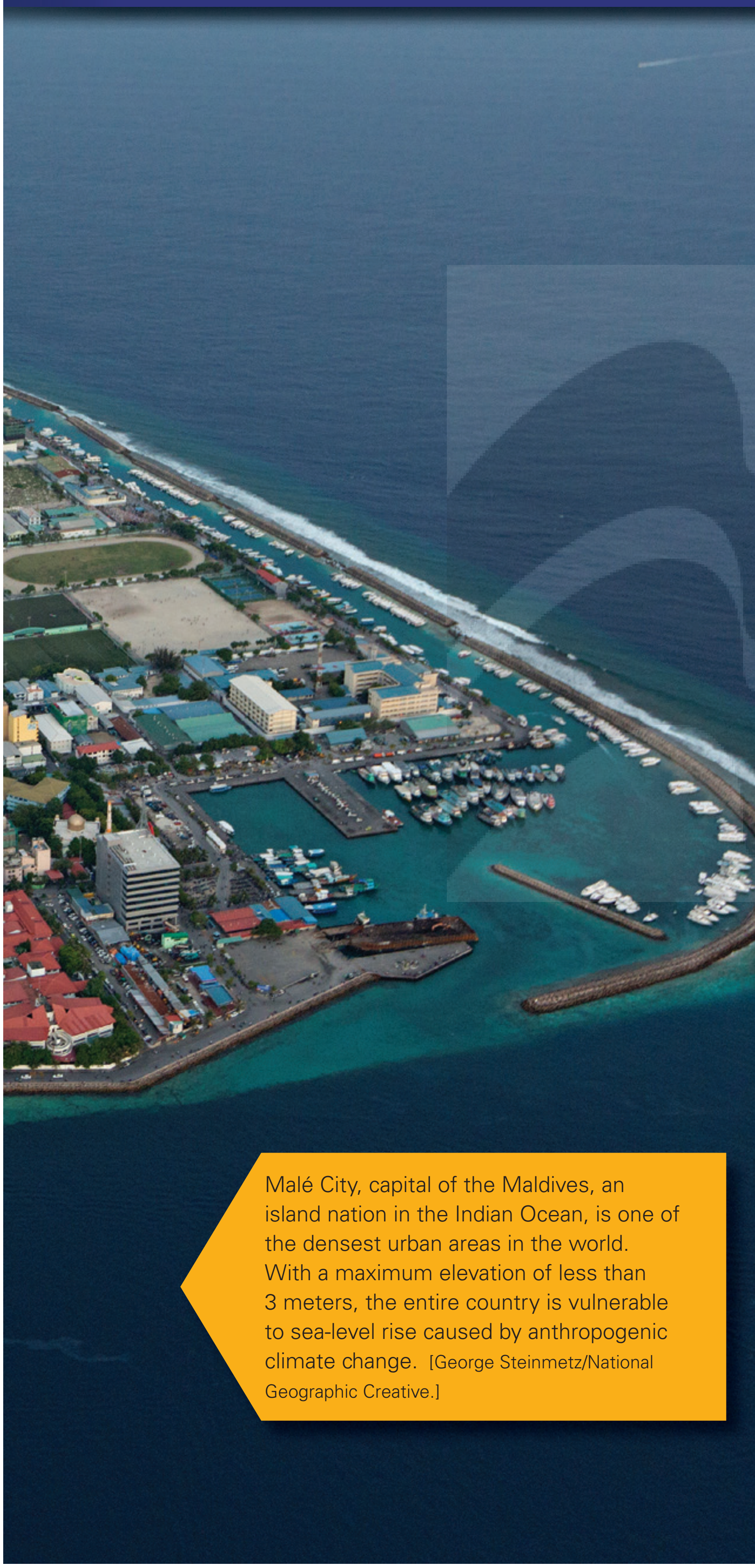
Anthropogenic Global Change 14



Malé City, capital of the Maldives, an island nation in the Indian Ocean, is one of the densest urban areas in the world. With a maximum elevation of less than 3 meters, the entire country is vulnerable to sea-level rise caused by anthropogenic climate change. [George Steinmetz/National Geographic Creative.]

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Learning Objectives

The goal of this chapter is to summarize what we know about anthropogenic global change, as well as the choices we have to manage this environmental change. From the information provided in this chapter, you should be able to:

14.1 Explain why scientists can assert with high confidence that fossil-fuel burning is increasing the atmospheric concentration of carbon dioxide.

14.2 Catalog the main types of anthropogenic global change and describe their main effects on the atmosphere, hydrosphere, cryosphere, and lithosphere.

14.3 Explain why scientists can assert with high confidence that fossil-fuel burning caused the twentieth-century warming and continues to cause the average surface temperature to increase.

14.4 Use scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) to project how much greenhouse gas concentrations, the average surface temperature, and sea level will rise during this century.

14.5 Assess the potential effects of anthropogenic global change on the biosphere, and evaluate the possibility that the beginning of the Anthropocene epoch will be marked by a mass extinction.

14.6 Illustrate with specific examples of changes in global energy production and usage that could stabilize or reduce carbon emissions.

Throughout geologic history, Earth's climate has been highly variable, swinging between periods of tropical warmth and glacial cold. We learned in Chapter 12 that the glacial cycles of the Pleistocene epoch resulted from atmospheric variations in greenhouse gases driven by the Milankovitch cycles of solar forcing. We saw in Chapter 13 how fossil-fuel burning is transforming carbon in the lithosphere to carbon dioxide in the atmosphere at an unprecedented rate, and we examined alternative sources of energy that will eventually lower this rate.

We now focus on the global changes to the Earth system that are likely to occur because of continuing human activities. We will discuss three of the most serious forms of anthropogenic global change: (1) global climate change owing to increased concentrations of carbon dioxide and other greenhouse gases in the atmosphere, (2) ocean acidification owing to increased carbon dioxide dissolved in the hydrosphere, and (3) loss of species diversity owing to changes in the biosphere. We explore how geoscientists are observing these changes and combining data with models of the Earth system to predict future changes. We will see that reducing the impacts of anthropogenic global change, and adapting to its consequences, will require concerted worldwide actions on an unprecedented scale.

The dire consequences of anthropogenic global change are motivating governments to work together in new ways to avoid the "tragedy of the commons"—the spoiling of our commonly held environmental resources by unregulated overexploitation. New multinational treaties, such as the Paris Agreement adopted by the United Nations in 2015, are being formulated in attempts to reduce carbon pollution of the atmosphere and consequent damage to the global environment.

Rise of Carbon Dioxide in the Atmosphere: The Keeling Curve

The expression *global change* entered the world's vocabulary in the late twentieth century when it became clear that emissions from fossil-fuel burning and other human activities were beginning to alter the chemistry of the atmosphere. The most convincing evidence of global change was collected by the chemist Charles David Keeling, who began a program to measure the concentration of carbon dioxide in the atmosphere in 1958.

Keeling developed instruments for measuring atmospheric CO_2 more easily and accurately than had been previously possible. He installed one of his instruments at the Mauna Loa Observatory at an elevation 11,000 feet on the Big Island of Hawaii, where he could sample pristine air from the Pacific Ocean, uncontaminated by local fossil-fuel emissions, and he maintained those measurements until his death in 2005. Others, including his son Ralph Keeling, are continuing them at Mauna Loa and other observing stations around the world.

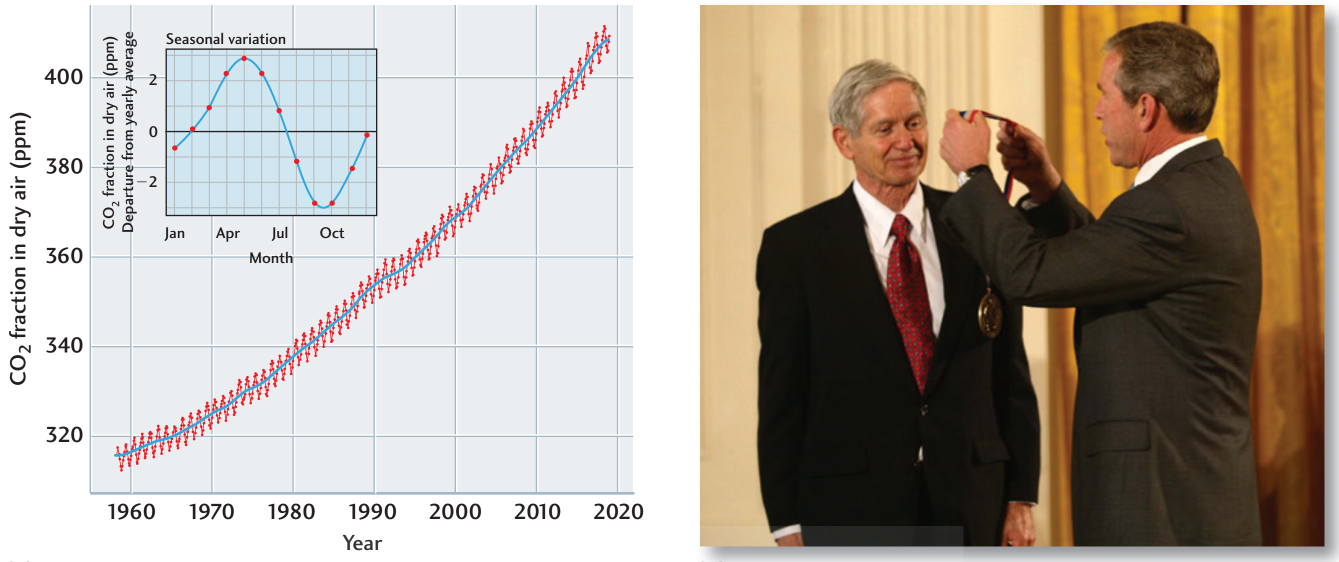
The product of these persistent efforts is the **Keeling curve**—the world's longest continuous record of carbon dioxide measurements in the atmosphere (**Figure 14.1**). The monthly values (red curve) show seasonal oscillations about yearly averages that are steadily rising (blue curve). The averages increase from 310 ppm in 1958, when Keeling first began his measurements, to 410 ppm in 2018, a 32 percent change in just 60 years. Owing to circulation and turbulence within the troposphere, the amount of CO_2 in the air sampled at Mauna Loa is representative of a global average. By direct observation, Keeling proved beyond a reasonable doubt that the atmospheric concentration of carbon dioxide, a powerful greenhouse gas, is increasing at the rapid clip of half a percent per year.

Scientists before Keeling, beginning with the chemist Svante Arrhenius in 1896, had speculated that human activities were increasing atmospheric carbon dioxide and that this rise might cause global warming. Arrhenius, a Swede, thought a little climate warming might be a good thing, at least for Sweden. Others argued that the natural variability in CO_2 concentration would be much larger and overwhelm any human contribution. Keeling confirmed that CO_2 measurements were very variable in dense forests and other biologically active zones, but not on the high, barren slopes of the Mauna Loa volcano.

There he observed the global activity of the biosphere from a completely new perspective: as small seasonal cycles imprinted on the anthropogenic rise of CO_2. The seasonal variation in atmospheric CO_2 ranges on average from 3 ppm higher than the annual mean value in May to 3 ppm lower in October, as shown in the inset diagram in Figure 14.1. These oscillations reflect cycles in global plant growth dominated by the temperate and boreal forests of the Northern Hemisphere. Net mass of land plants increases during the Northern Hemisphere summer, when photosynthesis draws CO_2 into plants, and decreases during the Northern Hemisphere winter, when plants respire CO_2 back into the atmosphere. This in-and-out flux of carbon dioxide, first observed by Keeling, is nothing less than the "global breathing of the biosphere."

But wait a minute. How can we be sure that the observed rise in the Keeling curve is not some sort of natural change unrelated to human activities? Keeling and fellow chemists answered this question by measuring the isotopes of carbon in his Mauna Loa air samples. These data demonstrated that the increase in atmospheric CO_2 could not be from natural sources, such as decaying vegetation; they instead matched the isotopic signature of fossil-fuel burning. Keeling's data imply that civilization is altering the chemistry of the atmosphere.

To get a geologic perspective on the Keeling curve, we can compare it with results from another heroic effort in



(a) (b)

FIGURE 14.1 (a) The Keeling curve is a plot of a 60-year recording of the CO_2 content of the atmosphere, measured in parts per million (ppm) at the Mauna Loa Observatory. The blue curve shows the average yearly values, which have risen by 32 percent in the last 60 years, and the red curve is plotted month by month, oscillating in a season cycle about the yearly mean. The inset diagram shows the average seasonal cycle; the red dots are monthly averages. (b) Charles Keeling receiving the Medal of Science from President George W. Bush in 2002. [(b) National Science Foundation.]

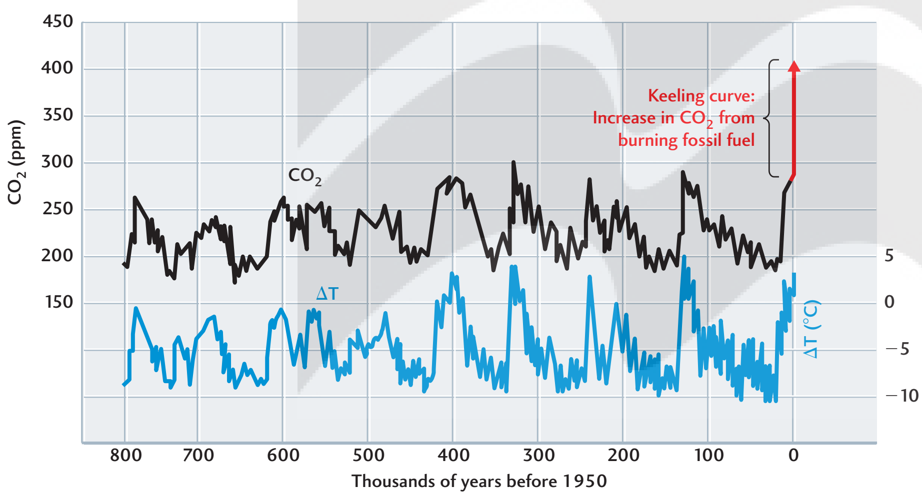


FIGURE 14.2 Atmospheric carbon dioxide and temperature data derived from Antarctic ice core measurements for the past 800,000 years. The Keeling curve is the nearly vertical segment appended to the ice core data at the upper right. [Data from D. C. Harris, *Anal. Chem.* 2010, 82, 7865–7870, and data from D. Lüthi et al., *Nature* 2008, 453, 379–382.]

environmental data collection—the CO_2 record derived from drilling into the Antarctic ice sheet (Chapter 12). What we see is alarming. In the two centuries since the Industrial Revolution, atmospheric CO_2 has spiked to levels way above those reached in the last 800,000 years of Earth history (**Figure 14.2**). At no time during the past 800,000 years have CO_2 concentrations been much higher than the preindustrial average of 280 ppm. In fact, you have to go far back into the geologic record to find a time when CO_2 concentrations were above 400 ppm. Studies of sediment cores indicate that those levels have not been reached since the Middle Miocene, more than 14 million years ago, when Earth's surface temperature was much warmer than it is today.

Types of Anthropogenic Global Change

The rising concentration of CO_2 documented by Keeling is a *chemical change* to the atmosphere. Along with this chemical change, there are *physical changes* to the climate system, and *biological changes* to the ecosystems that support life on Earth. One type of change can cause other types of change through interactions within the Earth system.

For instance, the atmospheric concentration of carbon dioxide is increasing by about half a percent per year. Some of this carbon dioxide is being absorbed by the oceans, causing acidification of seawater. The excess CO_2 not drawn into the oceans or continental forests is enhancing the greenhouse effect, leading to warming at the planetary surface and other physical changes to the climate system. Climate change and ocean acidification are in turn perturbing the biosphere, leading to the loss of species and potentially the collapse of entire ecosystems.

Chemical Change

Since the beginning of the industrial era, fossil-fuel burning, deforestation, land-use changes, and other human activities have caused a rapid rise in the concentrations of greenhouse gases in the atmosphere. Figure 14.3 shows the atmospheric concentrations of three greenhouse gases—carbon dioxide, methane, and nitrous oxide—over the past 10,000 years. In all three cases, the concentrations remained relatively constant through most of the Holocene epoch, but shot upward after the Industrial Revolution.

