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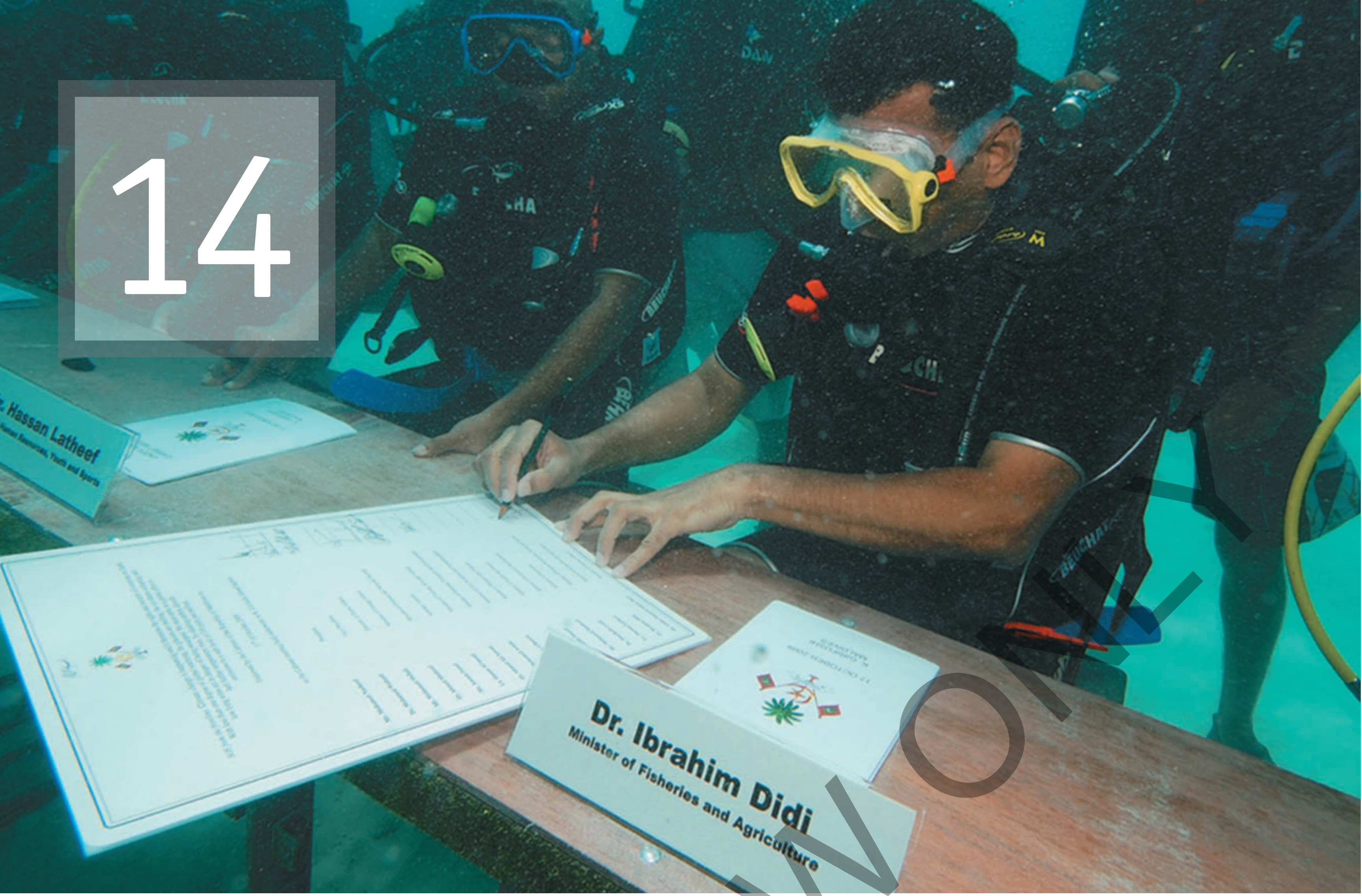


Global Climate Change

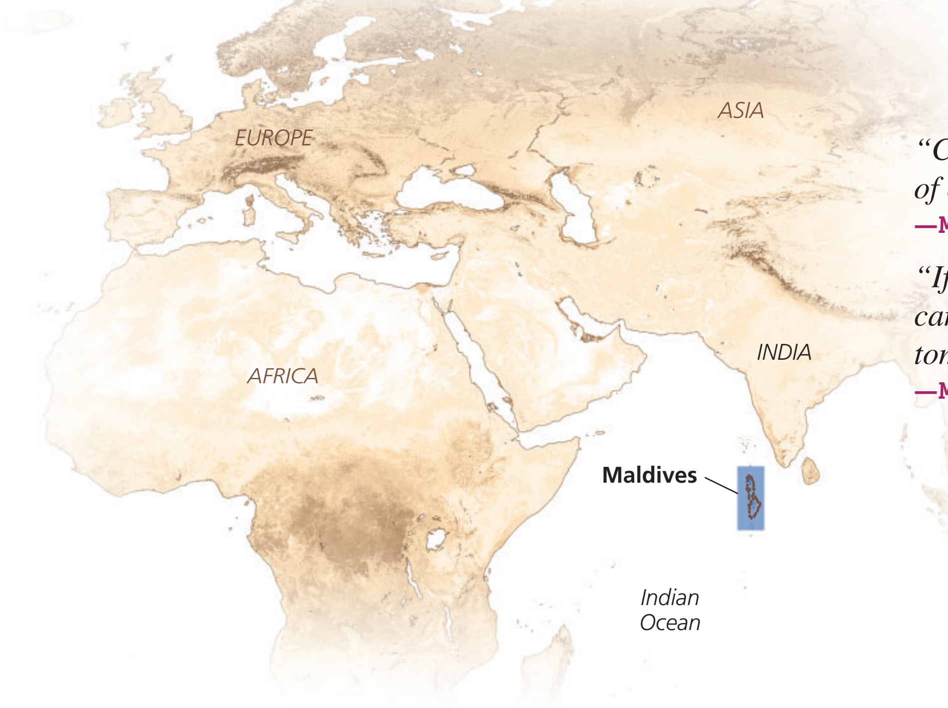
Upon completing this chapter, you will be able to:

- ☐ Describe Earth's climate system and explain the factors that influence global climate
- ☐ Identify greenhouse gases and characterize human influences on the atmosphere and on climate
- ☐ Summarize how researchers study climate
- ☐ Outline current and future trends and impacts of climate change in the United States and across the world
- ☐ Suggest and assess ways we may respond to climate change

Photo: The Maldives' underwater cabinet meeting

CENTRAL CASE STUDY

Rising Seas May Flood the Maldives



"Climate change threatens the very existence of our country."

