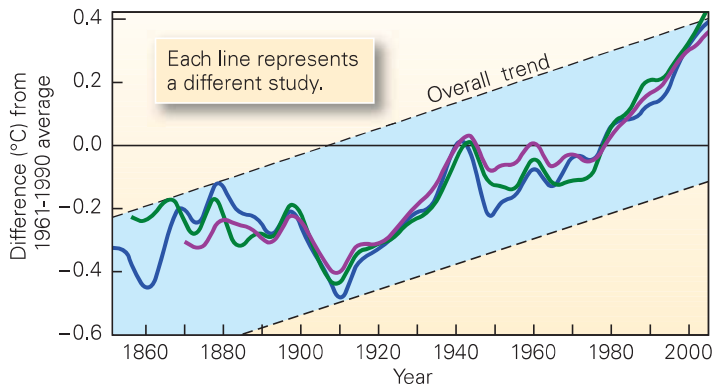
Climate data are not easy to obtain and are not easy to interpret. Because climate studies can have major implications for global policy decisions, a group of leading scientists founded the Intergovernmental Panel on Climate Change (IPCC) in 1988. This panel, sponsored by the World Meteorological Organization and the United Nations, reviews published research on climate change and, every five years, summarizes the conclusions in an assessment report. The language describing the likelihood that global warming is happening, and that humans have contributed significantly to causing it, has become progressively less equivocal in successive versions of the report. *The Fourth Assessment Report*, published in 2007, states:

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. . . . The understanding of anthropogenic [human-caused] warming and cooling influences on climate has improved since the Third Assessment Report, leading to very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming.

In other words, most climate researchers have concluded that global warming is real, and that the actions of people—burning fossil fuels, cutting down forests, paving over wetlands—have played a significant role in causing it. Other possible causes, such as changes in solar radiation or cosmic-ray flux, do not appear to be of sufficient magnitude to cause observed warming.

If the *Fourth Assessment* of the IPCC is correct, then society faces the challenge of either slowing climate change or dealing with the consequences. The effects of global warming over the coming decades to centuries remains the subject of intense

FIGURE 19.16 Measurements of average global temperature in shallow waters of the ocean.



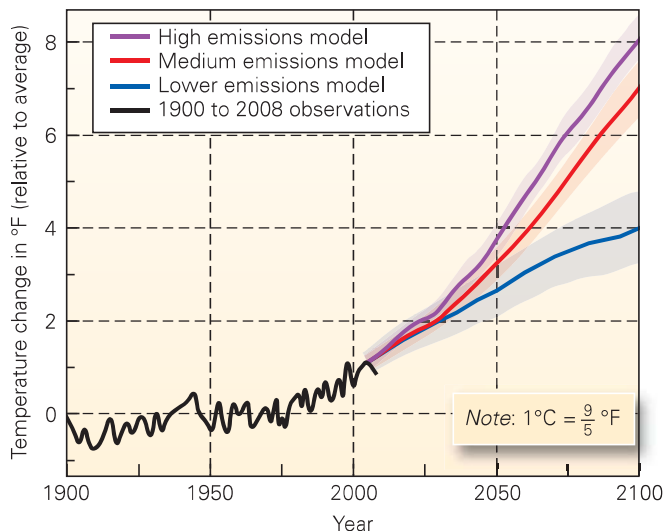
debate, because predictions depend on computer models and not all researchers agree on how to construct or interpret these models. The role of clouds in climate change, for example, remains poorly understood and inadequately addressed by such models. In the worst-case scenario, global warming will continue into the future at the present rate, so that by 2050—within the lifetime of many readers of this book—the average annual temperature will have increased in some parts of the world by 1.5° to 2.0°C. At these rates, by the end of the century, temperatures could be almost 4°C warmer depending on the model used (Fig. 19.17a), and by 2150, global temperatures may be 5° to 11°C warmer than at present—the warmest since the Eocene Epoch, 40 million years ago. Models predict that warming will not be the same everywhere—the greatest impact will be in the Arctic (Fig. 19.17b).