The global atmospheric concentration of methane has increased by 150 percent from its preindustrial value, and that of carbon dioxide has increased almost 50 percent. In both cases, the observed increases can be explained by human activities. The energy sector is the predominant source of atmospheric methane—specifically from the production, processing, storage, and distribution of coal and natural gas. Another significant source of methane is from microbial activity in wetlands, rice paddies, and the guts of cows and other ruminants.

Methane's greenhouse effect is weaker than that of carbon dioxide, however, so even though its relative concentration has gone up more, its contribution to greenhouse warming is only about 30 percent as large. The postindustrial increase in nitrous oxide, primarily from fertilized agricultural soils, has contributed about 20 percent, an even smaller fraction of the greenhouse warming.

Two other global chemical changes deserve our attention: acidification of the oceans as they absorb increasing amounts of carbon dioxide from the atmosphere, a chemical process described in Chapter 12, and depletion of the stratospheric ozone layer. The latter is a case study in how human society can successfully respond to a clear and present ecological danger.

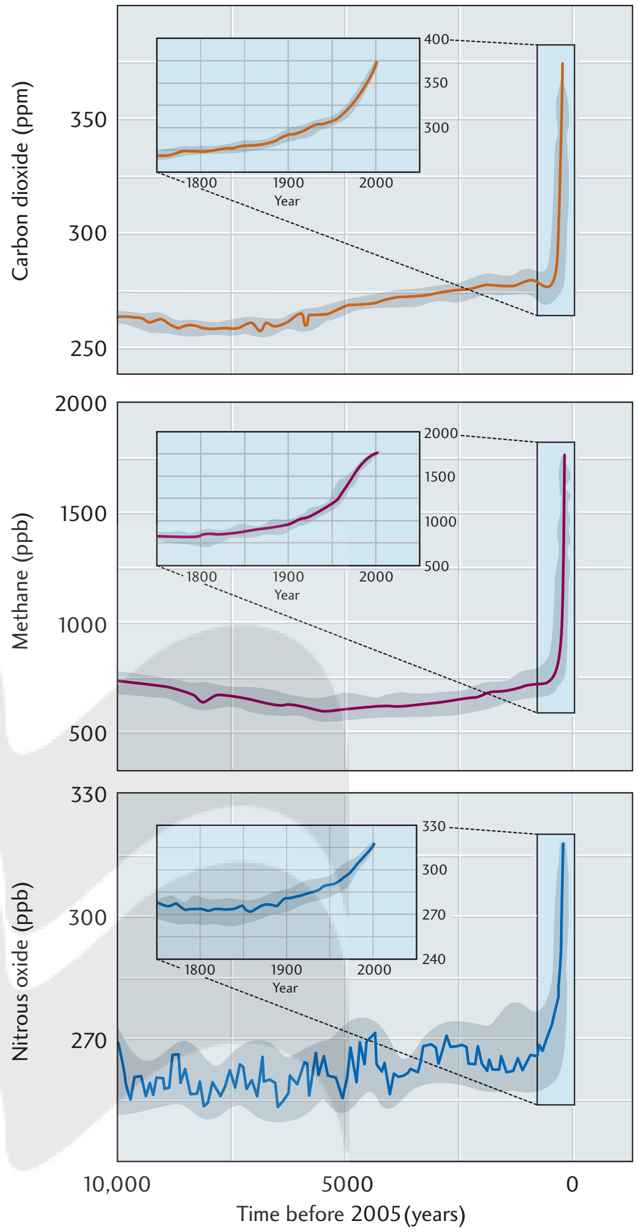


FIGURE 14.3 Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide over the last 10,000 years (large panels) and for 1750–2000 (inset panels). These measurements, compiled by the Intergovernmental Panel on Climate Change, were derived from ice cores and atmospheric samples. Shaded bands show the uncertainties in the measurements. [Data from IPCC, *Climate Change 2007: The Physical Science Basis*. Figure SPM.1, Cambridge University Press.]

Reducing Ozone Depletion: An Environmental Success Story Near Earth's surface, ozone is a major constituent of smog and a powerful greenhouse gas. Low-lying ozone forms when sunlight interacts with nitrogen oxides and other chemical wastes from industrial processes and automobile exhausts. Ozone in Earth's stratosphere, which is concentrated in a layer 20–30 km above the surface (see Figure 12.2), is another matter. There, solar radiation ionizes oxygen gas (O_2) into ozone (O_3^+), forming a protective layer that shields the planetary surface from ultra-violet (UV) radiation. Skin cancer, cataracts, impaired immune systems, and reduced crop yields are attributable to excessive UV exposure. Ozone acts as "Earth's sunscreen" to block much of this harmful radiation.

In 1995, the Nobel Prize in chemistry was awarded to Paul Crutzen, Mario Molina, and Sherwood Rowland for the hypotheses they had advanced more than 20 years earlier about how the protective ozone layer can be depleted by reactions involving human-made compounds. One class of compounds, chlorofluorocarbons (CFCs), were widely used as refrigerants, spray-can propellants, and cleaning solvents. CFCs are stable and harmless except when they migrate to the stratosphere. High above Earth, the intense sunlight breaks down these compounds,

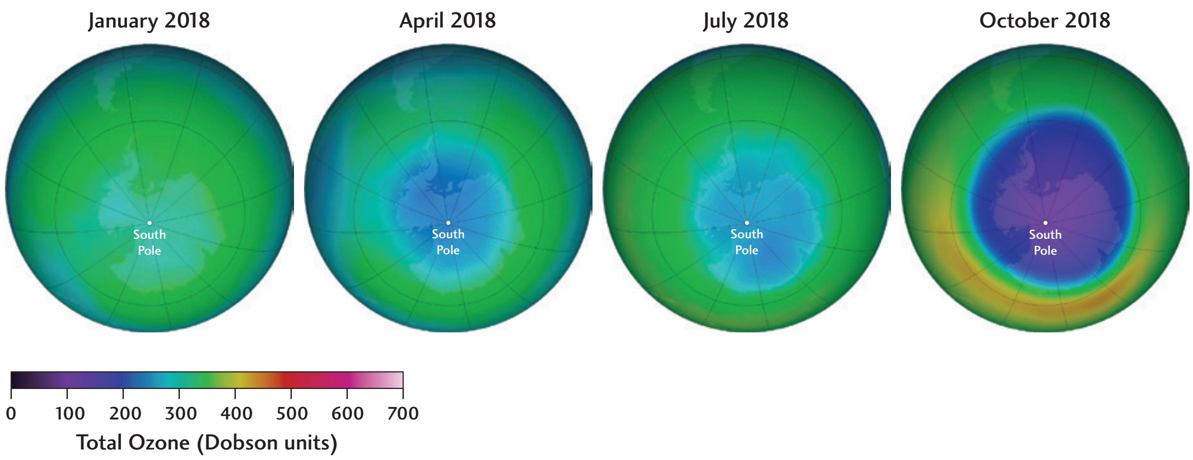


FIGURE 14.4 Total ozone in the Antarctic atmosphere, imaged by NASA satellites in January, April, July, and October 2018, measured in Dobson units. The Antarctic ozone hole is the dark blue/purple region seen on the October image (ozone values below 220 Dobson units). The ozone hole develops during the austral winters, when extreme cold precipitates ice clouds in the stratosphere that catalyze the destruction of ozone by the chlorine from CFCs. [NASA Ozone Watch.]

releasing their chlorine. Molina and Rowland proposed that chlorine reacts with the ozone molecules in the stratosphere and thins the protective ozone layer.

Molina and Rowland's hypothesis was confirmed when a large hole in the ozone layer was discovered over Antarctica in 1985 (Figure 14.4). Subsequently, **stratospheric ozone depletion** was found to be a global phenomenon. Elevated surface levels of UV radiation due to stratospheric ozone depletion have been observed since the early 1990s.

In the 1980s, when scientists were trying to convince government and industry officials that the ozone layer was possibly being depleted due to CFCs, a senior government official remarked that the solution was for people to wear hats, sunscreen, and dark glasses. Fortunately, environmental wisdom prevailed. In 1989, a group of nations entered into a global treaty to protect the ozone layer. This treaty, called the **Montreal Protocol** on Substances that Deplete the Ozone Layer, has been signed by all of the world's 195 countries. The Montreal Protocol phased out CFC production in 1996 and set up a fund, paid for by developed nations, to help developing nations switch to ozone-safe chemicals.

Continuing negotiations have produced amendments aimed at limiting emissions of other ozone-depleting chemicals. The most recent, called the Kigali Amendment, went into force on January 1, 2019; it commits countries to cut the production and consumption of hydrofluorocarbons (HFCs) by more than 80 percent over the next 30 years. Owing to these successful efforts, the long-term projections indicate diminished destruction of the ozone layer by anthropogenic chlorine. Monitoring of the ozone hole by satellites and other images confirms that chlorine levels in the stratosphere are declining and the ozone hole is gradually healing.

The Montreal Protocol has become a model for how scientists, industrial leaders, and government officials can work together to head off an environmental disaster.

Physical Change

Warming of Earth's surface is an example of global physical change. Humans have been tracking global temperatures for some time. The thermometer was invented in the early seventeenth century, and Daniel Fahrenheit set up the first standard temperature scale in 1724. By 1880, temperatures around the world were being reported by enough meteorological stations on land and on ships at sea to allow accurate estimation of Earth's average annual surface temperature. Although the average annual surface temperature fluctuates substantially from year to year and from decade to decade, the overall trend has been upward (Figure 14.5). Between the late nineteenth century and the early twenty-first, the average annual surface temperature rose by about 0.8°C (Figure 14.5a). This increase is referred to as the **twentieth-century warming.**

The twentieth-century warming was not uniform over the globe. Figure 14.6 shows the geographic variation of the yearly average temperatures for 1912, 1962, and 2012, colored according to the temperature differences relative to the baseline period 1951–1980. Globally averaged, the difference between 1912 and 2012 is about 0.8°C, consistent with the twentieth-century warming. But some of the regional differences are larger, and some are smaller. In the Arctic region, for example, the temperature rise has been several times higher than the mean value, whereas in the central Pacific Ocean, there has been very little. In general, the land surfaces have warmed more than the oceans. Most of the warming has occurred during the last 50 years. In large regions of the northern continents, the temperature rise between 1962 and 2012 has exceeded 1°C.

We know that human activities are responsible for the increasing concentrations of CO_2 in the atmosphere because, as Keeling demonstrated, the carbon isotopes of fossil fuels have a distinctive signature that precisely

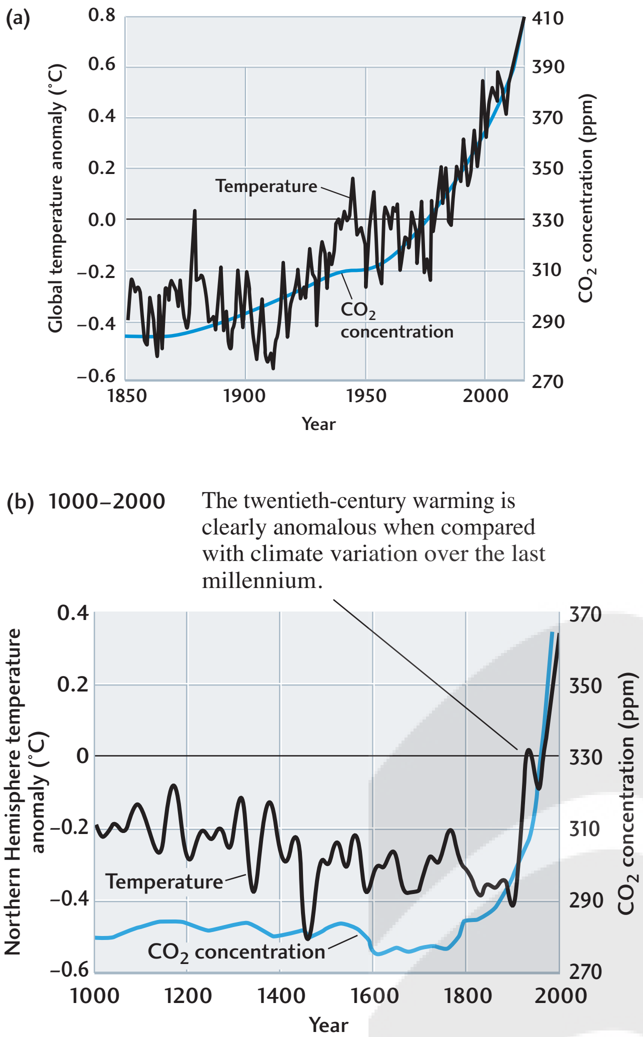


FIGURE 14.5 Comparison of average annual surface temperature anomalies (black lines) with atmospheric CO_2 concentrations (blue lines) shows a recent warming trend that is correlated with increases in atmospheric CO_2 concentrations. (a) Average global annual surface temperature anomalies, calculated from thermometer measurements, and CO_2 concentrations between 1850 and 2017. The small bump in the temperature rise during World War II, 1939–1945, is due to a wartime bias in the way temperature measurements were averaged by the British and U.S. fleets. (b) Average annual surface temperature anomalies for the Northern Hemisphere, estimated from tree rings, ice cores, and other climate indicators; and atmospheric CO_2 concentrations for the last millennium. In both of these figures, the temperature anomaly is defined as the difference between the observed temperature and the temperature average for the period 1961–1990. [Data from IPCC, *Climate Change 2001: The Scientific Basis,* and IPCC, *Climate Change 2013: The Physical Science Basis.*]

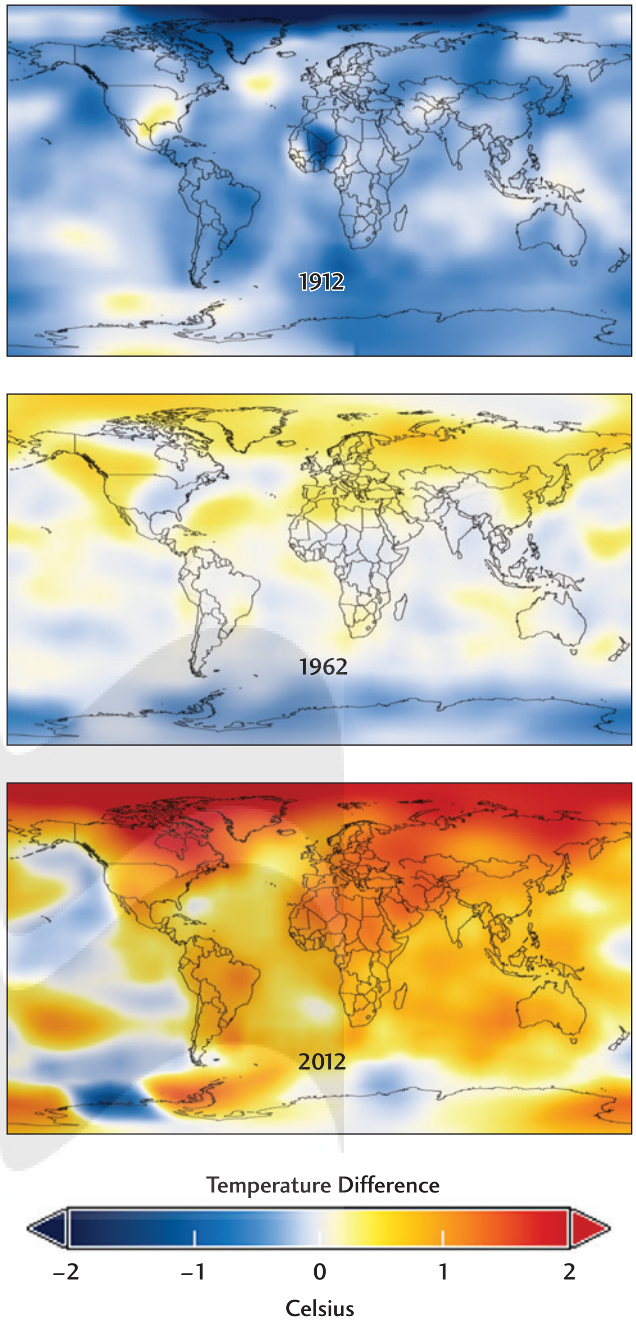


FIGURE 14.6 Surface temperature anomalies for the years 1912 (top), 1962 (middle), and 2012 (bottom) measured relative to the mean local temperatures for the baseline period 1951–1980. The globally averaged difference between 1912 and 2012 is about 0.8°C, consistent with the twentieth-century warming (see Figure 14.5). In the arctic region, the warming has been several times higher than this mean value, whereas in the central Pacific Ocean, it has been much less. [NASA's Goddard Space Flight Center Scientific Visualization Studio.]

matches the changing isotopic composition of atmospheric carbon. But how certain can we be that the twentieth-century warming was a direct consequence of the anthropogenic CO_2 increase—that is, a result of an enhanced greenhouse effect—and not some other kind of change associated with natural climate variation?