—Mohamed Waheed, recent president, Maldives

"If we can't save the Maldives today, we can't save London, New York, or Hong Kong tomorrow."

—Mohamed Nasheed, former president, Maldives

With sun-drenched beaches, colorful coral reefs, and a spectacular tropical setting, the Maldives seems a paradise to the many tourists who visit. For its 370,000 residents, this island nation in the Indian Ocean is home. But residents and tourists alike now fear that the Maldives could soon be submerged by the rising seas brought by global climate change.

In this nation of 1200 islands, the highest point is just 2.4 m (8 ft) above sea level, and four-fifths of the land lies less than 1 m (39 in.) above sea level. The world's oceans rose 20 cm (8 in.) in the 20th century as warming temperatures expanded seawater and as melting polar ice discharged water into the ocean. Scientists predict that sea level will rise another 26–98 cm (10–39 in.) in this century.

Higher seas are beginning to flood large areas of the Maldives and cause salt water to contaminate drinking water supplies. Storms intensified by warmer water are eroding beaches and damaging the coral reefs that are vital to the nation's tourism and fishing industries. Residents have had to be evacuated from several low-lying islands, and political leaders have looked to buy land in mainland nations in case the Maldives' people one day need to abandon their homeland.

Small island nations like the Maldives are responsible for very few of the carbon emissions that drive global climate change, yet these nations are the ones bearing the earliest consequences. The Maldives' leaders have made sure the world knows this. In 2009, President Mohamed Nasheed donned scuba gear and dove into the blue waters of Girifushi Island lagoon, followed by his entire cabinet. These officials held the world's first underwater cabinet meeting. Sitting at a table beneath the waves, they signed a declaration reading:

> *SOS from the front line:* Climate change is happening and it threatens the rights and security of everyone on Earth. With less than one degree of global warming, the glaciers are melting, the ice sheets collapsing, and low-lying areas are in danger of being swamped. We must unite in a global effort to halt further temperature rises, by slashing carbon dioxide emissions to a safe level of 350 parts per million.

The underwater cabinet meeting was part of a campaign to draw global attention to the impacts of climate change. Nasheed then played a high-profile role at international climate talks in Copenhagen, where he pleaded with the United States, China, India, and other nations to unite in efforts to reduce emissions of polluting gases that warm the atmosphere. Back home in the Maldives, Nasheed announced a plan to make his nation carbon-neutral by 2020.

In 2012, Nasheed—the nation's first democratically elected president—was forced from power. His supporters called it a coup d'etat; his detractors said he had abused power. He was put on trial and narrowly lost the 2013 presidential election. Yet despite their nation's political turmoil, the people of the Maldives remain united in their concern over climate change. They are not alone in their predicament. Other island nations, from the Galápagos to Fiji to the Seychelles, also face a future of encroaching seawater. These island nations have organized to make their concern over climate change known to the world through AOSIS, the Alliance of Small Island States.

(a) Malé, capital of the Maldives

(b) Miami, on the Florida coast

FIGURE 14.1 From the Maldives to Miami, rising sea levels threaten damage to vulnerable coastal areas.

Coastal areas around the world will face challenges from rising sea levels (**FIGURE 14.1**). In the United States, the hurricane-prone shores of Florida, Louisiana, Texas, and the Carolinas are at risk, as are coastal cities such as San Francisco, Houston, Boston, and New York City. Superstorm Sandy in 2012 was a wake-up call. The lost lives and billions of dollars of damage this massive hurricane brought to New York, New Jersey, and other states made clear that the costs inflicted by rising seas can be enormous.

Indeed, scientists now know that the Atlantic seaboard and the Gulf coast of the United States are especially vulnerable to impacts from sea level rise (p. 316). From Maine to Miami, and from Cape Cod to Corpus Christi, millions of Americans who live in coastal communities will experience increasing expense, disruption, and property damage as beaches erode, neighborhoods flood, aquifers are contaminated, and storms strike with more force.

Impacts from rising seas are just a few of the many imminent consequences of global climate change. In one way or another, climate change will affect each and every one of us for the remainder of our lifetimes. Putting solutions into action stands as a central challenge for our society today and for the foreseeable future. ◻

Our Dynamic Climate

Climate influences virtually everything around us, from the day's weather to major storms, from crop success to human health, and from national security to the ecosystems that support our economies. If you are a student in your teens or twenties, the accelerating change in our climate today may well be *the* major event of your lifetime and the phenomenon that most shapes your future.

Climate change is also the fastest-developing area of environmental science. New scientific studies that refine our understanding of climate are published every week, and policymakers and businesspeople make decisions and take actions just as quickly. By the time you read this chapter, some of its information will already be out of date. We urge you to explore further, with your instructor and on your own, the most recent information on climate change and the impacts it will have on your future.

What is climate change?

Climate describes an area's long-term atmospheric conditions, including temperature, precipitation, wind, humidity, barometric pressure, solar radiation, and other characteristics. *Climate* differs from *weather* (p. 281) in that weather specifies conditions over hours or days, whereas climate summarizes conditions over years, decades, or centuries.

Global climate change describes an array of changes in aspects of Earth's climate, such as temperature, precipitation, and the frequency and intensity of storms. People often use the term *global warming* synonymously in casual conversation, but **global warming** refers specifically to an increase in Earth's average surface temperature. Global warming is only one aspect of global climate change, but warming does in turn drive other components of climate change.

Over the long term, our planet's climate varies naturally. However, today's climatic changes are unfolding at an exceedingly rapid rate, and they are creating conditions humanity has never experienced. Scientists agree that human activities, notably fossil fuel combustion and deforestation, are largely responsible. Some researchers point out that the term "climate change" is so mild-sounding as to be misleading, and that a more accurate term would be "climate disruption."