The effects of such a change are controversial, but according to some climate models, the following events might happen:

- *A shift in climate belts:* As the climate overall warms, temperate and desert regions would occur at higher latitudes. Thus, regions that are now agricultural areas may dry out and become unfarmable. The change in climate would also affect the amount and distribution of precipitation (rain and snow) that falls.
- *Ice retreat and snow-line rise:* Global warming will decrease the volume of water held in glacial reservoirs and will cause areas covered by sea ice to decrease. It will also cause snow-line elevations in mountainous areas to rise—this change will affect the amount of water held in the winter snowpack, and therefore, will decrease summer runoff, and may even impact tourism by shortening the ski season at resorts.
- *Melting permafrost:* Warming climates will cause areas of unglaciated land that previously had remained frozen most of the year to thaw during the summer. Such melting of permafrost will permit organic matter that had been stored in frozen form to decompose and release methane.
- *A rise in sea level:* Water expands when heated, so warming of the global ocean causes sea level to rise. Glacial melting due to global warming adds to the rise. Sea level has already changed noticeably in the last century (Fig. 19.18a, b), and as a result, some coastal wetlands have flooded and some oceanic islands have become submerged. Dikes that protect coastal areas of the Netherlands from flooding will need to be raised in coming decades to counter sea-level rise.

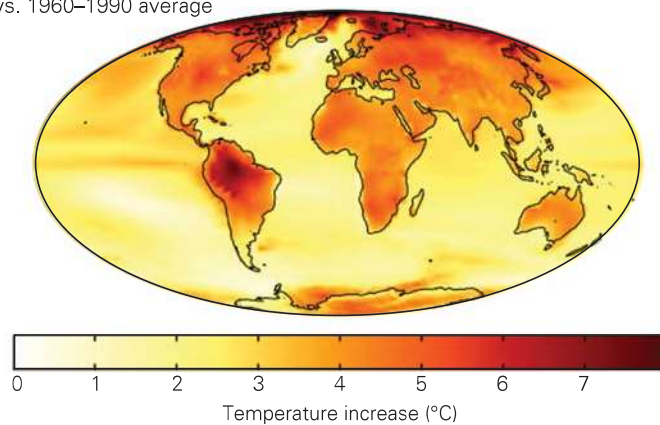
The amount of sea-level rise in the future depends on the rate of global warming. Models suggest that by 2100, it may rise by an additional 20 to 60 cm. A map showing the elevations of coastal areas emphasizes that a meter or two of sea-level rise could inundate regions of the world where 20% of the human population currently lives (Fig. 19.18c).

FIGURE 19.17 Model predictions of future global warming.

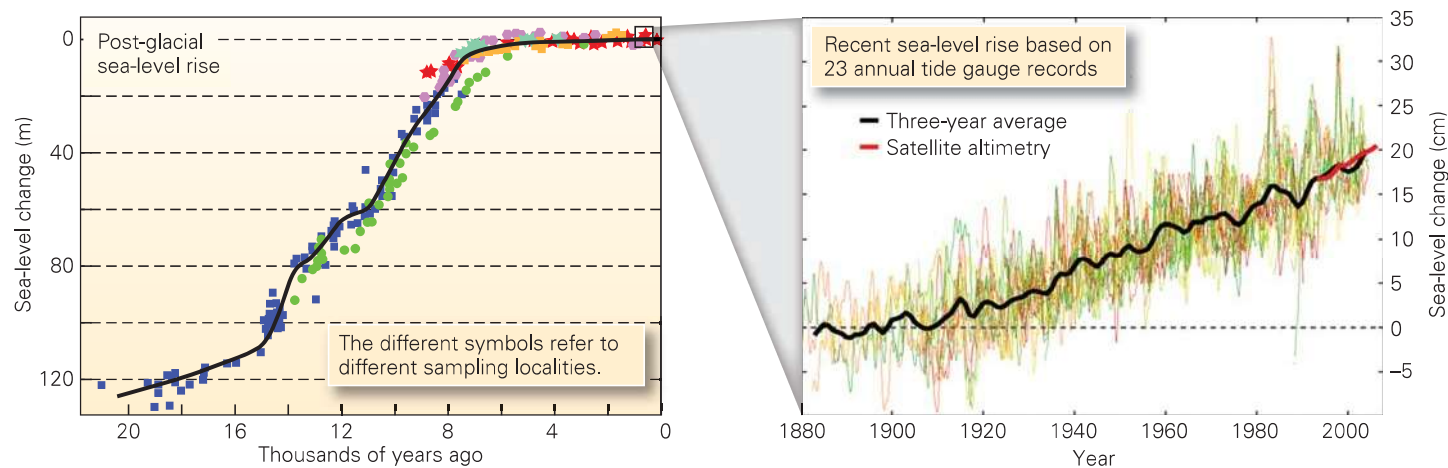
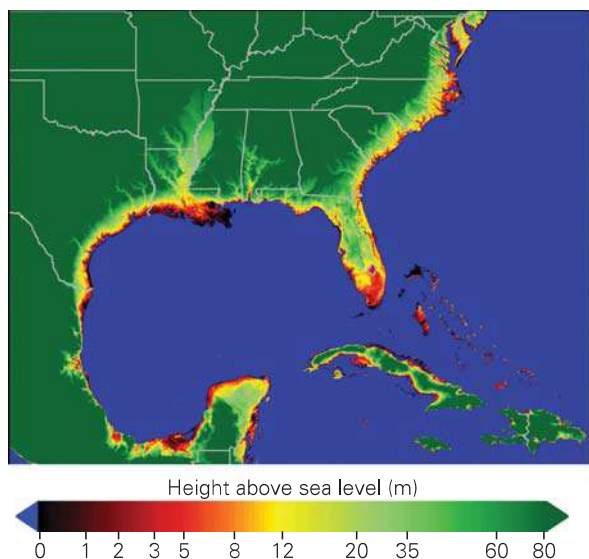