To answer this and other questions about how Earth's climate is changing, the United Nations established in 1988 the **Intergovernmental Panel on Climate Change (IPCC)**, an international scientific organization that reviews all research on climate and its variations. The IPCC is charged with developing a consensus, science-based view on how Earth's climate has changed in the past and what might happen in the future, including the potential environmental and socioeconomic impacts of anthropogenic climate change. This textbook portrays the scientific consensus on anthropogenic global change documented in the IPCC Assessment Reports (see Earth Issues 14.1) and in the more recent *Fourth National Climate Assessment,* released by U.S. Global Change Research Program in 2017.

Earth Issues 14.1 The Intergovernmental Panel on Climate Change

Earth's climate system is incredibly complex, so predicting its response to anthropogenic emissions of greenhouse gases is hardly a straightforward task. No one person can keep up with the vast amount of climate-change research that is being conducted worldwide by thousands of scientists. In 1988, the United Nations (UN) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) to provide government leaders and the public at large with a clear scientific view of current knowledge about climate change and its potential environmental and socioeconomic impacts.

The IPCC is open to all UN and WMO members, and all of the world's 195 countries are currently participating. The main product of the IPCC has been a series of Assessment Reports released every five to six years since 1990. Thousands of scientists from all over the world have contributed to the work of the IPCC on a voluntary basis as authors, contributors, and reviewers of these major reports. Each report in succession has laid out the most definitive scientific summaries of how climate has changed in the past and how it might change in the future.

IPCC's *First Assessment Report,* published in 1990, played a key role in the creation of the United Nations Framework Convention on Climate Change, the main international treaty to reduce global warming and deal with the consequences of climate change. The IPCC *Second Assessment Report* of 1995 provided important material for negotiators of the Kyoto Protocol in 1997. The *Third Assessment Report* was published in 2001, and the *Fourth* in 2007.

In 2007, the Nobel Peace Prize was awarded jointly to the IPCC and former U.S. Vice President Al Gore "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."

The *Fifth Assessment Report,* finalized in 2014, comprised sub-reports from the three IPCC working groups, entitled *The Physical Science Basis of Climate Change, Climate Change Impacts, Adaptation and Vulnerability,* and *Mitigation of Climate Change*. This report paved the way to the Paris Agreement, in which all 195 countries committed themselves to the goal of "holding the increase in the global average temperature to well below 2°C (3.6°F) above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C (2.7°F)." The Paris Agreement was adopted on December 12, 2015, by the United Nations Framework Convention on Climate Change and unanimously ratified by all nations. As of this writing (December, 2018), only one country, the United States, has threatened to withdraw from the agreement.

The IPCC began the process of producing its sixth assessment in 2017. In October 2018, it released *Global Warming of 1.5°C: An IPCC Special Report,* which lays out in stark terms the manifestations and consequences of global warming to 1.5°C above preindustrial levels, which is 0.5°C above the current average surface temperature. The *New Yorker Magazine* (October 9, 2018) called this pessimistic report "a collective scream sieved through the stern, strained language of bureaucratese."

The material on climate change described in this chapter and elsewhere in this textbook draws heavily from the scientific consensus documented in the IPCC reports.

A 2018 meeting of the co-chairs and lead authors of the IPCC's *Fifth Assessment Report* (AR5). [Photo by IISD/Sean Wu (enb.iisd.org/climate/ipcc48/6oct.html).]

The twentieth-century warming lies within the range of temperature variations that have been inferred for the Holocene. In fact, average temperatures in many regions of the world were probably warmer 10,000 to 8000 years ago than they are today. The twentieth-century record is clearly anomalous, however, when compared with the pattern and rate of climate change documented during the last millennium. Although direct temperature measurements are not available from before the nineteenth century, climate indicators such as ice cores and tree rings have allowed climatologists to reconstruct a temperature record for the Northern Hemisphere during that period (Figure 14.5b). That record shows an irregular but steady global cooling of about 0.2°C in the nine centuries between 1000 and 1900. It also shows that fluctuations in average surface temperature during each of these centuries were less than a few tenths of a degree.

The second argument, and to many a more compelling one, comes from the agreement between the observed pattern of warming and the pattern predicted by the best climate models. Models that include changes in atmospheric greenhouse gas concentrations not only reproduce the twentieth-century warming, but also reproduce the observed patterns of temperature change both geographically and with altitude in the atmosphere—the fingerprints of an **enhanced greenhouse effect.** For example, these models predict that, as human-enhanced greenhouse warming occurs, nighttime low temperatures at Earth's surface should increase more rapidly than daytime high temperatures, thus reducing daily temperature variation. Climate data for the last century confirm this prediction.

Another fingerprint of global warming has been the changes seen in mountain glaciers at lower latitudes. Glaciers found above 5000 m in Africa, South America, and Tibet have been shrinking during the last hundred years, an observation that is also consistent with the predictions of climate models (**Figure 14.7**).

FIGURE 14.7 Glaciologist Lonnie Thompson at an altitude of 5300 m (17,390 ft) on Tibet's Dasuopu Glacier. Ice coring on this glacier provides evidence of abnormal global warming during the twentieth century. [Lonnie Thompson/Byrd Polar Research Center, Ohio State University.]

Biological Change

The biosphere has been evolving throughout its multi-billion-year history. The geologic record shows long periods of stability punctuated by brief intervals of rapid and radical changes to the biosphere. The most extreme events of global biological change are marked by *mass extinctions*—dramatic losses in the number of species over short periods. Some of these cataclysms were caused by extraterrestrial events, such as the meteorite impact that killed off the dinosaurs at the end of the Cretaceous period. Others may have been due to climate change and ocean acidification, including the biggest mass extinction ever, at the end of the Permian period, when 95 percent of all species vanished from the fossil record. The end-Permian extinction, which marks the boundary between the Paleozoic and Mesozoic eras, appears to have been stimulated by huge, gaseous outpourings of the basaltic lavas that formed the Siberian Traps (see Chapter 5).

Earth is now undergoing another period of global biological change, but this time not from the hammer blow of some extreme extraterrestrial or subterrestrial event, but because a single biological species—*homo sapiens*—has recently evolved into an active agent of global physical change. We are at the cusp of an extreme event that will leave its mark in the geologic record when seen millions of years from now. Many geoscientists believe that we are now leaving the equitable natural conditions of the Holocene epoch and entering a new epoch of human-dominated change—the *Anthropocene*. We do not know what features of this event will be most recognizable to some geologist far in the future, because that geologic record is just now being written. What it will say depends on how our species responds to its own success.

Climate Change

In its Fifth Assessment Report, finalized in 2014, the IPCC drew the following conclusions:

- From the beginning of the twentieth century until 2012, the average temperature of Earth's surface has risen, on average, by about 0.9°C.
- Most of this warming has been caused by anthropogenic increases in atmospheric greenhouse gas concentrations.
- Concentrations of atmospheric greenhouse gases will continue to increase throughout the twenty-first century, primarily because of human activities.
- The increase in atmospheric greenhouse gas concentrations will cause significant global warming during the twenty-first century.

The last prediction is strongly supported by temperature trends at the time of this writing (late 2018). The four years since the IPCC report was published have been the four warmest years since modern recordkeeping began in 1880. The warmest year on record, 2016, beat the previous record, set just the year before, by 0.13°C. The 10 warmest years on record have all occurred since 1998; the 20 warmest years have all occurred since 1995. The surface of our planet is definitely getting hotter (Figure 14.5b).

Projecting Future Climate Change

How much hotter will it get, and how will this global warming affect local climates and ecosystems? The projections are uncertain, first, because we do not completely understand how the climate system works—our models are uncertain—and, second, because the projections depend strongly on how human population and the global economy will evolve, including how energy resources will be exploited and what political decisions will be made to limit greenhouse gas emissions. The IPCC has forecast increases in atmospheric CO_2 concentrations under a series of scenarios that sample the possibilities. Each scenario is characterized by a **representative concentration pathway** or "RCP" that corresponds to a net concentration of greenhouse gases in Earth's atmosphere by the year 2100. Three of these scenarios are depicted in Figure 14.8:

- **Scenario A** (red line) assumes a continued reliance on fossil fuels as our major energy source and thus an increasing concentration of greenhouse gases. In this scenario, called "RPC8.5" by the IPCC, the carbon dioxide concentration would top 900 ppm by 2100, more than three times its preindustrial level, and the radiative forcing would be 8.5 W/m^2 in 2100. **Radiative forcing** by a climate variable such as greenhouse gas concentration is a change in Earth's energy balance between incoming solar energy and outgoing thermal infrared energy when the variable is changed while all other factors are held constant. A radiative forcing of 8.5 W/m^2, which specifies this particular RCP scenario, can be compared to the average solar forcing of 240 W/m^2.
- **Scenario B** (green line, "RCP6.0") assumes that carbon dioxide concentrations will begin to stabilize in the later part of the twenty-first century, reaching just over 600 ppm, more than twice the preindustrial level, by 2100. This scenario reduces the radiative forcing to 6.0 W/m^2, but achieving it would require a big shift toward nuclear energy and renewable energy sources, as well as fossil fuels with less carbon intensity, such as natural gas. As we saw in Chapter 13, the fossil-fuel burning still dominates the energy economy, although the transition to less carbon-intensive energy sources is under way.
- **Scenario C** (blue line, "RCP2.6") has a peak in carbon dioxide concentrations around 2050, followed by a modest decline to carbon dioxide concentrations near the present level (400 ppm) by the end of the century. To achieve a scenario with such little radiative forcing (2.6 W/m^2) would require a much more rapid conversion from fossil fuels to cleaner alternatives than scenario B.

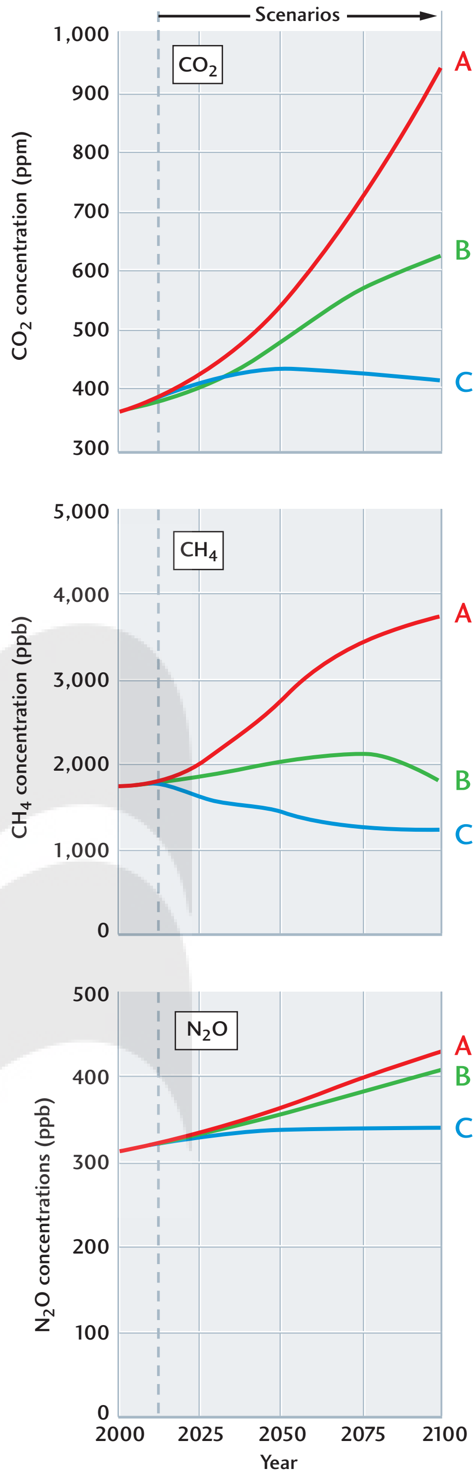


FIGURE 14.8 Three scenarios or "representative concentration pathways" (RCPs) projected by the IPCC for carbon dioxide, methane, and nitrous oxide during the twenty-first century. Scenario A (red line) implies continuing high rates of fossil-fuel burning (RCP8.5); scenario B (green line) implies stabilization of emission rates in the latter part of the twenty-first century (RCP6.0); scenario C (blue line) implies a rapid conversion to non-fossil fuels (RCP2.6). [Data from IPCC, *Climate Change 2013: The Physical Science Basis*.]

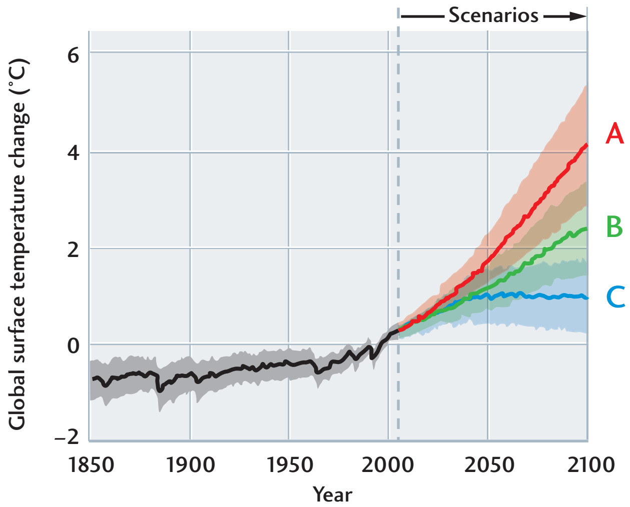


FIGURE 14.9 IPCC predictions of average surface temperatures over the twenty-first century derived from scenarios A (red line), B (green line), and C (blue line). Gray-shaded band gives the uncertainties in past measurements; color-shaded band shows the prediction uncertainties of each scenario, which are due to incomplete knowledge of the climate system as well as natural climate fluctuations. [Data from IPCC, *Climate Change 2013: The Physical Science Basis*.]

The IPCC has used its scenarios, along with other types of projections, to predict average global surface temperatures up to 2100 (Figure 14.9). Allowing for uncertainties in the Earth system models, it found that global temperature increases during the twenty-first century could range from 0.5°C to 5.5°C, depending on the scenario. The lower values of scenario C can be achieved only through rapid reductions in fossil-fuel burning and conversion to clean and resource-efficient energy technologies. Under the less radical (but still optimistic) scenario B, the temperature rise in the twenty-first century would likely exceed 2°C, over twice the twentieth-century warming. In scenario A, the most pessimistic, the temperature increase would probably exceed 4°C.

How will the enhanced greenhouse effect, along with related factors, such as deforestation, change temperatures across Earth's surface? Figure 14.10 maps the regional temperature increases predicted by the three IPCC scenarios. The predicted geographic patterns of temperature change display similarities to the observed pattern of late-twentieth-century warming in Figure 14.5. In particular, the warming is greater over land than over the oceans, and the temperate and polar regions of the Northern Hemisphere show the most warming.

Human Population and Global Change

Anthropogenic global change is inextricably tied to human population size. This population exploded after the Industrial Revolution, increasing from about 1 billion people in 1800 to more than 7.6 billion today (Figure 14.11).