Three factors influence climate

Three natural factors exert the most influence on Earth's climate. The first is the sun. Without the sun, Earth would be dark and frozen. The second is the atmosphere. Without this protective and buffering layer of gases, Earth would be as much as 33°C (59°F) colder on average, and temperature differences between night and day would be far greater than they are. The third is the oceans, which store and transport heat and moisture.

The sun supplies most of our planet's energy. Earth's atmosphere, clouds, land, ice, and water together absorb about 70% of incoming solar radiation and reflect the remaining 30% back into space (**FIGURE 14.2**).

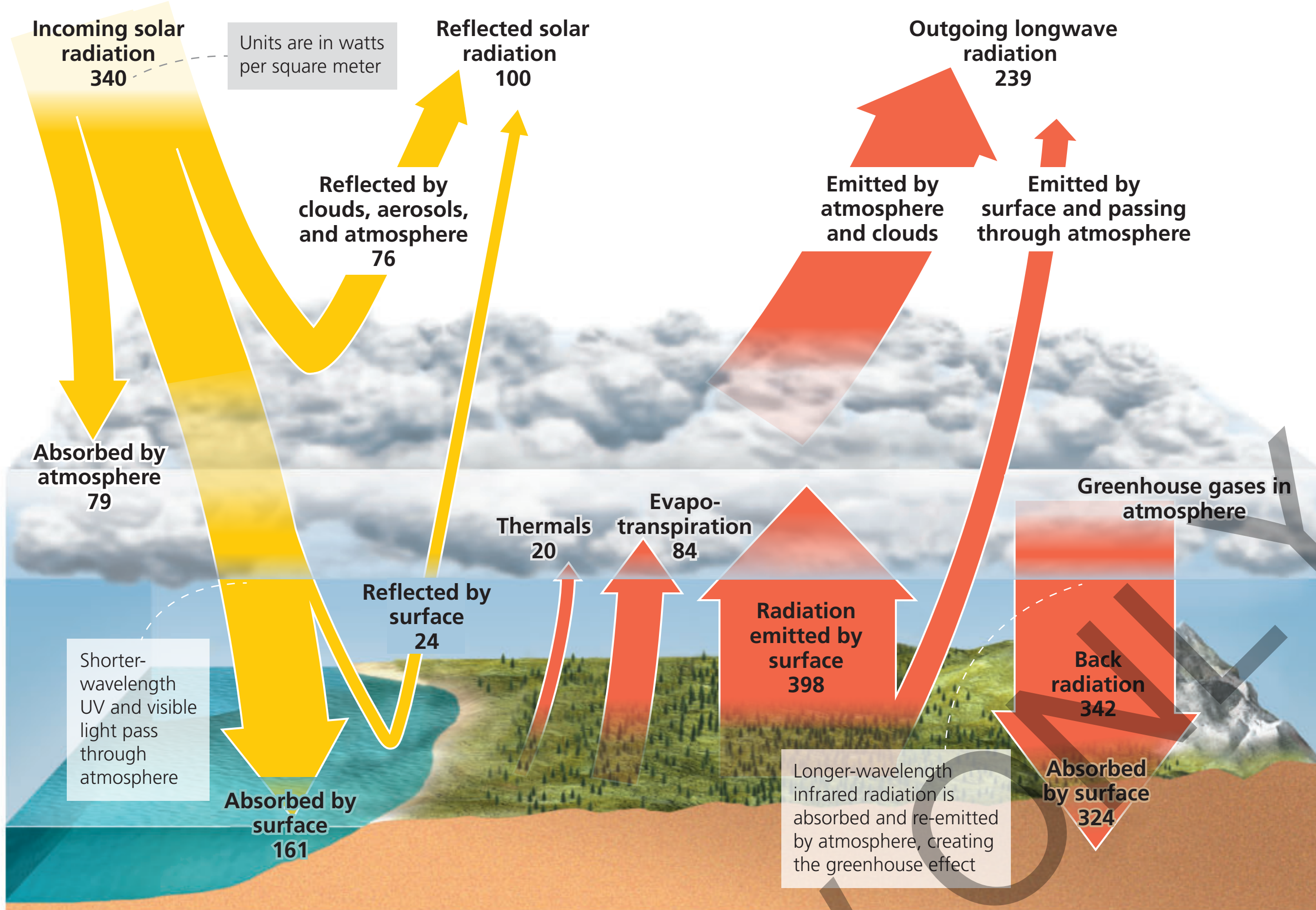


FIGURE 14.2 Our planet receives about 340 watts of energy per square meter from the sun, and it naturally reflects and emits this same amount. Earth absorbs 70% of the solar radiation it receives and reflects the rest back into space **(yellow arrows)**. The energy absorbed is re-emitted **(orange arrows)** as infrared radiation, which has longer wavelengths. Greenhouse gases in the atmosphere absorb a portion of this radiation and then re-emit it, sending some downward to warm the atmosphere and the surface by the greenhouse effect.
Data from Intergovernmental Panel on Climate Change (IPCC), 2013. Fifth assessment report. The physical science basis: Contribution of Working Group I.

Greenhouse gases warm the lower atmosphere

As Earth's surface absorbs solar radiation, the surface increases in temperature and emits infrared radiation (p. 31), radiation with wavelengths longer than those of visible light. Atmospheric gases having three or more atoms in their molecules tend to absorb infrared radiation. These include water vapor (H_2O), ozone (O_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), as well as halocarbons, a diverse group of mostly human-made gases that includes chlorofluorocarbons (CFCs; p. 293). All these gases are known as **greenhouse gases**. After absorbing radiation emitted from the surface, greenhouse gases re-emit infrared radiation. Some of this re-emitted energy is lost to space, but most travels back downward, warming the lower atmosphere (specifically the troposphere; p. 281) and the surface, in a phenomenon known as the **greenhouse effect**.