(a) Model calculations of global warming. Different models assume different rates of CO₂ emissions. All suggest significant global temperature increase by 2100.

2070–2100 prediction
vs. 1960–1990 average



(b) Global warming does not mean that all locations warm by the same amount. This map shows a model prediction of how temperature may vary with location for the time period 2070 to 2100.

FIGURE 19.18 Sea-level rise of the recent past, and possible sea-level rise of the future.**(a)** Sea level rose rapidly after the last ice age, due to melting of continental glaciers.**(b)** Tide gauges document sea-level rise of the past 130 years.**(c)** The red and black areas of this map are so low that they could be flooded if sea level rose a few meters.

and soon. But what can be done? The 160 nations that signed the 1997 Kyoto Accord, at a summit meeting held in Japan, propose that the first step would be to slow the input of greenhouse gases into the atmosphere by decreasing the burning of fossil fuels and/or by forcing the CO_2 produced at power plants down wells into pore space underground by a process called **carbon capture and sequestration (CCS)**. Such proposals, needless to say, remain very controversial.

Take-Home Message

Human activities impact the landscape and ecosystems. Evidence indicates that, globally, glacial and sea ice volume is decreasing, sea level is rising, and climate belts are shifting. Researchers conclude that release of greenhouse gases causes global warming.

- **Stronger storms:** An increase in average ocean temperatures means that more of the ocean evaporates when a tropical depression passes over. This evaporation might nourish stronger hurricanes. In nondesert areas, there might be more precipitation and, therefore, flooding.
- **An increase in wildfires:** Warmer temperatures may lead to an increase in the frequency of wildfires because the moisture content of plants is lower.
- **An interruption of the oceanic heat conveyor:** Oceanic currents play a major role in transferring heat across latitudes. If global warming melts polar ice, the resulting freshwater would dilute surface ocean water at high latitudes. This water could not sink, and thus thermohaline circulation would be shut off (see Chapter 15), preventing the water from conveying heat.

The potential changes described above, along with other studies that estimate the large economic cost of global warming, imply that the issue needs to be addressed seriously

19.7 The Future of the Earth

Most of the discussion in this book has focused on the past, for the geologic record preserved in rocks tells us of earlier times. Let's now bring this book to a close by facing in the opposite direction and speculating what the world might look like in geologic time to come.

In the geologic near term, the future of the world depends largely on human activities. Whether the Earth System undergoes a major disruption and shifts to a new equilibrium, whether a catastrophic mass-extinction event takes place, or whether society achieves **sustainable growth** (an ability to prosper within the constraints of the Earth System) will depend on our own foresight and ingenuity.