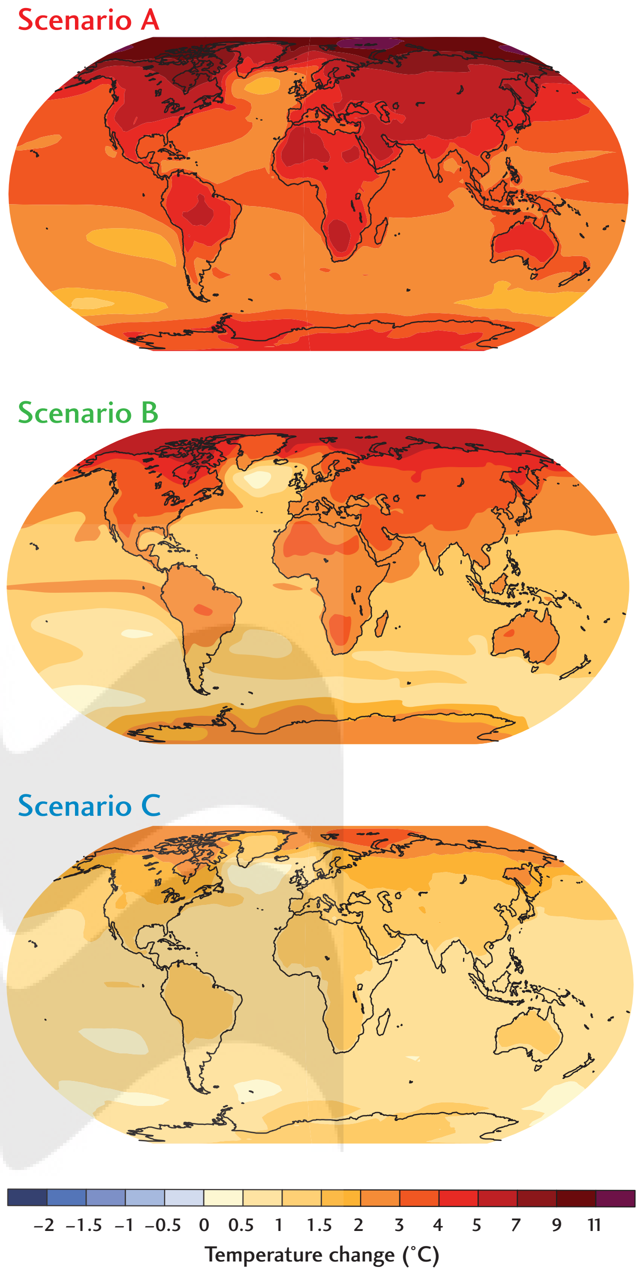


FIGURE 14.10 Average surface temperatures predicted for 2080–2100 by the three IPCC scenarios, expressed as differences from average surface temperatures measured at the same locations during the baseline period 1986–2005. [Data from IPCC, *Climate Change 2013: The Physical Science Basis*.]

Population is the dominant variable in any predictions of future anthropogenic change, because it so strongly controls anthropogenic emissions of greenhouse gases. Owing to their dependence on population, the representative concentration pathways used by the IPCC necessarily make implicit assumptions about population growth. Figure 14.11 shows the population growth curves consistent with these scenarios. Population projections to the year 2100 range from 12.4 billion for scenario A to 8.8 billion for scenario C.

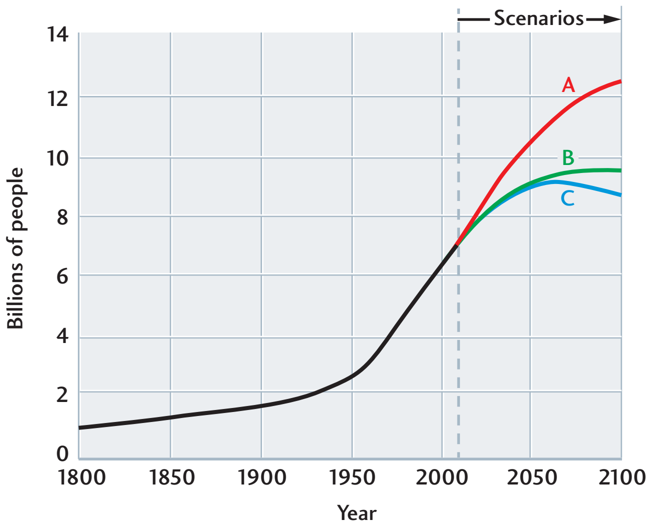


FIGURE 14.11 Black-line charts the global growth of human population since 1800. Colored lines show future population growth projected by the three IPCC scenarios in Figure 14.8. In scenario A (red line), world population continues to grow into the twenty-second century. In scenario B (green line), it levels off in the late twenty-first century, and in scenario C (blue line), it declines after 2070. [Data from IPCC, *Climate Change 2013: The Physical Science Basis*.]

We can compare these scenario-based projections with demographic predictions by the United Nations. The UN's median projection, its "best guess," pegs the human population in 2100 at 11.3 billion, about halfway between scenarios A and B. The UN assigns uncertainties to its projections. When these uncertainties are taken into account, one finds that the chances are greater than 95 percent that the *actual* world population curve will fall somewhere within the band between scenarios A and C.

The probabilities given by the UN are not symmetrically distributed across this band, however. The chance that the population trajectory will lie between scenarios A and B is almost 80 percent, and there is less than a 5 percent chance that it will fall between B and C. In other words, scenario C is a much less likely representation of future global change than either A or B. In fact, over the last decade, human population and its greenhouse gas emissions are following scenario A rather closely. A climate future conforming to scenario B is becoming a harder goal to achieve.

Consequences of Climate Change

As documented by the IPCC, human emissions of greenhouse gases are certain to cause further global warming. These changes have the potential to affect civilization in both positive and negative ways. Some regional climates may become more hospitable to humans, while others may deteriorate. On the balance, however, the adaptation of civilization and the biosphere to a much warmer planet will not be easy, and it will certainly be costly. The authors' home city of Los Angeles, for example, is likely to become hotter and drier. Some potential effects of climate change are listed in Table 14.1.

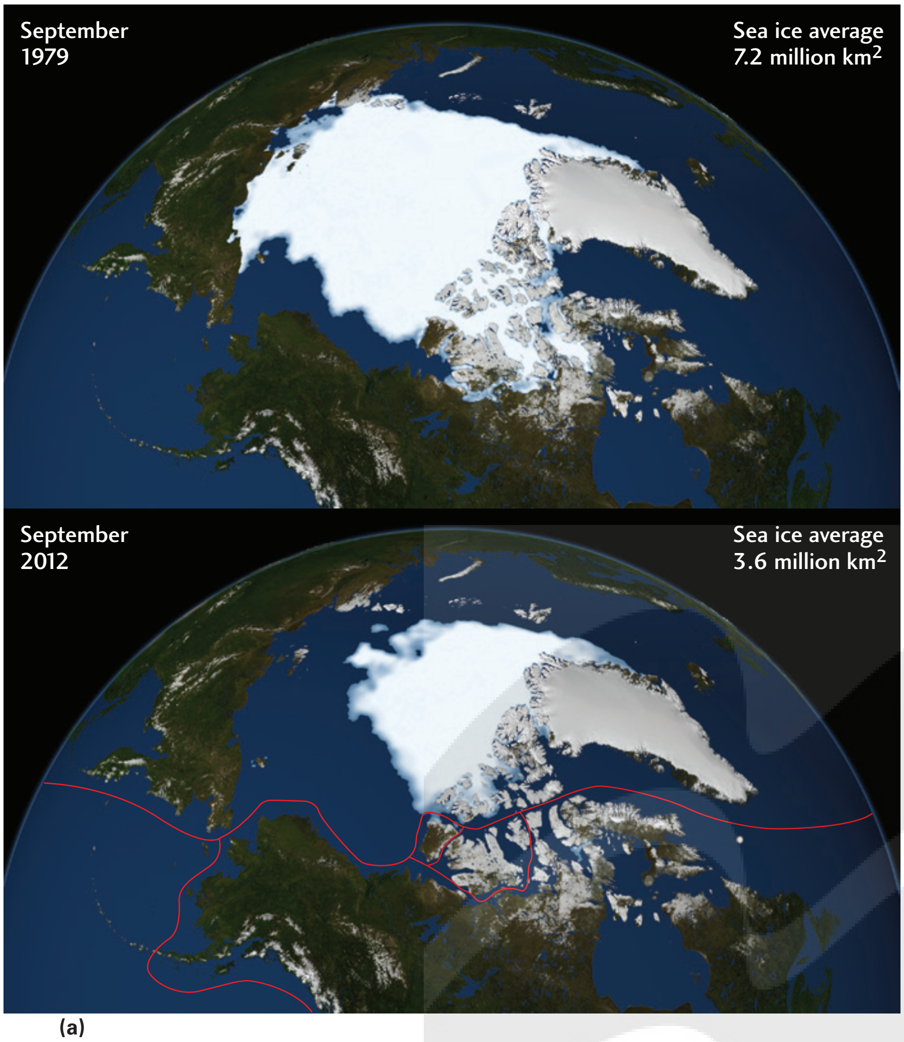
TABLE 14.1 Potential Effects of Climate Change on Ecosystems and Resources

SYSTEM	POTENTIAL EFFECTS
Forests and other ecosystems	Migration of vegetation; reduction in ecosystem ranges; altered ecosystem composition
Species diversity	Loss of diversity; migration of species; invasion of new species
Coastal wetlands	Inundation of wetlands; migration of wetland vegetation
Aquatic ecosystems	Loss of habitat; migration to new habitats; invasion of new species
Coastal resources	Inundation of coastal structures; increased risk of flooding
Water resources	Changes in water supplies; changes in patterns of drought and flooding; changes in water quality
Agriculture	Changes in crop yields; shifts in relative productivity among regions
Human health	Shifts in ranges of infectious disease organisms; changes in patterns of heat-stress and cold-weather afflictions
Energy	Increase in cooling demand; decrease in heating demand; changes in hydroelectric energy resources

Source: Office of Technology Assessment, U.S. Congress.

Changes in Regional Weather Patterns The large-scale geographic patterns of climate change in the twenty-first century are likely to be similar to those observed over the past several decades. The IPCC has documented a number of current trends in regional weather patterns that are likely to continue:

- The relative humidity and frequency of heavy precipitation events have increased over many land areas, consistent with the observed temperature increases. Increased precipitation has been observed in eastern parts of North and South America, northern Europe, and northern and central Asia. For example, 2018 was wettest year on record in many cities in the eastern United States, including Washington, D.C., and Pittsburgh.
- Drying has been observed in the Sahel, the Mediterranean, southern Africa, and parts of southern Asia. More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics.



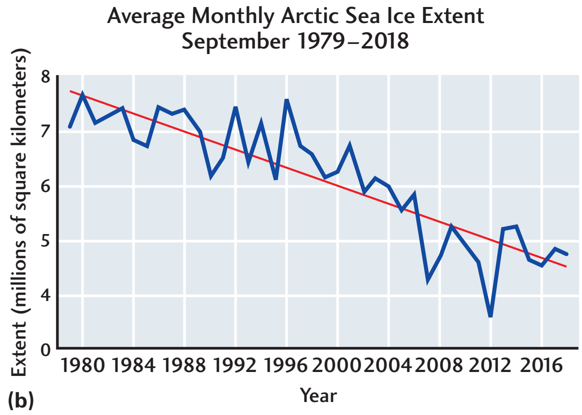


FIGURE 14.12 (a) Global warming is melting the Arctic ice cap. These images of the Arctic, derived from NASA satellite data, compare the minimum extent of the polar ice cap in September 1979 (top) with the minimum extent in 2012 (bottom). One near-term benefit to human society will be the opening of the Northwest Passage and other shorter sea routes between the Atlantic and Pacific Oceans (shown in the bottom panel as red lines). (b) Graph showing that the average sea ice extent during the month of September has decreased since 1979. [NASA/Goddard Scientific Visualization Studio.]

- Widespread changes in temperature extremes have been observed over the last 50 years. Cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent.
- Intense hurricane activity in the North Atlantic has increased, consistent with increases in tropical sea surface temperatures. Although there is no clear trend in the annual number of hurricanes, the number of very strong hurricanes (category 4 and 5 storms) has almost doubled over the past three decades.

Changes in the Cryosphere Nowhere are the effects of global warming more evident than in polar regions. The amount of sea ice in the Arctic Ocean is decreasing with time. The sea ice cover in September 2012 was the lowest for that month since the keeping of satellite records began in 1978: 3.6 million square kilometers, down by a factor of two from the 1979 minimum of 7.2 million square kilometers (Figure 14.12). According to climate models, much of the Arctic Ocean will become ice-free within a few decades. The shrinkage of sea ice is already severely disrupting Arctic ecosystems (Figure 14.13).

Temperatures at the top of the permafrost layer—the exposed, permanently frozen ground of the Arctic continents (see Chapter 15)—have risen by 3°C since the 1980s, and the melting of permafrost is destabilizing structures such as the

FIGURE 14.13 Climate change is already disrupting Arctic ecosystems, adversely affecting the habitat of Arctic animals such as polar bears. [Ralph Lee Hopkins/Getty Images.]

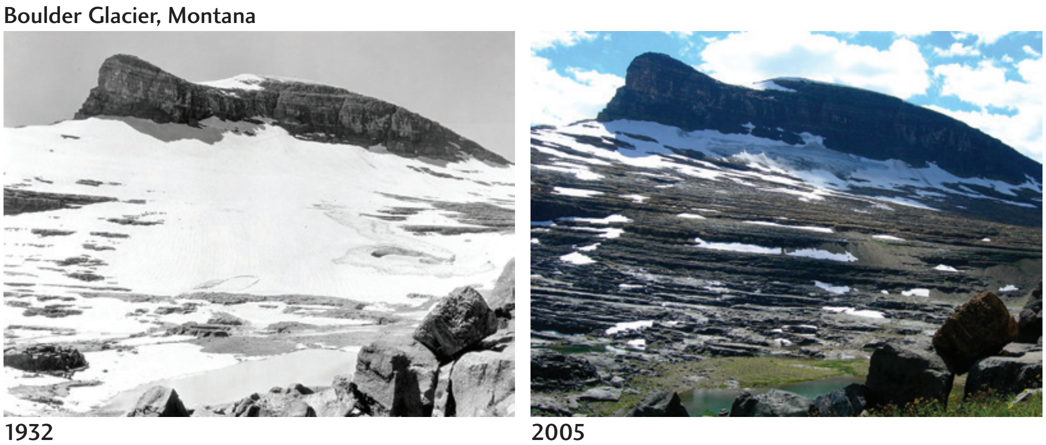


FIGURE 14.14 Glacier National Park's Boulder Glacier in 1932 (left) and 2005 (right). [Photo courtesy T.J. Hileman, Glacier National Park Archives (*left*); photo by Greg Pederson, U.S. Geological Survey (*right*).]

Trans-Alaska oil pipeline. The maximum area covered by seasonally frozen ground has decreased by about 7 percent in the Northern Hemisphere since 1900, with a decrease in spring of up to 15 percent. Valley glaciers at lower latitudes retreated during the twentieth-century warming (**Figure 14.14**). The 37 glaciers remaining at Glacier National Park have lost about 40 percent of their mass in the last half century, and most of them will disappear in the next half century.

Sea-Level Rise The melting of sea ice does not affect the sea level, but the melting of continental glaciers causes the sea level to rise. The sea level also rises as the temperature of ocean water increases, expanding its overall volume. The sea level has risen more than 200 mm since the Industrial Revolution, and it is currently rising at about 3 mm per year. Most of this increase is due to ocean warming (see this chapter's Practicing Geology Exercise).

Climate models based on the IPCC scenarios indicate that the sea level could rise by as much as a meter during the twenty-first century (**Figure 14.15**), creating serious problems for low-lying countries such as Bangladesh (**Figure 14.16**). Island nations like the Maldives, where the highest ground is just a few meters above sea level, will be especially vulnerable (see the chapter-opening photo). On the Eastern Seaboard and Gulf Coast of the United States, flooding during coastal storm surges, such as those witnessed in Hurricanes Katrina (2005), Sandy (2012), and Michael (2018), could become much worse. Some parts of the southeastern United States are already experiencing the "sunny day" flooding of coastal towns during the highest (king) tides that occur once or twice per year (**Figure 14.17**).