Greenhouse gases differ in their ability to warm the troposphere and surface. *Global warming potential* refers to the relative ability of one molecule of a given greenhouse gas to contribute to warming. **TABLE 14.1** shows global warming potentials for several gases. Values are expressed in relation to carbon dioxide, which is assigned a value of 1. For example, at a 20-year time horizon, a molecule of methane is 84 times more potent than a molecule of carbon dioxide. Yet because a typical methane molecule resides in the atmosphere for less time than a typical carbon dioxide molecule, methane's global warming potential is reduced at longer time horizons (it is 28 at a 100-year horizon).

TABLE 14.1 Global Warming Potentials of Four Greenhouse Gases

GREENHOUSE GAS	RELATIVE HEAT-TRAPPING ABILITY (IN CO_2 EQUIVALENTS)	
	Over 20 years	Over 100 years
Carbon dioxide	1	1
Methane	84	28
Nitrous oxide	264	265
Hydrochlorofluorocarbon HFC-23	10,800	12,400

Data are for 20-year and 100-year time horizons, from IPCC, 2013. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth assessment report.

Although carbon dioxide is less potent on a per-molecule basis than most other greenhouse gases, it is far more abundant in the atmosphere. Moreover, greenhouse gas emissions from human activity consist mostly of CO_2. For these reasons, carbon dioxide has caused nearly twice as much warming since the industrial revolution as methane, nitrous oxide, and halocarbons combined.

Greenhouse gas concentrations are rising fast

The greenhouse effect is a natural phenomenon, and greenhouse gases have been in our atmosphere for all of Earth's history. It's a good thing, too. Without the greenhouse effect, Earth would be too cold to support life as we know it. Thus, it is not the natural greenhouse effect that concerns scientists today, but rather the *anthropogenic* (human-generated) intensification of the greenhouse effect. By adding novel greenhouse gases (certain halocarbons) to the atmosphere, and by increasing the concentrations of several natural greenhouse gases over the past 250 years (**FIGURE 14.3**), we are intensifying the greenhouse effect beyond what our species has ever experienced.

We have boosted Earth's atmospheric concentration of carbon dioxide from 280 parts per million (ppm) in the late 1700s to 399 ppm in 2014 (see Figure 14.3). Today the concentration of CO_2 in our atmosphere is far higher than it has been in over 800,000 years, and it is likely the highest in the last 20 million years.

Why have atmospheric carbon dioxide levels risen so rapidly? Most carbon is stored for long periods in the upper layers of the lithosphere (p. 227). The deposition, partial decay, and compression of organic matter (mostly plants and phytoplankton) in wetland or marine areas hundreds of millions of years ago led to the formation of coal, oil, and natural gas in buried sediments (p. 337). In the past two centuries, we have extracted these fossil fuels from the ground and burned them in our homes, factories, and automobiles, transferring large amounts of carbon from one reservoir (the underground deposits that stored the carbon for millions of years) to another (the atmosphere). This sudden flux of carbon is the main reason atmospheric CO_2 concentrations have risen so dramatically.

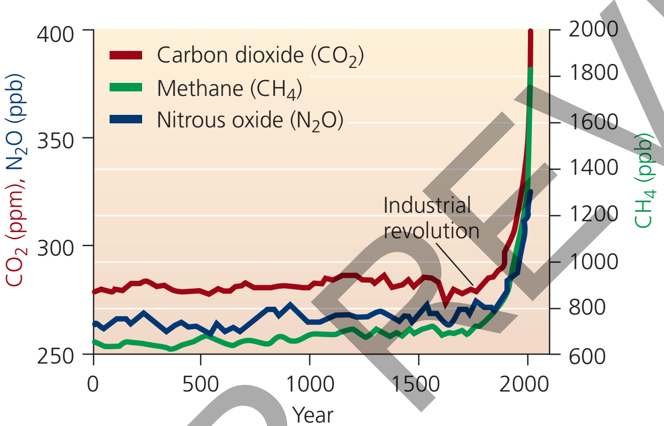


FIGURE 14.3 Since the start of the industrial revolution around 1750, global concentrations of carbon dioxide, methane, and nitrous oxide in the atmosphere have increased markedly. *Data from IPCC, 2013.* Fifth assessment report. The physical science basis: Contribution of Working Group I.

DATA Q By about what percentage has atmospheric carbon dioxide concentration increased since 1750?

At the same time, people have cleared and burned forests to make room for crops, pastures, villages, and cities. Forests serve as a reservoir for carbon as plants conduct photosynthesis (pp. 31–32) and store carbon in their tissues. When we clear forests, we reduce the biosphere's ability to remove carbon dioxide from the atmosphere. In this way, deforestation (pp. 189–192) contributes to rising atmospheric CO_2 concentrations. **FIGURE 14.4** summarizes scientists' current understanding of the fluxes (natural and anthropogenic) of carbon dioxide between the atmosphere, land, and oceans.

Methane concentrations are also rising—2.6-fold since 1750 (see Figure 14.3)—and today's atmospheric concentration is the highest by far in over 800,000 years. We release methane by tapping into fossil fuel deposits, raising livestock that emit methane as a metabolic waste product, disposing of organic matter in landfills, and growing certain crops, such as rice.

Human activities have also elevated atmospheric concentrations of nitrous oxide. This greenhouse gas, a by-product of feedlots, chemical manufacturing plants, auto emissions, and synthetic nitrogen fertilizers, has risen by 20% since 1750 (see Figure 14.3).

Among other greenhouse gases, ozone concentrations in the troposphere (associated with photochemical smog, p. 291) have risen roughly 36% since 1750. The contribution of halocarbon gases to global warming has begun to slow because of the Montreal Protocol and subsequent controls on their production and use (p. 294). Water vapor is the most abundant greenhouse gas in our atmosphere and contributes most to the natural greenhouse effect. Its concentrations vary locally, but because its global concentration has not changed, it is not thought to have driven industrial-age climate change.

Other factors warm or cool the surface

Whereas greenhouse gases exert a warming effect on the atmosphere, **aerosols**, microscopic droplets and particles, can have either a warming or a cooling effect. Soot particles, or "black carbon aerosols," generally cause warming by absorbing solar energy, but most other tropospheric aerosols cool the atmosphere by reflecting the sun's rays. Sulfate aerosols produced by fossil fuel combustion may slow global warming, at least in the short term. When sulfur dioxide enters the atmosphere, it undergoes various reactions, some of which lead to acid deposition (pp. 295–297). These reactions can form a sulfur-rich aerosol haze in the upper atmosphere that blocks sunlight. For this reason, aerosols released by major volcanic eruptions can exert cooling effects on Earth's climate for up to several years. This occurred in 1991 with the eruption of Mount Pinatubo in the Philippines.