Projecting thousands of years into the future, we might well wonder if the Earth will return to ice-age conditions, with glaciers growing over major cities and the continental shelf

becoming dry land, or if the ice age is over for good because of global warming. No one really knows for sure.

If we project millions of years into the future, it is clear that the map of the planet will change significantly because of the continuing activity of plate tectonics. For example, during the next 50 million years or so, the Atlantic Ocean will probably become bigger, the Pacific Ocean will shrink, and the western part of California will migrate northward. Eventually, Australia will crush against the southern margin of Asia, and the islands of Indonesia may be flattened in between.

Predicting the map of the Earth hundreds of millions of years into the future is hard, because we don't know for sure where new subduction zones will develop. Perhaps subduction of the Pacific Ocean will lead to the collision of the Americas with Asia, to produce a supercontinent ("Amasia"). A subduction zone eventually will form on one side of the Atlantic Ocean, and the ocean will be consumed. As a consequence, the eastern margin of the Americas will likely collide with the western margin of Europe and Africa. The sites of major cities—New York, Miami, Rio de Janeiro, Buenos Aires, and London—will be incorporated into a collisional mountain belt, and likely will be subjected to metamorphism and igneous intrusion before being uplifted and eroded. Shallow seas may once again cover the interiors of continents and then later retreat, and glaciers may once again cover the continents—it happened in the past, so it could happen again. And if the past is the key to the future, we *Homo sapiens* might not be around to watch our cities enter the rock cycle, for biological evolution may have introduced new species to the biosphere, and there is no way to predict what these species will be like.

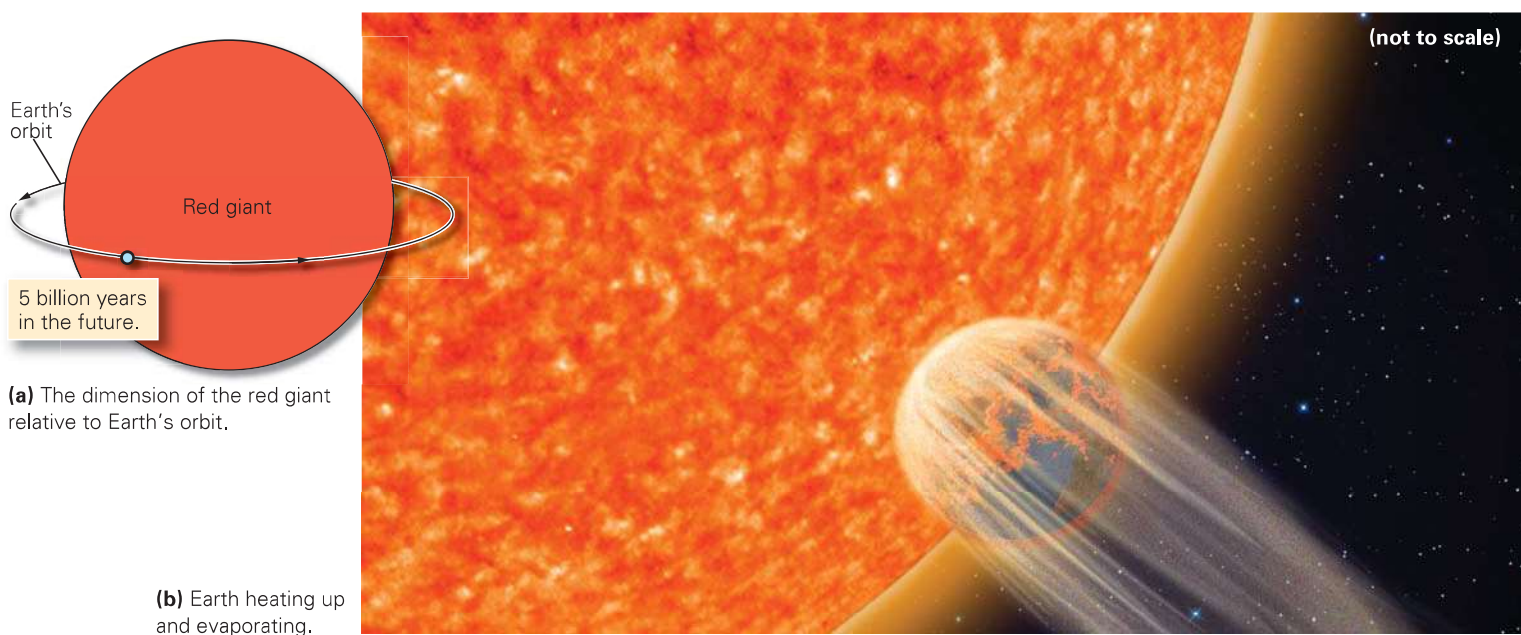
And what of the end of the Earth? Geologic catastrophes resulting from asteroid and comet collisions will undoubtedly