Melting of the great continental ice sheets that cover Antarctica and Greenland has thus far contributed only a small amount to sea-level rise, but the rate of glacial thinning is increasing, primarily because of accelerating glacial flow. Satellite observations reveal that flow accelerations of 20 to 100 percent have occurred over the past decade (see

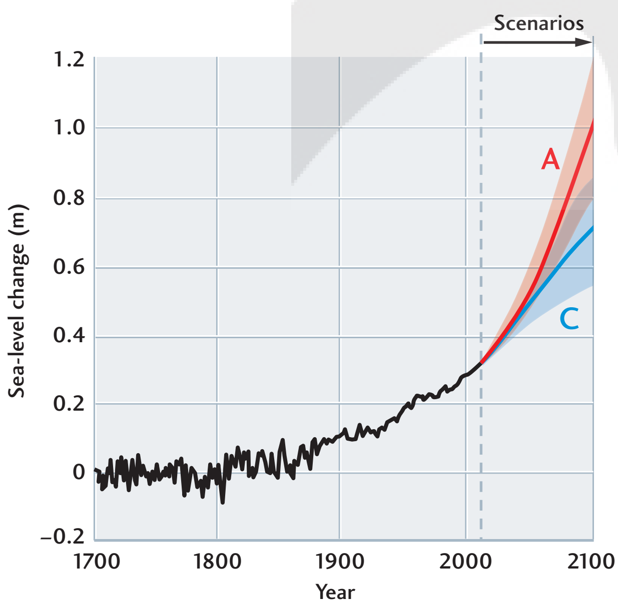


FIGURE 14.15 Sea-level rise 1700–2100. The black line shows the observed value through 2010. The red curve is the IPCC prediction of future sea-level rise during the remainder of the twenty-first century according to scenario A; the blue curve is the prediction according to scenario C.

FIGURE 14.16 Flooded village south of Dhaka, Bangladesh. [Yann Arthus-Bertrand/Getty Images.]

Chapter 15). Climate scientists are concerned that these accelerations will continue as the polar regions become warmer and the loss of ice leads to further warming through the albedo feedback described in Chapter 12.

Species and Ecosystem Migration As local and regional climates change, ecosystems will change with them. Many plant and animal species will have difficulty adjusting to rapid climate change or migrating to more suitable climates. The IPCC's most recent report on global warming estimates that, under conditions similar to scenario B, 18 percent of all insect species and 16 percent of all plants would lose more than half of their climatic habitat by 2100.

Ecosystem stress will be higher in arid zones than in humid zones. Deserts and arid vegetation will encroach on the Mediterranean climate zone, for example, causing changes not seen by humans in the last 10,000 years. Many

FIGURE 14.17 Seasonal high tides combined with rising sea levels caused street flooding on September 29, 2015, in Miami Beach, Florida. [Joe Raedle/Getty Images.]

PRACTICING GEOLOGY EXERCISE

Why Is Sea Level Rising?

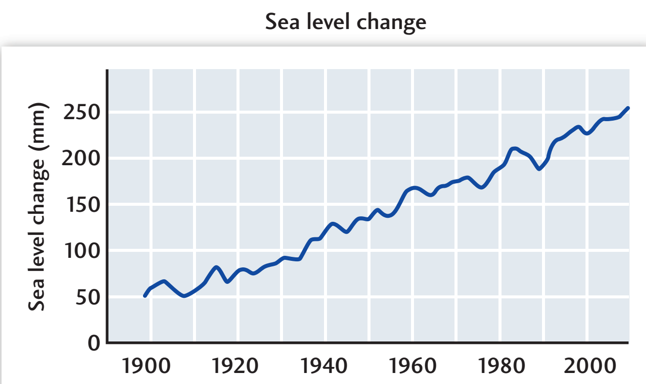
Over the twentieth century, the sea level rose about 200 mm, and it is currently rising at a rate of about 3 mm/year, as shown in the figure below. Why is sea level rising?

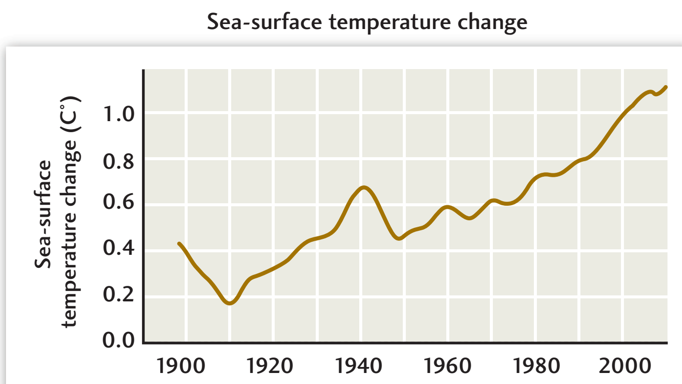
We know that anthropogenic warming of the polar regions is reducing the amount of sea ice and causing the breakup of large ice shelves. Because of isostasy, however, this decrease in the volume of floating ice does not contribute to sea-level rise (see Chapter 15). Melting ice can cause the sea level to change only if the ice is on land, not floating in water (see Figure 15.13).

Most of the world's ice is locked up in the huge continental glaciers that cover Antarctica and Greenland. Is global warming causing these ice sheets to melt faster than they can be regenerated by new snowfall? Radar instruments mounted on Earth-orbiting satellites can directly measure changes in the ice volume of a region. The results have been surprising.

First, according to the IPCC's most recent assessment, the East Antarctic ice sheet, the largest ice reservoir on Earth, has been *gaining* ice mass at about 21 Gt/year in the period 1993–2010. Recent climate changes have evidently increased the amount of snowfall in East Antarctica. This net accumulation is good news because it subtracts from any sea-level rise. Unfortunately, the West Antarctic ice sheet is losing mass at a much higher rate, at about 118 Gt/year, and the smaller Greenland ice sheet is losing about 121 Gt/year.

Most surprising of all is a net loss of 57 Gt/year in the mass of continental valley glaciers and smaller ice sheets (such as those in Iceland), which together account for less than 1 percent of the total ice volume of the cryosphere. The rates are especially high for valley glaciers in temperate and





During the twentieth century, the sea level rose by about 200 mm (top panel), and the global average sea surface temperature increased by about 1°C (bottom panel). [Sea-level change data from B. C. Douglas; sea-surface temperature change data from British Meteorological Office.]

ecosystem impacts will be larger at higher latitudes owing to cold-season warming rates that are well above the global average. High-latitude tundra and boreal forest are particularly at risk; woody shrubs are already encroaching into tundra.

Marine organisms will face progressively lower oxygen levels and high rates of ocean acidification; ecological stress will be exacerbated by rising extremes in ocean temperature. Changes to water temperatures will drive some mobile species, such as plankton and fish, to relocate at higher latitudes. Novel ecosystems may appear. Especially vulnerable are coral reefs, which can move only slowly, and polar ecosystems, which have nowhere to go (**Figure 14.18**). Ecosystems that cannot migrate with climate change or adapt to its consequences may face disruption and even collapse. Under the most favorable climate scenarios, the majority of warm-water coral reefs that exist today will disappear by 2100; more realistic scenarios predict catastrophic losses—greater than 99 percent.

FIGURE 14.18 Bleached coral in the Indian Ocean in the Maldives. [THE OCEAN AGENCY / XL CATLIN SEAVIEW SURVEY.]

tropical regions, which are vanishing very quickly (see Figure 14.14).

Summing up these numbers yields 275 Gt/year as the current rate of continental ice loss. Essentially all of this mass goes into the ocean. One gigaton of water occupies one cubic kilometer (its density is 1 g/cm^3), so the increase in ocean volume is about 275 km^3/year. We can convert this volume change into sea level change using the formula

$$\textit{sea-level rise} = \textit{ocean volume increase} \div \textit{ocean area}$$

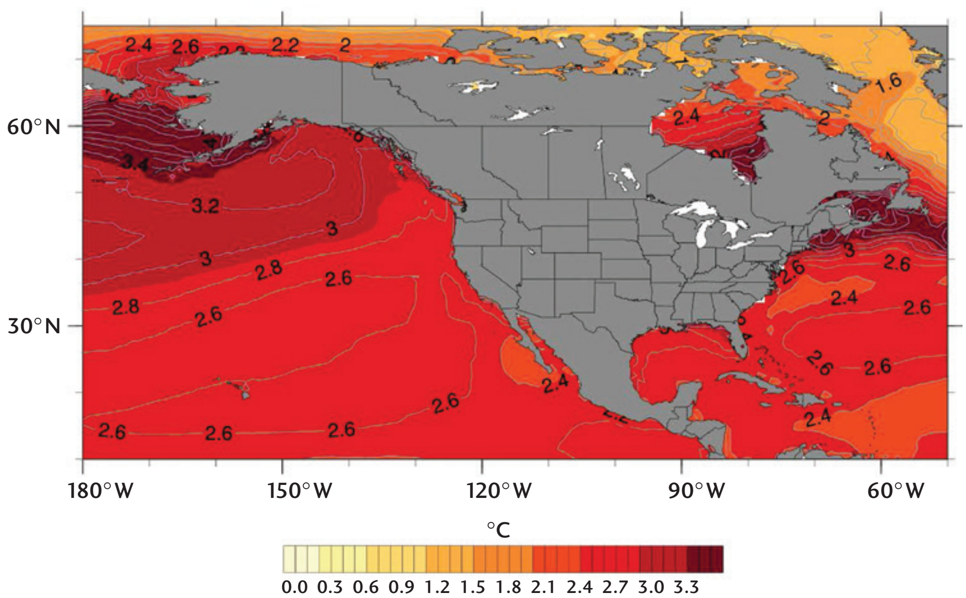
In Appendix 2, we find that the ocean area is 3.6×10^8 km^2, so

$$\textit{sea-level rise} = 275\ km^3/year \div 3.6 \times 10^8\ km^2 = 7.6 \times 10^{-7}\ km/year$$

or about 0.8 mm/year.

This figure is only a fraction of the current rate of sea-level rise. The rest comes from the warming of the ocean itself. Over 90 percent of the heat generated by the enhanced greenhouse effect is taken up by the oceans. On average, surface waters have warmed by almost 1°C during the last century. This warming has caused the water in the upper portion of the ocean to expand a tiny fraction, about 0.01 percent. That small increase in volume can account for most of the 200 mm rise in sea level during that period. If Earth's climate changes according to scenario A, the average sea surface temperature could increase by 2.7°C during the twenty-first century, with even higher changes along some coastal regions (see the figure below).

BONUS PROBLEM: If seawater expands by 0.01 percent for each 1°C of temperature increase, how deep is the layer of the ocean that must be heated by 1°C to explain the twentieth-century sea-level rise of 200 mm?



Projected changes in sea surface temperature (°C) for the coastal United States under scenario A. Map shows the difference between the average sea-surface temperature for the period 2050–2099 period and the average sea-surface temperatures for 1956–2005. [NOAA, from *Climate Science Special Report: Fourth National Climate Assessment*, Volume I. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.). U.S. Global Change Research Program.]

The Potential for Catastrophic Changes to the Climate System The current atmospheric concentrations of carbon dioxide and methane far exceed anything seen in the last 800,000 years (see Figure 14.2). Our climate system is entering unknown territory. While some criticize the IPCC climate change projections, believing they generate unnecessary anxiety, most scientists think that current projections are too conservative because they do not properly take into account some of the positive feedbacks that could greatly enhance global change. We briefly describe a few examples of feedbacks and tipping points that could create more catastrophic change than current observations predict.

- *Acceleration of climate change by albedo feedback.* Earth's *albedo* is the fraction of solar energy reflected by its surface. Albedo feedback occurs when a rise in temperature reduces the accumulation of ice and snow in the cryosphere, which decreases Earth's albedo and thus increases the heat energy Earth's surface absorbs; this increased warming enhances the temperature rise in a positive feedback. Climate models explicitly include this important feedback, and it has been accounted for in the IPCC projections, but aspects of the problem, such as short-term snow-albedo feedback and cloud-albedo feedback, remain uncertain.
- *Destabilization of continental glaciers.* The surface melting of the Greenland glacier in 2012 was the largest on record, and glacial streams within the ice sheet are accelerating much faster than expected. If the Greenland and Antarctic glaciers begin to shed ice much faster than snowfall can generate new glacial ice, the sea level could begin to rise much faster than the current IPCC predictions. The best estimate for Greenland puts this threshold only about 0.6°C above the current level of global warming, conditions that will be reached by mid-century, even under projections as optimistic as scenario C.
- *Carbon release from permafrost and seafloor sediments.* A massive release of methane from shallow seafloor sediments about 55 million years ago might have caused abrupt global warming and led to the mass extinction at the Paleocene-Eocene boundary. Today, there is far more organic carbon stored in permafrost and shallow seafloor sediments than was released at the end of the Paleocene. If global warming begins to thaw those carbon deposits, the feedback would enhance the warming. Models indicate that carbon dioxide released from permafrost could play a significant role in climate change during this century. Methane released from seafloor sediments will likely contribute little to global warming by 2100 but could substantially enhance the warming over the longer term (**Figure 14.19**).
- *Reduction of thermohaline circulation.* Anthropogenic warming of the sea surface, which decreases the density of surface waters, is causing the oceans to become more stratified. The stratification is strengthening because new precipitation and evaporation patterns are decreasing the salinity, and thus the density, of seawater at middle and high latitudes. The net effect is to inhibit surface water from sinking as part of oceans' thermohaline circulation (see Figure 12.5). Under scenario A, thermohaline circulation could weaken by as much as 10 to 50 percent, which would result in less absorption of heat and CO_2 by the ocean—a positive feedback to global warming. Major changes in the Gulf Stream, a strong current in the thermohaline circulation, could alter the climates of North America and Europe.

FIGURE 14.19 Bubbles of methane gas frozen into clear ice in Lake Baikal near the Mongolian border in Russia. [Streluk/Getty Images.]

Ocean Acidification

Not only are the oceans warming, but their chemistry is changing as well. *Ocean acidification,* sometimes called global warming's evil twin, is also born from fossil-fuel burning. About 30 percent of the carbon dioxide emitted into the atmosphere by human activities is being absorbed into the oceans (see Figure 12.20). The carbon dioxide reacts with seawater to form carbonic acid, which is followed by a series of reactions (shown in Figure 12.18) that ultimately leach carbonate ions from seawater. The increase in seawater acidity and resulting decrease in carbonate ion concentration inhibit the calcification processes that sea creatures use to form their shells and coral polyps use to form a coral reef.

You may recall from chemistry class that the acidity of an aqueous solution is measured on the pH scale. At room temperature, a neutral solution such as pure water has a pH of 7. More alkaline (basic) solutions have higher pH values (~11 for household ammonia), and more acidic solutions have lower values (~2 for lemon juice). The mean pH of the today's oceans is about 8.1, so it's on the alkaline side of the scale (in an acidic ocean, no shells or coral could

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grow). The carbon dioxide content of the ocean is following the Keeling curve upward, and pH of seawater therefore is going downward (**Figure 14.20**). The total drop since the Industrial Revolution has been about 0.1 pH unit.

This pH difference may not seem like much, but remember that the pH scale, like the Richter scale for measuring earthquakes, is base-10 logarithmic. One unit represents a factor of ten in the concentration of H^+ ions, so a drop of 0.1 pH unit represents a 26 percent increase in seawater acidity ($10^{0.1} = 0.259$). The biochemical reactions needed to sustain life are very sensitive to small changes in pH. For instance, your body normally regulates your blood pH within a narrow range around 7.4. A sudden drop of 0.2–0.3 pH units can send you into a coma or even kill you. Similarly, a small change in the pH of seawater can harm marine life.