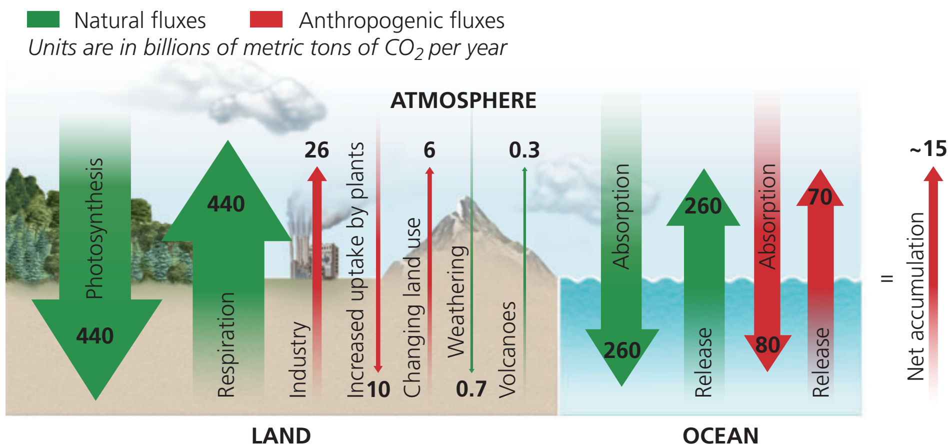


FIGURE 14.4 Human activities are sending more carbon dioxide from Earth's surface to its atmosphere than is moving from the atmosphere to the surface. Shown are all current fluxes of CO_2, with arrows sized according to mass. Green arrows are natural fluxes, and red arrows are anthropogenic fluxes. *Adapted from IPCC, 2007.* Fourth assessment report.

DATA Q For every metric ton of carbon dioxide we emit as a result of changes in land use (e.g. deforestation), how much do we emit from industry?

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To measure the degree of impact that a given factor exerts on Earth's temperature, scientists calculate its **radiative forcing**, the amount of change in thermal energy that the factor causes. Positive forcing warms the surface, whereas negative forcing cools it. When scientists sum up the effects of all factors, they find that Earth is now experiencing radiative forcing of about 2.3 watts/m^2 (**FIGURE 14.5**). This means that our planet today is receiving and retaining 2.3 watts/m^2 more thermal energy than it is emitting into space. (By contrast, the pre-industrial Earth of 1750 was in balance, emitting as much radiation as it was receiving.) This extra amount is equivalent to the power converted into heat and light by 200 incandescent lightbulbs (or over 900 CFLs) across a football field. As Figure 14.2 shows, Earth is estimated naturally to receive and give off about 340 watts/m^2 of energy. Although 2.3 may seem like a small proportion of 340, heat from this imbalance accumulates, and over time this is enough to alter climate significantly.

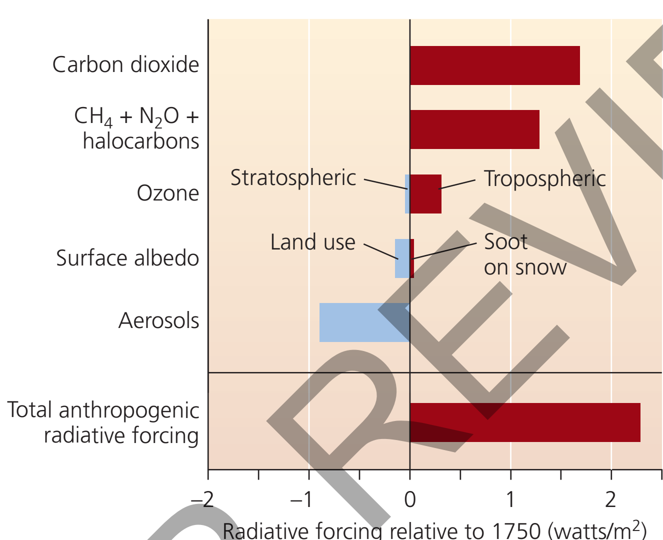


FIGURE 14.5 Radiative forcing quantifies the influence that aerosols, greenhouse gases, and other factors exert over Earth's energy balance. In this graph, radiative forcing is expressed as the warming or cooling effect that each factor has on temperature today relative to 1750, in watts/m^2. Red bars show positive forcing (warming), and blue bars show negative forcing (cooling). *Albedo* (p. 316) refers to the reflectivity of a surface. A number of more minor influences are not shown. *Data from IPCC, 2013.* Fifth assessment report. The physical science basis: Contribution of Working Group I.

Climate varies naturally for several reasons

Atmospheric composition is one of several factors that influence climate. Other factors include variation in energy released by the sun, absorption of carbon dioxide by the oceans, ocean circulation patterns, and cyclic changes in Earth's rotation and orbit. However, scientific data indicate that none of these four natural factors can fully explain the rapid climate change that we are experiencing today.

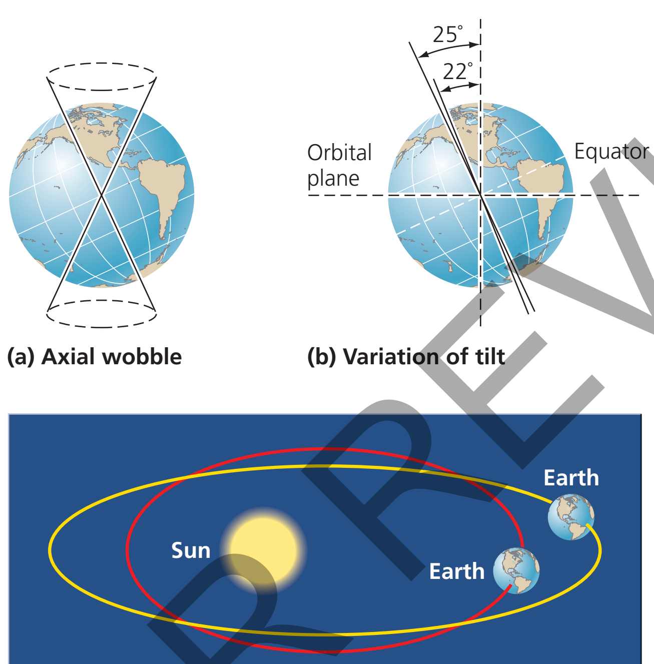
Solar output The sun varies in the amount of radiation it emits, over both short and long timescales. However, scientists are concluding that the variation in solar energy reaching our planet in recent centuries has simply not been great enough to drive significant temperature change on Earth's surface. Estimates place the radiative forcing of natural changes in solar output at only about 0.05 watts/m^2—less than any of the anthropogenic causes shown in Figure 14.5.