occur in the future as they have in the past. We can't predict when the next strike will come, but unless the object can be diverted, Earth is in for another radical readjustment of surface conditions. But it's not likely that such collisions will destroy our planet. Rather, astronomers predict that the end of the Earth will occur some 5 billion years from now, when the Sun begins to run out of nuclear fuel. When this happens, thermal pressure caused by fusion reactions will no longer be able to prevent the Sun from collapsing inward, because of the immense gravitational pull of its mass. Were the Sun a few times larger than it is, the collapse would trigger a supernova explosion that would blast matter of the Universe out into space to form a new nebula, perhaps surrounding a black hole. But since the Sun is not that large, the thermal energy generated when its interior collapses inward will heat the gases of its outer layers sufficiently to cause them to expand. As a result, the Sun will become a red giant, a huge star (Fig. 19.19a, b). Our planet will then vaporize, and its atoms will join an expanding ring of gas—the ultimate global change. If this happens, the atoms that once formed Earth and all its inhabitants through geologic time may eventually be incorporated in a future solar system, where the cycle of planetary formation and evolution will begin anew.

Take-Home Message

In the near term, Earth's surface will be affected by decisions of human society. Over longer time scales, the map of the Earth will change due to plate interactions and sea-level change. The end of the Earth will likely happen when the Sun becomes a red giant.

FIGURE 19.19 In about 5 billion years, the Sun will become a red giant. When that happens, the Earth will first dry out, then vaporize; initially, it may look like a giant comet.



Chapter Summary

- We refer to the global interconnecting web of physical and biological phenomena on Earth as the Earth System. Global change involves the transformations or modifications of physical and biological components of the Earth System through time. Unidirectional change results in transformations that never repeat, whereas cyclic change involves repetition of the same steps over and over.
- Examples of unidirectional change include the gradual evolution of the solid Earth from a homogeneous collection of planetesimals to a layered planet, the formation of the oceans and the gradual change in the composition of the atmosphere, and the evolution of life.
- Examples of physical cycles that take place on Earth include the supercontinent cycle, the sea-level cycle, and the rock cycle.
- A biogeochemical cycle involves the passage of a chemical among nonliving and living reservoirs. Examples include the hydrologic cycle and the carbon cycle. Global change occurs when factors change the relative proportions of the chemical in different reservoirs.
- Tools for documenting global climate change include the stratigraphic record, paleontology, oxygen–isotope ratios, bubbles in ice, growth rings in trees, and human history.
- Studies of long-term climate change show that, at times in the past, the Earth experienced greenhouse (warmer) periods; at other times, there were icehouse (cooler) periods. Factors leading to long-term climate change include the positions of continents, volcanic activity, the uplift of land, and the addition or removal of CO₂, an important greenhouse gas.
- Short-term climate change can be seen in the record of the last million years. In fact, during only the past 15,000 years, we see that the climate has warmed and cooled a few times. Causes of short-term climate change include fluctuations in solar radiation and cosmic rays, changes in Earth’s orbit and tilt, changes in reflectivity, and changes in ocean currents.
- Mass extinction, a catastrophic change in biodiversity, may be caused by the impact of a comet or asteroid or by intense volcanic activity associated with a superplume.
- During the last two centuries, humans have changed landscapes; modified ecosystems; and added pollutants to the land, air, and water at rates faster than the Earth System can process.
- The addition of CO₂ and CH₄ to the atmosphere appears to be causing global warming, which could shift climate belts and lead to a rise in sea level. Sources for the added CO₂ include fossil fuel burning, cement production, and deforestation.
- In the future, in addition to climate change, the Earth will witness a continued rearrangement of continents resulting from plate tectonics and will likely suffer the impact of asteroids and comets. The end of the Earth may come in about 5 billion years, when the Sun runs out of fuel and becomes a red giant.