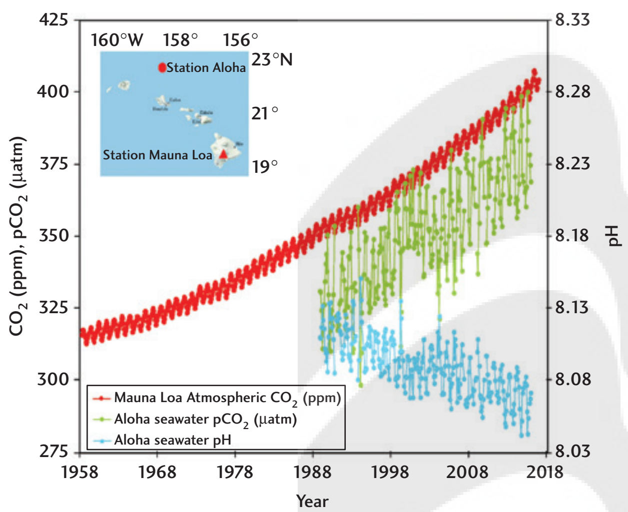


FIGURE 14.20 Comparison of the Keeling curve from the Mauna Loa Observatory (red line) with the CO_2 content (green points) and acidity (blue points) of seawater samples taken at Station Alpha, just north of Oahu (see inset map). CO_2 content of the atmosphere is measured in parts per million, and CO_2 content of seawater is measured as a partial pressure in millionths of an atmosphere (scale on left); acidity is measured in pH units (scale on right). [NOAA PMEL Carbon Program.]

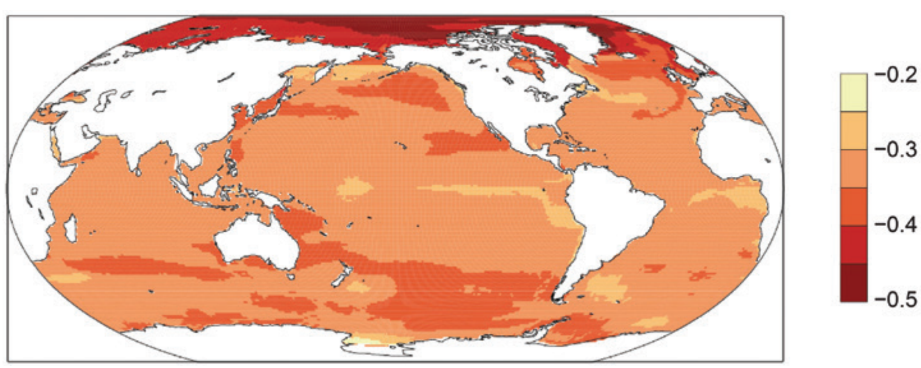
Ocean acidification is likely to affect many types of marine organisms, not just those with shells and skeletons. Anemones and jellyfish, for example, appear to be susceptible to even small changes in seawater acidity, and larger increases cause changes in seawater chemistry that can undermine the health of sea urchins and squid. The growing acidity of ocean surface waters is also likely to affect the concentrations of trace metals such as iron, an essential nutrient for the growth of many organisms. Oceanic ecosystems at higher latitudes typically have a lower buffering capacity against acidity influx, exhibiting seasonally corrosive conditions sooner than low-latitude ecosystems.

As human activities continue to pump more CO_2 into the atmosphere, the ocean will continue to acidify at a rate not seen at any time during the Cenozoic era. Under scenario A, the pH of surface water will likely drop from 8.1 to 7.8 or 7.7, corresponding to a 100 or 150 percent increase in acidity (**Figure 14.21**). In January 2009, more than 150 marine scientists from 26 countries convened under the auspices of the United Nations and issued the Monaco Declaration, which states, “We are deeply concerned by recent, rapid changes in ocean chemistry and their potential, within decades, to severely affect marine organisms. . . . Severe damages are imminent.” The scientists pointed specifically to observations of acidification-related decreases in shellfish weights and slowed growth of coral reefs.

Whether marine organisms can adapt to the changes in store remains to be seen, but the effects on human society could be substantial. In the short term, damage to coral reef ecosystems and the fisheries and recreation industries that depend on them could result in economic losses amounting to many billions of dollars per year. In the longer term, changes in the stability of coastal reefs may reduce the protection they offer to coasts, and there may also be direct and indirect effects on commercially important fish and shellfish species.

Ocean acidification is essentially irreversible during our lifetimes. Even if we were magically able to reduce the atmospheric concentration of CO_2 to the level of 200 years ago, it would take tens of thousands of years for ocean chemistry to return to the conditions that existed at that time.

FIGURE 14.21 Predicted change in sea-surface pH in 2090–2099 relative to 1990–1999 under scenario A. [U.S. Environmental Protection Agency.]



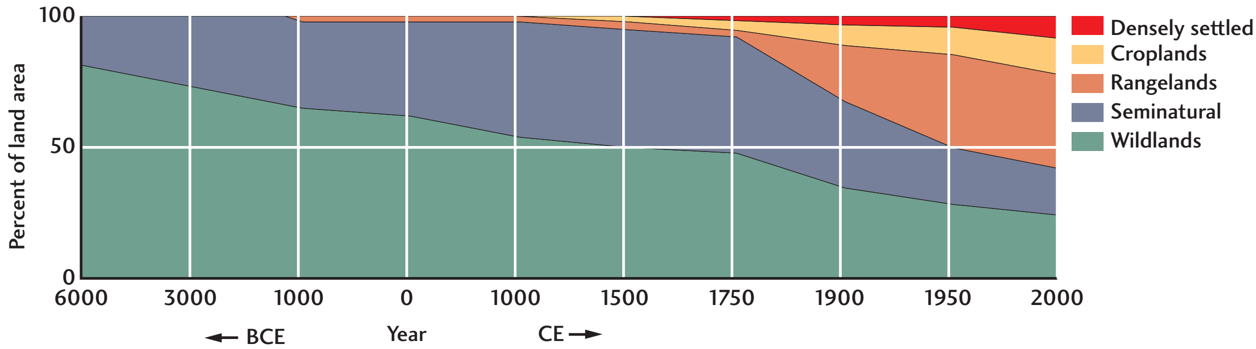


FIGURE 14.22 Anthropogenic transformation of the biosphere can be measured by land use, shown here for the last 8000 years as percentages of global ice-free land area. Land occupied by human settlements (red) or used by humans as croplands (yellow) or rangelands (orange) increased from less 10 percent in 1750 to almost 60 percent in 2000. The time scale is not linear. [Data from E. C. Ellis, 2011, *Proceedings of the Royal Society of London, 369,* 1015–1035.]

Loss of Biodiversity

Humans have been altering Earth's biosphere since before the development of agriculture around 8000 years ago, driving species to extinction and transforming entire ecosystems. Neolithic populations of a few million affected perhaps 20 percent of ice-free global lands in measurable ways, but they directly occupied only a tiny fraction of what was then a vast wilderness. Human land occupation remained a small fraction of the global total between the agricultural and industrial revolutions. In 1750, less than 10 percent of global land was occupied by settlements or directly used as croplands or rangelands (**Figure 14.22**). The subsequent population boom increased that fraction to almost 60 percent in 2000.

According to the United Nations, over 150,000 km^2 of tropical rain forests—about 1 percent of the total resource—are being converted each year to other land uses, mostly agricultural, and deforestation continues to rise. In 1950, forests covered approximately 25 percent of Haiti (a Caribbean island country the size of Maryland); its forested area now stands at less than 2 percent (**Figure 14.23**). Other developing nations face similar problems.

Given these rates of habitat loss, it is not surprising that the number of extant species—the most important measure of biodiversity—is declining. About one-quarter of the bird species on Earth have gone extinct in the last two millennia, and biologists have recently documented disturbing drops in insect populations. The abundance of invertebrates such as beetles and bees plunged more than 45 percent in the past 40 years.

Among the vertebrates, at least 322 vertebrate species have become extinct in the last 500 years, and 16 to 33 percent of all species are threatened or endangered. There has been a mean decline of almost 30 percent in number of individuals across vertebrate species in the past four decades.

Biologists estimate that there are over 9 million different species alive on the planet today, but only 1.5 million have been officially classified. This lack of data makes extinction rates difficult to quantify. Rough estimates suggest that 10,000 to 60,000 species are lost each year. Some scientists believe that up to one-fifth of all species could disappear during the next 30 years, and that as many as one-half may go extinct during the twenty-first century. One respected biologist, Peter Raven, has put the problem bluntly:

FIGURE 14.23 The Caribbean island of Haiti is now 98 percent deforested. This photo shows Haiti's brown landscape, which contrasts sharply with the rich forests of its neighbor, The Dominican Republic. [James P. Blair/National Geographic/Getty Images.]

> *We are confronting an episode of species extinction greater than anything the world has experienced for the past 65 million years. Of all the global problems that confront us, this is the one that is moving the most rapidly and the one that will have the most serious consequences. And, unlike other global ecological problems, it is completely irreversible.*

Dawning of the Anthropocene

In 2003, atmospheric chemist and Nobel laureate Paul Crutzen proposed the recognition of a new geologic epoch—the **Anthropocene,** or Age of Man—beginning

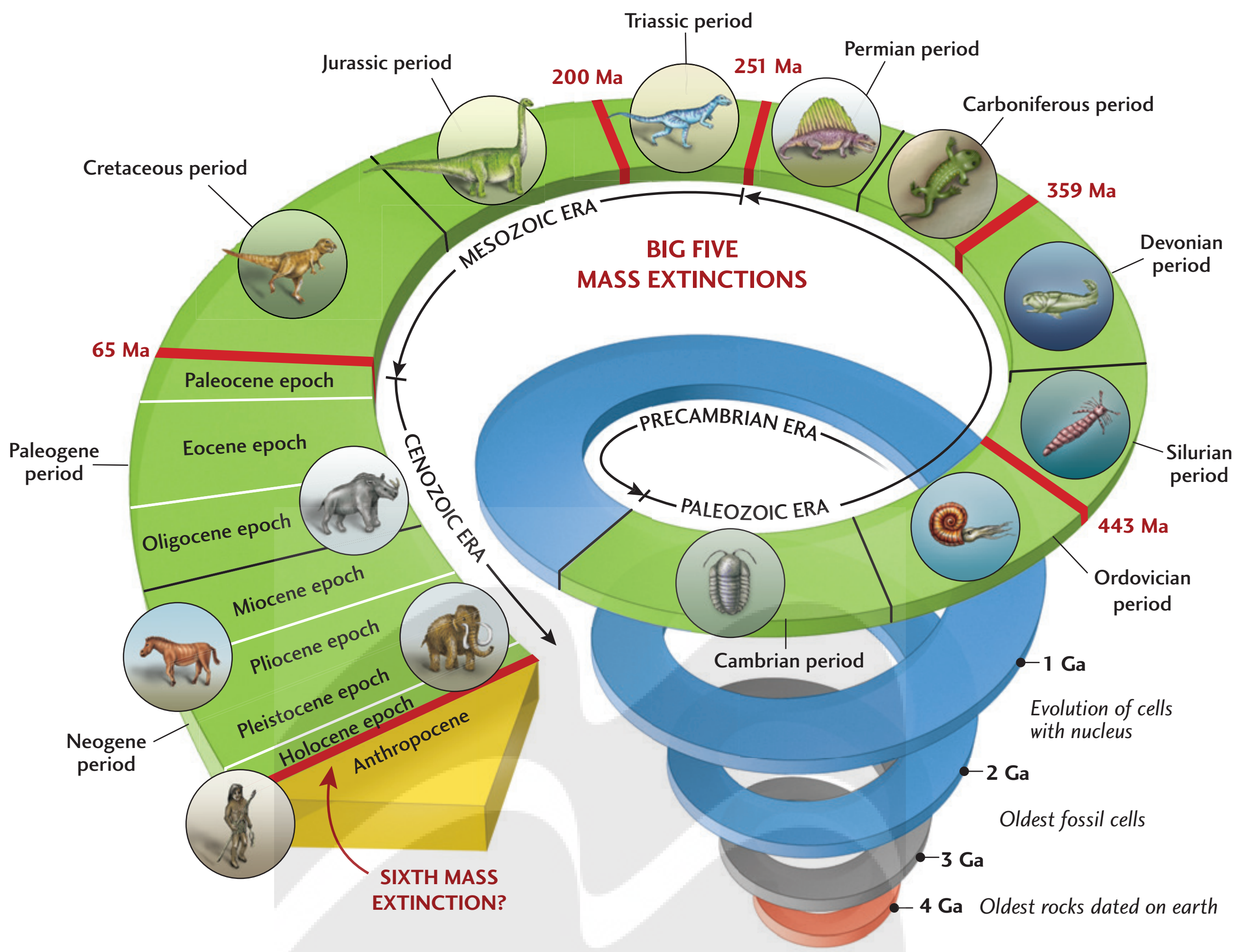


FIGURE 14.24 The Phanerozoic eon has seen many mass extinction events. The Big Five are marked as red lines on this spiral of geologic time. The current transition from the Holocene to the Anthropocene is likely to mark a sixth mass extinction.

about 1780, when James Watt's coal-powered steam engine launched the Industrial Revolution. The global changes that will characterize the Holocene-Anthropocene boundary are still happening, so future geologists may place that boundary at a somewhat different date. As with many previous geologic boundaries, the main marker will be a mass extinction.

Some observers, such as sociobiologist E. O. Wilson and science writer Elizabeth Kolbert, have gone so far as to call the current decline in biodiversity the "Sixth Extinction," placing it in the same rank as the "Big Five" mass extinctions of the Phanerozoic eon (see Figure 14.24 and Kolbert's piece in *The New Yorker,* May 25, 2009). The causes of the Big Five extinctions are different, but they are all marked in the geologic record by losses of more than three-quarters of all species. How many more years it will take for current extinction rates to produce species losses equivalent to the Big Five? The answer is not long at all.

If all "threatened" species became extinct within this century, and that rate continued, the extinction magnitude among land vertebrates would reach Big Five levels (75 percent) in surprisingly short times: approximately 240 years for terrestrial amphibians, 330 years for mammals, 540 years for birds. Limiting extinctions to "critically endangered" species over the next century and continuing those rates into the future increases the rise times by about a factor of four, which is still blindingly fast compared to the Big Five extinction rates. The current extinction rates of oceanic fauna are not as well known as those on land, but the situation is similarly dire. Under the most plausible climate-change scenarios (A and B), bleaching and die-offs will destroy 99 percent of all coral reefs before the end of this century, likely causing a collapse of reef-based ecosystems. The fish biomass that feeds much of humanity will also continue to decline.

Debate continues as to which key signatures of the Anthropocene should be used to define when that epoch actually started. A strong candidate is the mid-twentieth century, when the atomic explosions first rained down dateable, long-lasting radiogenic isotopes, such as plutonium-239, easily detected in the stratigraphic record. Around that time, emissions from fossil-fuel burning also became evident as a distinctive shift in carbon isotope compositions.

There are other perspectives. Archeologists agree that human impacts on the Earth are dramatic enough to merit a new epoch name, but they argue that the human imprint on the geologic record—the beginning of the Anthropocene—has been visible for thousands of years. Other observers would say "not yet"; the mass extinction now under way will leave its most distinctive mark sometime in the future. The final authority on matters related to geologic time scale rests with the International Commission on Stratigraphy, which has formed a working group to recommend definition of the Holocene-Anthropocene boundary.

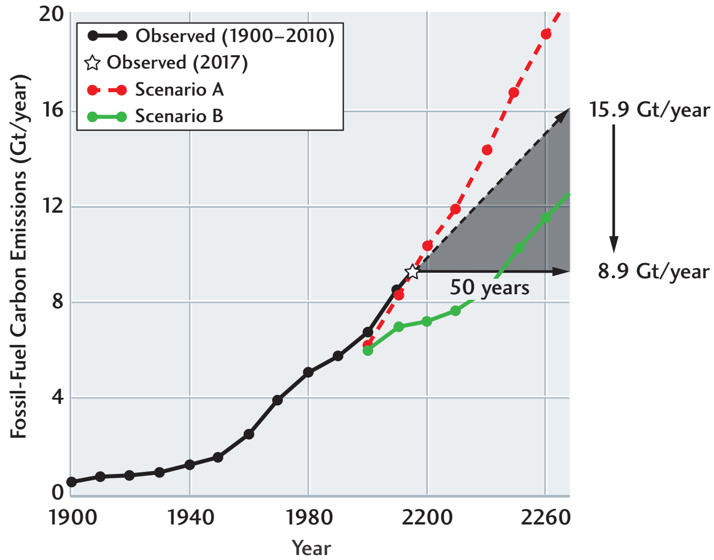


FIGURE 14.25 Fossil-fuel emissions of carbon dioxide measured in gigatons of carbon per year (Gt/year). Observations from 1900–2010 (black points) and 2017 (white star) are compared with fossil-fuel emissions projected according to scenario A (red points) and scenario B (green points). At the current growth rate, carbon emissions will rise by at least 7 Gt/year in 50 years, reaching 15.9 Gt/year in 2067 (dashed black arrow). Under this growth scenario, stabilizing carbon emissions at the 2017 level of 8.9 Gt/year would require special actions to reduce total carbon emissions by 175 Gt over the next 50 years—the area of the shaded "stabilization triangle." [Data from International Energy Agency.]