Ocean absorption The oceans hold 50 times more carbon than the atmosphere. Oceans absorb carbon dioxide from the atmosphere when CO_2 dissolves directly in water and when marine phytoplankton use it for photosynthesis. However, the oceans are absorbing less CO_2 than we are adding to the atmosphere (see Figure 2.20, p. 40). Thus, oceanic carbon absorption is slowing global warming but is not preventing it. Moreover, as ocean water warms, it absorbs less CO_2 because gases are less soluble in warmer water—a positive feedback effect (pp. 23–24) that accelerates warming of the atmosphere.

Ocean circulation Ocean water exchanges heat with the atmosphere, and ocean currents move energy from place to place. For example, the oceans' thermohaline circulation system (pp. 254–255) moves warm tropical water northward toward Europe, providing Europe a far milder climate than it would otherwise have. Scientists are studying whether freshwater input from Greenland's melting ice sheet might shut down this warm-water flow—an occurrence that could plunge Europe into much colder conditions.

Multiyear climate variability results from the El Niño–Southern Oscillation (pp. 255–256), which involves systematic shifts in atmospheric pressure, sea surface temperature, and ocean circulation in the tropical Pacific Ocean. These shifts overlie longer-term variability from a phenomenon known as the Interdecadal Pacific Oscillation. El Niño and La Niña events alter weather patterns from region to region in diverse ways, often leading to rainstorms and floods in dry areas and drought and fire in moist areas. This leads to impacts on wildlife, agriculture, and fisheries.

Milankovitch cycles In the 1920s, Serbian mathematician Milutin Milankovitch described three types of periodic changes in Earth's rotation and orbit around the sun. Over thousands of years, our planet wobbles on its axis, varies in the tilt of its axis, and experiences change in the shape of its orbit, all in regular long-term cycles of different lengths. These variations, known as **Milankovitch cycles**, alter the way solar radiation is distributed over Earth's surface (**FIGURE 14.6**). By modifying patterns of atmospheric heating, these cycles trigger long-term climate variation. This includes periodic episodes of *glaciation* during which global surface temperatures drop and ice sheets advance from the poles toward the midlatitudes. These cycles are highly influential in the very long term, but science shows that they do not account for the very recent, rapid, extreme climate change we are experiencing today.



(c) Variation of orbit

FIGURE 14.6 There are three types of Milankovitch cycles: **(a)** an axial wobble that occurs on a 19,000- to 23,000-year cycle; **(b)** a 3-degree shift in the tilt of Earth's axis that occurs on a 41,000-year cycle; and **(c)** a variation in Earth's orbit from almost circular to more elliptical, which repeats every 100,000 years.

FAQ The climate changes naturally, so why worry about climate change?

Earth's climate does indeed change naturally across very long periods of time, but there is nothing "natural" about today's climate change. We know that human beings are directly causing the unnaturally rapid change we are now seeing. Moreover, humanity has never experienced the sheer amount of change predicted for this century. The quantity by which the world's temperature is forecast to rise is greater than the amount of cooling needed to bring on an ice age. Greenhouse gas concentrations are already higher than they've been in over 800,000 years, and they are rising. The human species has existed for only 200,000 years, and our civilization arose only in the last few thousand years during an exceptionally stable period in Earth's climate history. Unless we reduce our emissions, we will soon be challenged by climate conditions our species has never lived through.

Studying Climate Change

To comprehend any phenomenon that changes, we must study its past, present, and future. Scientists monitor present-day climate, but they also devise clever means of inferring past change and sophisticated methods to predict future conditions.

Proxy indicators tell us of the past

To understand past climate, scientists decipher clues from thousands or millions of years ago by taking advantage of the record-keeping capacity of the natural world. **Proxy indicators** are types of indirect evidence that serve as proxies, or substitutes, for direct measurement.

For example, Earth's ice caps, ice sheets, and glaciers hold clues to climate history. In frigid areas near the poles and atop high mountains, snow falling year after year compresses into ice. Over the ages, this ice accumulates to great depths, preserving within its layers tiny bubbles of the ancient atmosphere. Scientists can examine the trapped air bubbles by drilling into the ice and extracting long columns, or cores. The layered ice, accumulating season after season for thousands of years, provides a timescale. By studying the chemistry of the bubbles in each layer, scientists can determine atmospheric composition, greenhouse gas concentrations, temperature, snowfall, solar activity, and frequency of forest fires and volcanic eruptions during each time period.

Recently, researchers drilled and analyzed the deepest ice core ever (**FIGURE 14.7**). At a remote site in Antarctica, they drilled down 3270 m (10,728 ft) to bedrock and pulled out more than 800,000 years' worth of ice! This core chronicles Earth's history across eight glacial cycles. By analyzing air bubbles trapped in the ice, researchers discovered that over the past 800,000 years, atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have never been as high as they are today. These data demonstrate that by emitting greenhouse gases since the industrial revolution, we have brought ourselves deep into uncharted territory.