Key Terms

acid rain (p. 558)	differentiation (p. 546)	global cooling (p. 551)	mass-extinction event (p. 556)
albedo (p. 555)	ecosystem (p. 557)	global warming (p. 551)	ozone hole (p. 558)
biogeochemical cycle (p. 550)	feedback mechanism (p. 552)	greenhouse effect (p. 552)	paleoclimate (p. 552)
carbon capture and sequestration (p. 564)	general circulation model (p. 551)	greenhouse gas (p. 552)	pollution (p. 558)
climate (p. 551)	global change (p. 546)	greenhouse (hothouse) period (p. 553)	steady-state condition (p. 550)
climate-change model (p. 551)	global climate change (p. 551)	icehouse period (p. 553)	supercontinent cycle (p. 547)
			sustainable growth (p. 564)

Review Questions

1. Why do we use the term *Earth System* to describe the components of processes operating on this planet?
2. How have the Earth’s crust and atmosphere changed since they first formed?
3. What processes control the rise and fall of sea level on Earth?
4. How does carbon cycle through the various Earth systems?
5. How do paleoclimatologists study ancient climate change?
6. Contrast icehouse and greenhouse conditions.
7. What are the possible causes of long-term climatic change?
8. What factors explain short-term climatic change?
9. Give some examples of events that cause catastrophic change.
10. Give some examples of how humans have changed the Earth.
11. What is the ozone hole, and how does it affect us?

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- A video-based exercise on how we measure the hole in the ozone layer.

- Drag-and-drop exercises on the carbon cycle.
- A problem that helps students calculate rates of deforestation.

12. Describe how CO₂-induced global warming takes place, and how humans may be responsible. What effects might global warming have on the Earth System?

13. What are some likely scenarios for the long-term future of the Earth?

On Further Thought

14. If global warming continues, how will the distribution of grain crops change? Might this affect national economies? Why?
15. Currently, tropical rain forests are being cut down at a rate of about 1.8% per year. At this rate, how many more years will the forests survive? In the eastern United States, the proportion of land with forest cover today has increased over the past century. In fact, most of the farmland that

existed in New York State in 1850 is forestland today. Why? How might this change affect erosion rates in the region?

16. Using the library or the Web, examine the change in the nature of world fisheries that has taken place in the last 50 years. Is the world's fish biomass sustainable if these patterns continue? What has happened to whale populations during the past 50 years?

SEE FOR YOURSELF S... Global Change

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet R of our **Geotours Workbook**.



Deforestation, Amazon

Latitude 4°4'22.81"S,
Longitude 54°54'43.06"W

From 100 km, you can see the patchwork of fields that have been cut into the Amazon rainforest, south of the Amazon River in Brazil. Note the pattern of cutting—the fields border a grid of logging roads bulldozed across the landscape. Uncut forest remains in the upper left.



Urbanizing a Desert, Arizona

Latitude 33°33'18.59"N,
Longitude 111°49'25.19"W

Viewed from 9 km, you can see the intense change that the growing population of Phoenix causes in a desert. The central portion of the image shows a network of dry washes in the original desert. To the north, we see new housing developments and a water canal, and to the south, farmlands and a golf course. Water usage in the area has increased dramatically.



Receding Glacier, Switzerland

Latitude 46°34'48.75"N,
Longitude 8°22'58.53"E

Look NNE, obliquely across the landscape from 4 km. You can see a valley glacier near the town of Gletsch. The bare land down from the toe of the glacier was ice-covered a century ago. Note that the lateral moraine now lies like a bathtub ring high above the present-day ice surface, because the glacier has thinned.



Fields and Villages, China

Latitude 35°6'46.35"N,
Longitude 114°30'7.81"E

Look down from 4 km, and you see a landscape that has been completely altered by human society. What was once forest or grassland has been divided into cultivated rectangles. In villages, houses and roads cover the surface. These changes affect both the carbon cycle and the hydrologic cycle.