Managing the Carbon Crisis

By any measure, the problems we face in confronting global change are daunting. Fossil-fuel burning is the main driver of anthropogenic global change. Fossil-fuel emissions have increased from 6.3 gigatons of carbon per year (Gt/year) in 2000 to 8.9 Gt/year in 2017. Under the high-growth scenario A, carbon emissions could increase to more than 22 Gt/year by 2100, leading to CO_2 concentration in the atmosphere that could exceed 900 ppm and continue to increase thereafter, with disastrous consequences. Controlling our carbon emissions—perhaps civilization's most important task—will require extraordinary, unprecedented actions by the global community.

In this section, we explore the magnitude of the task by considering the following problem. We suppose the human population and its per capita energy use continue to grow at their current rates. Then, fossil-fuel burning will cause the rate of carbon emissions to increase from 8.9 Gt/year in 2017 to about 15.9 Gt/year in 2067, an increase of 7 Gt/year in 50 years (Figure 14.25). What specific actions might be taken that could significantly reduce these increases?

Energy Policy

One set of questions policy makers must tackle is how much money we should spend to curb anthropogenic carbon emissions, and whether the benefits of doing so will justify the costs. Too much spending could depress the economy, yet preventing the most drastic effects of climate change might be less costly than coping with those disasters after they happen.

A partial solution—and certainly the most economical one—is to improve energy use efficiency and reduce waste. In a real sense, using energy more efficiently is like discovering a new source of fuel. We have seen that the U.S. energy system has an efficiency of only 32 percent; 68 percent of the total energy produced is wasted somewhere along the way (see Figure 13.5). Implementing efficiency measures costs relatively little—for example, insulating buildings, replacing incandescent light bulbs with fluorescent bulbs, increasing the fuel efficiency of motor vehicles, and making greater use of natural gas. The savings in energy costs could amount to hundreds of billions of dollars per year. These modest steps offer other fringe benefits, including improved air quality.

Another issue to consider is that fossil fuels are relatively cheap in the United States. At present, carbon emissions are not taxed, as they are in many other developed nations; creating incentive for energy conservation or conversion to new energy sources. The full economic costs of fossil fuels include the costs of cleaning up atmospheric pollution, oil spills, and other environmental damage; the costs of trade deficits; and the military costs of defending oil supplies, as well as the costs of global warming. If these costs were included in energy pricing, alternative energy sources would become much more competitive with fossil fuels. Such full-cost accounting has not been politically popular in the United States, however. In fact, the American Clean Energy and Security Act of 2009, which provided for several ways to curb carbon emissions, was approved by the House

FIGURE 14.26 A large coal-fired power plant near Ordos, a city in northern China. In 2007, China replaced the United States as the nation with the highest rate of greenhouse gas emissions. The carbon economies of China, India, and other developing countries will have a huge influence on future climates. [ZumaWire / Newscom.]

of Representatives in 2009, but was never made it to the Senate for a discussion or a vote.

We also face the issue of fairness in international politics. The United States, Canada, the European Union, and Japan—with less than one-quarter of the world's population—are responsible for about three-quarters of the global increase in atmospheric greenhouse gas concentrations. These rich industrial nations are better able to pay the costs of reducing their greenhouse gas emissions than the developing countries. China, for example, depends on its huge coal deposits for its rapid economic growth; it became the world's leader in greenhouse gas emissions in 2007 (Figure 14.26). Developing nations argue that they will need financial and technological support from the developed countries to help them reduce emissions. Policy makers have come to agree that the problems of global climate change cannot be solved on a national scale and will have to be addressed through international cooperation and investment.

Use of Alternative Energy Resources

As we have seen, no one alternative energy source will be able to replace fossil fuels quickly. However, some renewable energy resources, such as solar power, wind power, and biofuels, are becoming more important contributors to our energy system. If these technologies were aggressively implemented during the next 50 years, together they could reduce carbon emissions by gigatons per year.

Another step that could be taken is to increase the use of nuclear energy. The capacity of nuclear power plants, which today is approximately 400 gigawatts, could easily be tripled in the next 50 years, but this option is unattractive to many people for the environmental and security concerns discussed in Chapter 13. The potential exists for cleaner nuclear technologies, such as fusion power: the use of small, controlled thermonuclear explosions to generate energy. But scientific progress toward this goal has been slow, and conceptual breakthroughs will be required.

Engineering the Carbon Cycle

What about the possibility of engineering the carbon cycle to reduce the accumulation of greenhouse gases in the atmosphere? Several promising technologies aim to reduce greenhouse gas emissions by pumping the CO_2 generated by fossil-fuel combustion into reservoirs other than the atmosphere—a procedure known as **carbon sequestration** (Figure 14.27).

Carbon dioxide captured from oil and gas wells is already being pumped back into the ground as a means of moving oil toward the wells. If capture and underground storage of

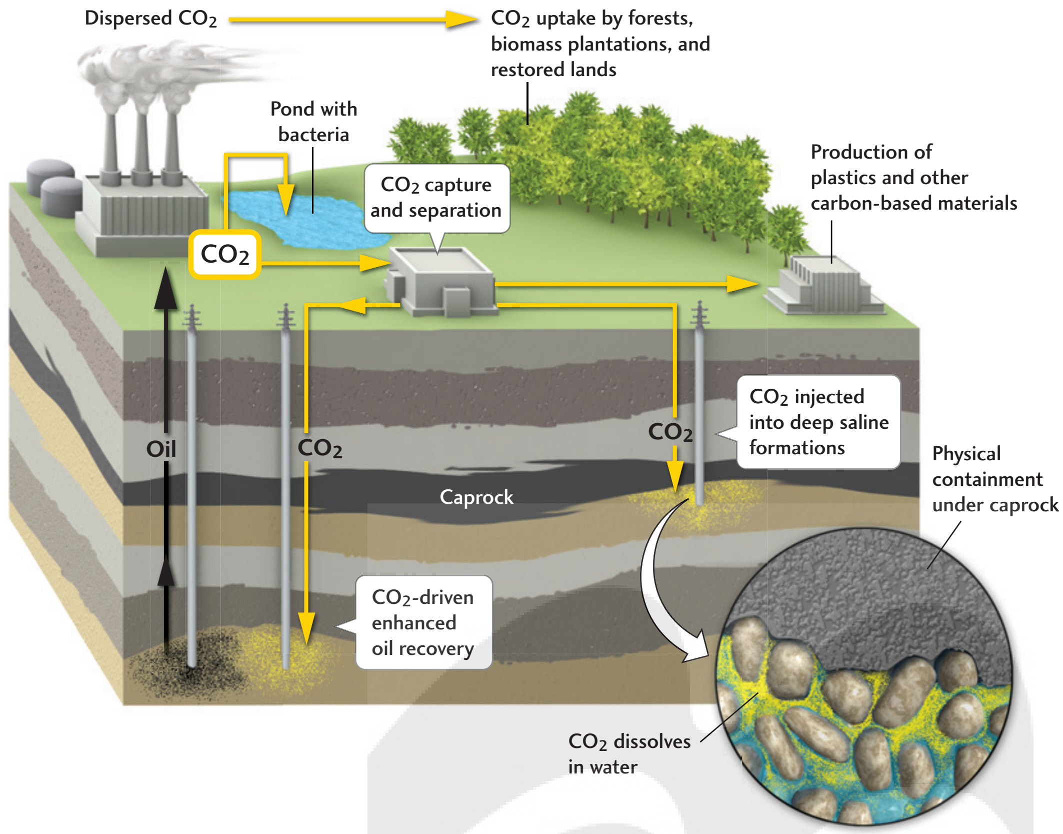


FIGURE 14.27 Carbon sequestration is the process of removing carbon from the atmosphere and depositing it into long-term reservoirs. A promising technology for carbon sequestration is capturing CO_2 at its source, such as a power plant, and storing it in underground reservoirs, such as depleted oil reservoirs and deep saline formations.

the CO_2 from coal-fired power plants were economically feasible, the world's abundant coal resources would become cleaner sources of fuel. So far, however, the technologies to remove and sequester carbon from the atmosphere are much too expensive to implement at a scale large enough to significantly reduce current carbon emissions.

The biosphere provides a natural mechanism for removing carbon already dispersed in the atmosphere. In Chapter 12, we saw that forests withdraw CO_2 from the atmosphere in surprisingly large amounts. Land-use policies that would not only slow the current high rates of deforestation but also encourage reforestation and other biomass production might help to mitigate anthropogenic climate change.

Another possibility is fertilization of the marine biosphere. We know that phytoplankton (small photosynthetic marine organisms) take up CO_2 from the atmosphere by photosynthesis. In most regions of the ocean, phytoplankton productivity is limited by the lack of nutrients, such as iron. Preliminary experiments in the 1990s suggested that the growth of phytoplankton could be stimulated by dumping modest amounts of iron into the ocean. Unfortunately, it appears that fertilizing the ocean in this manner also stimulates the growth of animals that eat the phytoplankton and quickly return the CO_2 to the atmosphere.

Stabilizing Carbon Emissions

At current growth rates, carbon emissions are expected to increase by at least 7 Gt/year during the next half century (see Figure 14.25). In the last two chapters, we have discussed ways that carbon emissions can be slowed. But there is no single "silver bullet."

In 2004, two scientists from Princeton University, Stephen Pacala and Robert Socolow, recognized that there will be a multitiered approach to lowering carbon emissions; they represented possible contributions to carbon reduction as **stabilization wedges,** each of which offsets the projected growth of carbon emissions by 1 Gt/year in the next 50 years (Figure 14.28). Therefore, one wedge roughly corresponds to one-seventh of the carbon reduction needed for stabilization.

Implementing each stabilization wedge will be a monumental task. To achieve wedge 1, for example, the average gasoline mileage of the world's entire fleet of passenger vehicles, which will grow to 2 billion by mid-century, will have to be steadily increased from 30 miles per gallon (mpg) to 60 mpg. This calculation assumes that a car is driven 10,000 miles per year, the current annual average. An alternative, not shown in Figure 14.29, would be to maintain gas mileage at 30 mpg but reduce the average amount of driving by half to 5000 miles per year. Yet

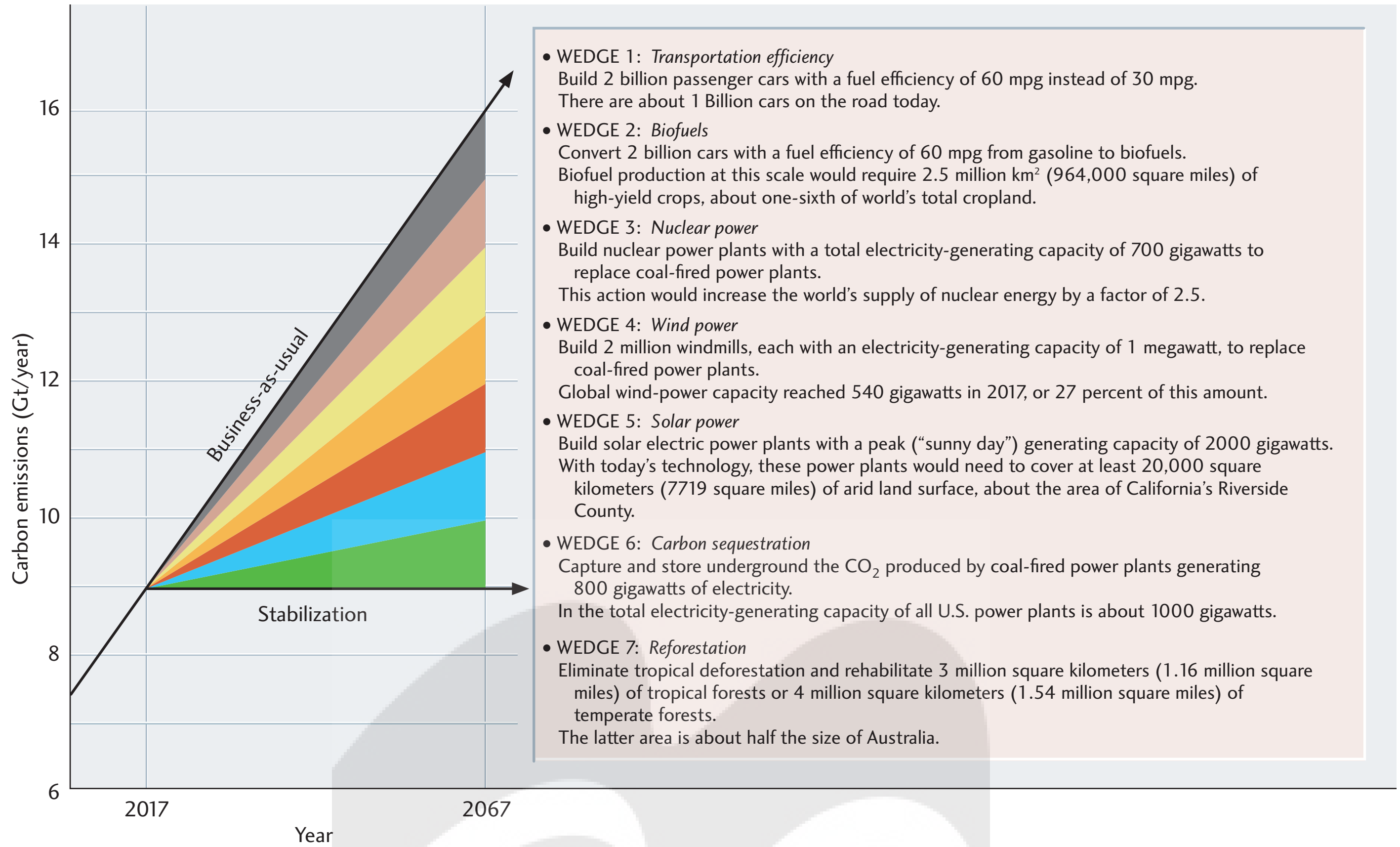


FIGURE 14.28 At current growth rates, carbon emissions are expected to increase by at least 7 Gt per year during the next 50 years. The problem of stabilizing carbon emissions at their 2017 level of about 9 Gt/year can be broken into seven stabilization wedges, each representing a reduction in emissions of 1 Gt per year by 2067. Possible actions that use existing technologies to achieve one-wedge reductions are listed next to each wedge. [Research from S. Pacala & R. Socolow. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science, 305*: 968–972 (2004).]

another alternative (wedge 2) would be to convert all cars to biofuels. Growing that much biofuel would take up one-sixth of the world's total cropland, so this strategy could adversely affect agricultural productivity and food supplies.

Some of the stabilization wedges involve controversial or expensive technologies, such as expanding nuclear power by a factor of 2.5 (wedge 3), increasing the number of large windmills into the millions (wedge 4), or covering large desert areas with solar panels (wedge 5). As we have seen, at least one of the proposed wedges, the capture and storage of carbon emitted from coal-fired power plants (wedge 6), is at the margin of current technological feasibility. The last option, elimination of tropical deforestation and the reforestation of huge additional land areas (wedge 7), is favored by many people in principle, but would be difficult to achieve without imposing severe restrictions on developing countries such as Brazil.