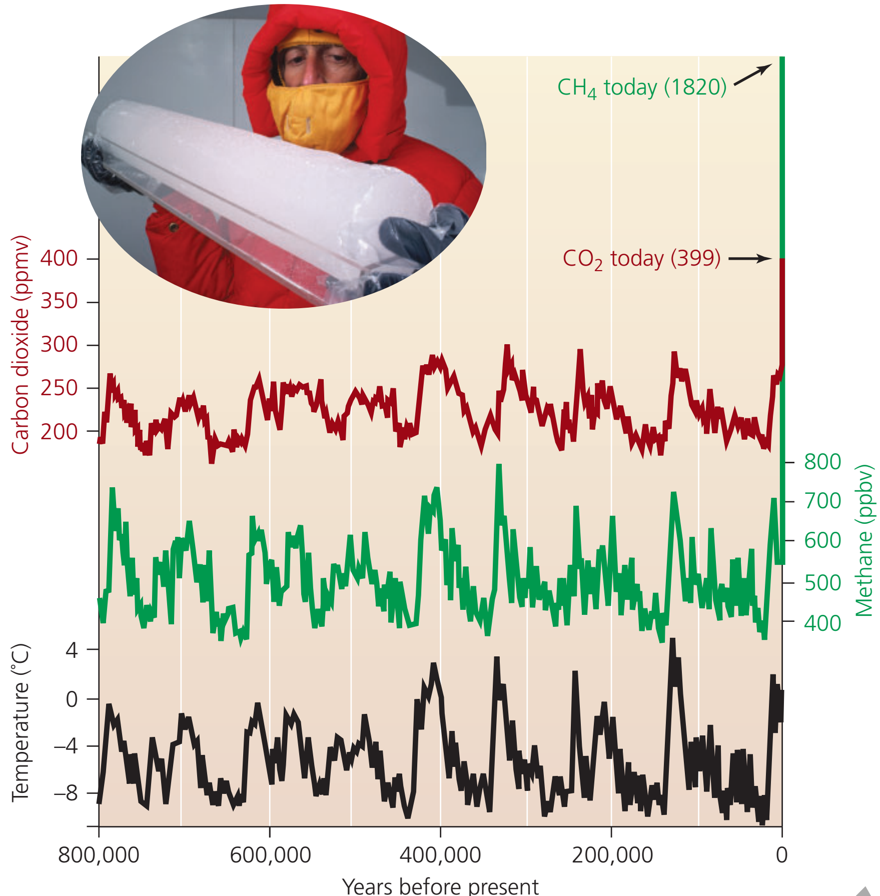


FIGURE 14.7 Data from the EPICA ice core reveal changes across 800,000 years. Shown are surface temperature **(black line)**, atmospheric methane concentration **(green line)**, and atmospheric carbon dioxide concentration **(red line)**. Concentrations of CO_2 and methane rise and fall in tight correlation with temperature. Today's current values are included at the top right of the graph, for comparison.

Adapted by permission of Macmillan Publishers Ltd: Brook, E. 2008. Paleoclimate: Windows on the greenhouse. Nature *453: 291–292, Fig 1a. www.nature.com.*

The ice core results also confirm that temperature swings in the past were tightly correlated with greenhouse gas concentrations (compare the top two data sets in Figure 14.7 with the temperature data set at bottom). This bolsters the scientific consensus that our greenhouse gas emissions are causing Earth to warm today.

Researchers also drill cores into beds of sediment beneath bodies of water. Sediments often preserve pollen grains and other remnants from plants that grew in the past (as described in the study of Easter Island; pp. 6–7). Because climate influences the types of plants that grow in an area, knowing what plants were present can tell us a great deal about the climate at that place and time. Other types of proxy indicators include tree rings (which reveal year-by-year histories of precipitation and fire), pack-rat middens (rodent dens in which plant parts may be preserved for centuries in arid regions), and coral reefs (p. 258), which reveal aspects of ocean chemistry.

Direct measurements tell us about the present

Today we measure temperature with thermometers, rainfall with rain gauges, wind speed with anemometers, and air pressure with barometers, using computer programs to integrate and analyze this information in real time. With these technologies and more, we document the fluctuations in weather day by day and hour by hour across the globe.

We also measure the chemistry of the atmosphere and the oceans. Direct measurements of carbon dioxide concentrations in the atmosphere reach back to 1958, when scientist Charles Keeling began analyzing hourly air samples from a monitoring station at Hawaii's Mauna Loa Observatory. These data show that atmospheric CO_2 concentrations have increased from 315 ppm in 1958 to 399 ppm in 2014.

Models help us predict the future

To understand how climate systems function and to predict future climate change, scientists simulate climate processes with sophisticated computer programs. **Climate models** are programs that combine what is known about atmospheric circulation, ocean circulation, atmosphere–ocean interactions, and feedback cycles to simulate climate processes (see **THE SCIENCE BEHIND THE STORY**, pp. 310–311). This requires manipulating vast amounts of data with complex mathematical equations—a task not possible until the advent of modern computers.

Climate modelers provide starting information to the model, set up rules for the simulation, and then let it run. Researchers test the efficacy of a model by entering past climate data and running the model toward the present. If a model accurately reconstructs current climate, then we have reason to believe that it simulates climate mechanisms realistically and may accurately predict future climate.

Plenty of challenges remain for climate modelers, because Earth's climate system is so complex. Yet as scientific knowledge builds and computing power intensifies, climate models are improving in resolution and are making predictions region by region across the world.

How Do Climate Models Work?

A researcher manipulates a 3D cloud simulator to help in modeling climate.

Models are indispensable for scientists studying climate today—and they are increasingly vital for society because they help predict what conditions will confront us in the future. Yet to most of us, a climate model is a mysterious black box. So how exactly do scientists create a climate model?

The colorful maps and data-rich graphs that scientists generate from a climate model are the end result, but the process begins when they put into the model a long series of mathematical equations. These equations describe how various components of Earth's systems function. Some equations are derived from physical laws such as those on the conservation of mass, energy, and momentum (p. 27). Others are derived from observational and experimental data on physics, chemistry, and biology. Converted into computing language, these equations are integrated with data on Earth's landforms, hydrology, vegetation, and atmosphere (**FIGURE 1**).

Earth's climate system is mind-bogglingly complex, but as computers grow more powerful, sophisticated models are including more and more factors that influence climate. Most models consist of submodels, each handling a different component—ocean water, sea ice, glaciers, forests, deserts, troposphere, stratosphere, and so on.