The stabilization of carbon emissions at current emission rates would reduce, but not eliminate, the threat of global climate change. The 50-year stabilization scenario (which is intermediate to scenarios B and C in Figure 14.8) would still allow the atmospheric concentration of CO_2 to grow to 500 ppm, almost twice the preindustrial value. Further reductions in carbon emissions during the second half of the twenty-first century would be necessary to maintain atmospheric concentrations below that value. Climate models indicate that such a scenario would still increase the average global temperature by about 2°C, more than three times the total twentieth-century warming.

Nevertheless, the continued rise of atmospheric CO_2 concentrations is not inevitable. The available inventory of stabilization wedges constitutes a technological framework for concerted action by governments. Taking on the stabilization problem involves other difficulties such as developing broad public consensus and creating binding international agreements. Yet, as the Pacala-Socolow analysis demonstrates, there is still time for actions that can substantially reduce anthropogenic global change. Whether we can grasp this opportunity will depend on our understanding of the problem, its potential solutions, and the consequences of inaction.

KEY TERMS AND CONCEPTS

Anthropocene (p. 410)
carbon sequestration (p. 413)
enhanced greenhouse effect (p. 400)
Intergovernmental Panel on Climate Change (IPCC) (p. 399)
Keeling curve (p. 394)
Montreal Protocol (p. 397)
radiative forcing (p. 401)
representative concentration pathway (p. 401)
stratospheric ozone depletion (p. 397)
stabilization wedges (p. 414)
twentieth-century warming (p. 397)

REVIEW OF LEARNING OBJECTIVES

14.1 Explain why scientists can assert with high confidence that fossil-fuel burning is increasing the atmospheric concentration of carbon dioxide.

Atmospheric chemists can directly measure the concentration of carbon dioxide (CO_2) in the atmosphere. The record of such measurements shows that the average CO_2 concentration has increased from about 280 ppm in preindustrial times to 410 ppm in 2018. The longest continuous instrumental record of CO_2 concentration is the Keeling curve (Figure 14.1). Monthly values show seasonal oscillations about yearly averages that have risen from 310 ppm in 1958 to 410 ppm in 2018. Data on the changing isotope ratios of atmospheric carbon demonstrate that most of the CO_2 increase is being produced by fossil-fuel burning.

Using air samples from ice cores, climate scientists have extended the record of greenhouse gas concentrations back through the Holocene (Figure 14.3) and into the Pleistocene (Figure 14.2). At no time during the past 800,000 years have CO_2 concentrations been much higher than the preindustrial average of 280 ppm. Based on the sediment record, CO_2 concentrations above 400 ppm have not been reached since the Middle Miocene.

Study Assignments: The Keeling curve, Figure 14.1; history of greenhouse gas concentrations, Figure 14.2 and Figure 14.3.

Exercises: (a) What is the average rate at which atmospheric CO_2 concentration increased during the 60-year history of the Keeling curve? Express your answer in ppm per year. (b) From the Keeling curve, estimate average rate of CO_2 concentration increase during the 20-year intervals beginning in 1958, 1978, and 1998. (c) Do these 20-year averages indicate that the rate is either increasing or decreasing with time? (d) What do these results imply about the future rate of anthropogenic CO_2 emissions?

Thought Questions: (a) The average seasonal variation in atmospheric CO_2 ranges from 3 ppm higher than the annual mean in May to 3 ppm lower in October, as shown in the inset diagram in Figure 14.1. Why is the CO_2 concentration higher in May and lower in October? (b) If you look very closely at the Keeling curve (red line in Figure 14.1), you will find that this "global breathing of the biosphere" has actually increased in amplitude by about 50 percent, from ± 2.5 ppm in 1958 to ± 3.8 ppm in 2018. In qualitative terms, how can this 50 percent increase be explained as a feedback between atmospheric chemistry and the biosphere? (c) How might you use this "deeper breathing" to illustrate human impact on the biosphere?

14.2 Catalog the main types of anthropogenic global change and describe their main effects on the atmosphere, hydrosphere, cryosphere, and lithosphere.

Anthropogenic global change can be chemical, physical, or biological. Examples of anthropogenic chemical change are (1) the increase in atmospheric CO_2 and other greenhouse gases, (2) the acidification of the oceans, and (3) the depletion of stratospheric ozone catalyzed by human-made chlorine compounds.

Change (1) is responsible for change (2). Human emissions of carbon are enhancing the greenhouse effect by increasing the concentration of carbon dioxide in the atmosphere. Some of this carbon dioxide dissolves in the oceans, where it combines with water to form carbonic acid. This ocean acidification acts to increase the concentration of bicarbonate ions at the expense of carbonate ions, making it harder for marine organisms to form shells and skeletons of calcium carbonate.

Examples of anthropogenic physical change are global warming and related reductions in the mass of the cryosphere, which decreases Earth's albedo and transfers water to the hydrosphere, raising the sea level. The cryosphere-albedo feedback is positive, enhancing global warming. Climate models that account for these feedbacks indicate an increase in global temperatures ranging from 0.5°C to 5.5°C, depending on how humans cope with the carbon crisis.

Atmospheric concentrations of greenhouse gases are likely to rise throughout the twenty-first century, skewing the warming projections towards the higher values (Figure 14.9). Global warming of this magnitude will disrupt ecosystems and increase the rates of species extinction. The oceans will warm and expand, and continental glaciers will begin to melt, raising the sea level as much as a meter by 2100. The Arctic ice cap will continue to shrink, and much of the Arctic Ocean is expected to become ice-free during the summer months. Storms, floods, and droughts will intensify.

Study Assignment: Review the section *Types of Anthropogenic Global Change.*

Exercises: (a) What large-scale physical changes to the climate system might be caused by anthropogenic chemical changes to the atmospheric composition? (b) How much did the sea level rise during the twentieth century? (c) What was the primary physical cause of this sea-level rise?

Thought Questions: (a) Among the various anthropogenic changes to the climate system described in this chapter, which do you think will be the hardest for humans to adapt to, and why? (b) What actions can humans take to adapt to this type of global change?

14.3 Explain why scientists can assert with high confidence that fossil-fuel burning caused the twentieth-century warming and continues to cause the average surface temperature to increase.

The observed increase of about 0.8°C in Earth's average annual surface temperature during the twentieth century is correlated with a significant rise in atmospheric concentrations of CO_2 and other greenhouse gases relative to preindustrial times. Carbon isotopes demonstrate that the CO_2 rise is due to fossil-fuel burning. The geologic record documents that feedbacks within the climate system have maintained the tight correlation between CO_2 concentrations and average surface temperature throughout the Holocene (Figure 14.3) and back into the Pleistocene (Figure 14.2). Based on the available data and model-based predictions, essentially all experts on Earth's climate are now convinced that the twentieth-century warming was human-induced and that the warming will continue into the twenty-first century as atmospheric concentrations of greenhouse gases continue to rise. The projections of future global warming made by climate models depend primarily on which actions humans take to reduce fossil-fuel burning and how quickly they are implemented.

Study Assignments: Figures 14.5 and 14.6

Exercises: (a) How much did the CO_2 concentration of the atmosphere increase during the twentieth century? (b) How do climate scientists know that the twentieth-century increase in CO_2 concentration was due to fossil-fuel burning and not natural causes? (c) In which regions were the surface temperature increases during the twentieth century larger than the global average?

Thought Question: Is one justified in insisting that developing countries that have historically burned much less fossil fuel than developed countries agree to limit their future carbon emissions?

14.4 Use scenarios developed by the Intergovernmental Panel on Climate Change to project how much greenhouse gas concentrations, the average surface temperature, and sea level will rise during this century.

The United Nations has authorized the IPCC to report on anthropogenic global change and make recommendations about how to reduce global change and adapt to its probable effects. The climate projections made in the IPCC's *Fifth Assessment Report,* discussed extensively in this chapter, are based on "representative concentration pathways" specified by a level of radiative forcing, measured in watts per square meter (W/m^2). The IPCC's RCP8.5 projection (scenario A) assumes continued reliance on fossil fuels; the resulting rise in greenhouse gas concentrations, to over 900 ppm for CO_2, would increase the radiative forcing by 8.5 W/m^2. The RCP6.0 projection (scenario B) assumes a more rapid shift to alternative energy resources, reducing the radiative forcing to 6.0 W/m^2, and the most optimistic projection, RCP2.6 (scenario C), reduces it to only 2.6 W/m^2. The corresponding projections for average surface temperature and sea level are plotted in Figure 14.10 and Figure 14.15.

Study Assignment: Review the section *Projecting Future Climate Change*.

Exercises: (a) Scenario A is shorthand for what the IPCC calls scenario "RCP8.5." Explain the meaning of each letter in the acronym "RCP." What does "8.5" represent? In what units is it measured? (b) The description of scenario A compares the radiative forcing of anthropogenic greenhouse emissions with the average solar forcing of 240 W/m^2. How is the average solar forcing computed from the values of incoming solar radiation and Earth's albedo given in Figure 12.9? (c) In which regions will the surface temperature increase more quickly than the global average? (d) What is the best estimate of the surface temperature rise during the twenty-first century, and what is its uncertainty?

Thought Questions: (a) An economist once wrote, "The predicted change in global temperature due to human activity is less than the difference in winter temperature between New York and Florida, so why worry?" Should we worry, and if so, why? (b) Do you expect the per capita carbon intensity to go up or down during the twenty-first century? (c) Does your answer to (b) explain why future anthropogenic global change is so strongly dependent on the projected human population, as shown in Figure 14.11?

14.5 Assess the potential effects of anthropogenic global change on the biosphere, and evaluate the possibility that the beginning of the Anthropocene epoch will be marked by a mass extinction.

Global chemical and physical changes are affecting the biosphere, inevitably leading to global biological change. The biodiversity of ecosystems on land is declining through loss of habitat as well as the effects of climate change. The oceans are warming and acidifying, and many ecosystems are vulnerable, especially coral reefs and polar habitats. Even under the most moderate scenarios for global warming (scenario C), most coral reefs are expected to die by 2100. The current rapid rate of species extinction may eventually lead to a decline in biodiversity equal to the "Big Five" mass extinctions of the Phanerozoic eon.

Study Assignments: Review the sections *Ocean Acidification* and *Loss of Biodiversity*.

Exercises: (a) Review the geologic time scale in Figure 9.12, and note the boundaries between geologic periods identified as the Big Five mass extinctions. Which of the Big Five mark boundaries between geologic eras? (b) Suggest three anthropogenic signatures in the geologic record that could be used to identify the beginning of the Anthropocene. (c) In which geologic formations would these signatures be best expressed?

Thought Question: At projected extinction rates, how long will it be before extinctions among the vertebrates reach Big Five proportions?

14.6 Illustrate with specific examples changes in our energy production and usage that could stabilize carbon emissions to its current rate.

Stabilizing carbon emissions at their current levels of about 9 Gt/year will require major reductions in the carbon intensity of our energy sources. If civilization continues to rely on fossil fuels, anthropogenic carbon emissions will increase by at least 7 Gt/year during the next 50 years. The stabilization triangle (shaded region in Figure 14.25) can be broken down into stabilization wedges, defined by specific types of action that, if implemented in the next 50 years, could reduce the projected growth of carbon emissions by 1 Gt/year. Achieving seven such wedges would stabilize carbon emissions to the 2017 level (see Figure 14.28).

Study Assignment: Review the section *Managing the Carbon Crisis*.

Exercise: Visual Literacy Exercise.

Thought Questions: (a) Do you think we should act now to reduce carbon emissions or delay until the functioning of the climate system is better understood? (b) Do you think that future scientists and engineers will be able to modify the natural carbon cycle to prevent catastrophic changes in the climate system? (c) What technologies do you think would be most effective in reducing the amount of global warming?

VISUAL LITERACY EXERCISE

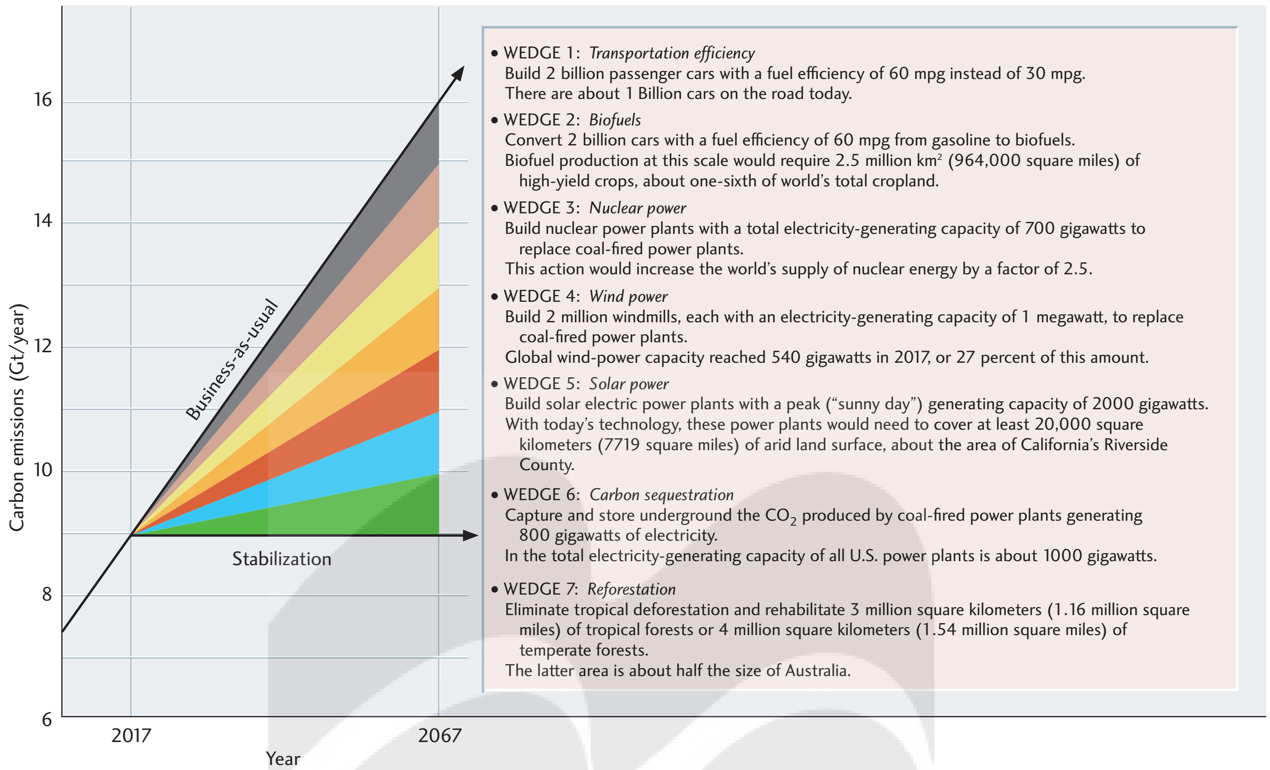


FIGURE 14.28 At current growth rates, carbon emissions are expected to increase by at least 7 Gt per year during the next 50 years. The problem of stabilizing carbon emissions at their 2017 level of about 9 Gt/year can be broken into seven stabilization wedges, each representing a reduction in emissions of 1 Gt per year by 2067. Possible actions that use existing technologies to achieve one-wedge reductions are listed next to each wedge. [Research from S. Pacala & R. Socolow. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science, 305*: 968–972 (2004).]

Figure 14.28 shows the "stabilization triangle," the reduction in carbon emissions needed to stabilize them at the 2017 level.

1. The vertical axis is carbon emissions measured in Gt/year.

- **a.** How much carbon was emitted into atmosphere by fossil-fuel burning in 2017?
- **b.** If we project the "business-as-usual" scenario at current growth rates, how much carbon will be emitted by fossil-fuel burning in 2067?

2. The area of the stabilization triangle can be measured in gigatons of carbon emission.

- **a.** What is the area of the stabilization triangle?
- **b.** How much carbon is represented by each stabilization wedge?
- **c.** By what percentage would carbon-emission stabilization reduce the total carbon emitted in the next 50 years under the business-as-usual scenario of Figure 14.28?

3. Among the seven stabilization wedges listed on the figure,

- **a.** Which would you judge to be the easiest to attain?
- **b.** Which would you judge to be the most difficult to attain?