The processes within a model must be given equations to make them behave realistically in space and time. In the real climate system, time is continuous, and spatial effects reach down to the level of molecules interacting with one another. But the virtual reality of climate models cannot be so detailed—there is simply not enough computer power available. Instead, modelers approximate reality by dividing time into periods (called time steps) and by dividing Earth's surface into cells or boxes in a grid (called grid boxes) (**FIGURE 2**).

Each grid box contains land, ocean, or atmosphere, much like a digital photograph is made up of discrete pixels of certain colors. The grid boxes are arrayed in a three-dimensional layer

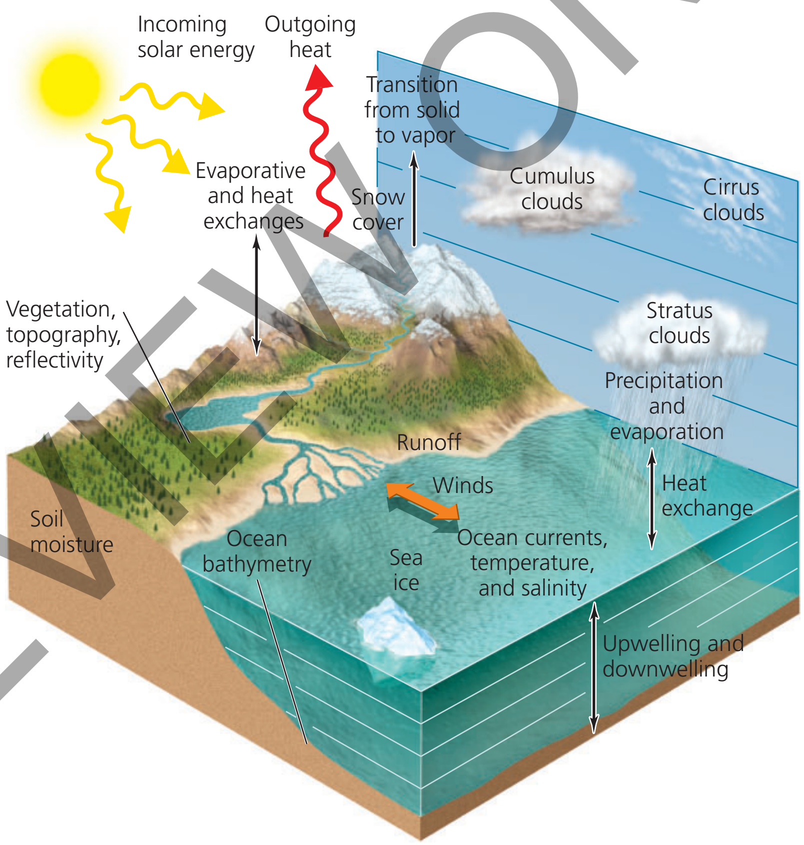


FIGURE 1 Climate models incorporate a diversity of natural factors and processes. Anthropogenic factors can then be added in.

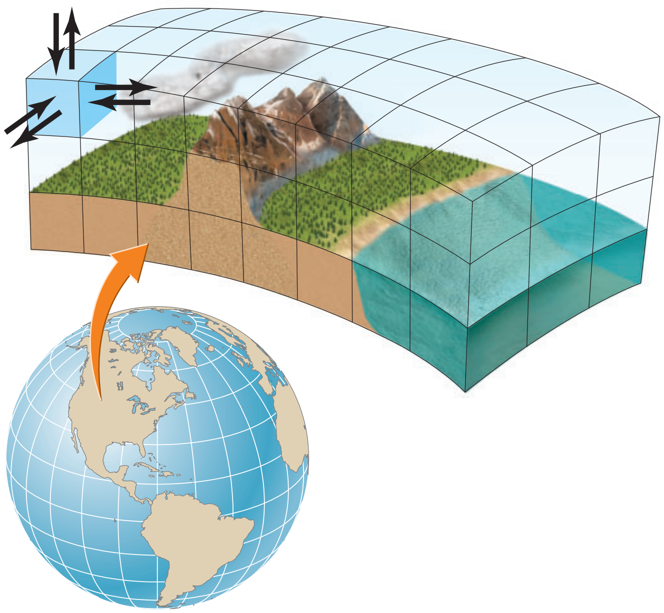


FIGURE 2 Climate models divide Earth's surface into a layered grid. Each grid box represents land, air, or water, and interacts with adjacent grid boxes via the flux of materials and energy. *Adapted from Bloom, Arnold J., 2010.* Global climate change: Convergence of disciplines. *Sinauer Associates, Sunderland, Mass.*

by latitude and longitude, or in equal-sized polygons. The finer the scale of the grid, the greater resolution the model will have, and the better it will be able to predict results region by region. However, more resolution requires more computing power, and climate models already strain the most powerful supercomputing networks. Today's best climate models feature dozens of grid boxes piled up from the bottom of the ocean to the top of the atmosphere, with each grid box measuring a few dozen miles wide, and time measured in periods of just minutes.

Once the grid is established, the processes that drive climate are assigned to each grid box, with their rates parceled out among the time steps. The model lets the grid boxes interact through time by means of the flux of materials and energy into and out of each grid box.

Once modelers have input all this information, learned from our study of Earth and the climate system, they let the model run through time and simulate climate, from the past into the future. If the computer simulation accurately reconstructs past and present climate, then that gives us confidence that it may predict future climate accurately as well.

A number of studies have compared model runs that include only natural processes, model runs that include only human-generated processes, and model runs that combine both. Repeatedly these studies find that the model runs that incorporate both human and natural processes are the ones that fit real-world climate observations the best (**FIGURE 3**). This supports the idea that human activities, as well as natural processes, are influencing our climate.

The major human influence on climate is our emission of greenhouse gases, and modelers need to select values to enter for future emissions if they want to predict future climate. Generally they will run their simulations multiple times, each time with a different emission rate according to a specified scenario. Differences between the results from such scenarios tell us what influence these different emission rates would have. You can see results from such a comparison in Figure 14.24 (p. 322).

Researchers are constantly testing and evaluating their models. They improve them by incorporating what is learned from new research and by taking advantage of what new computing technologies allow. As their work proceeds, we can expect increasingly precise and accurate predictions about future climate conditions. ☐

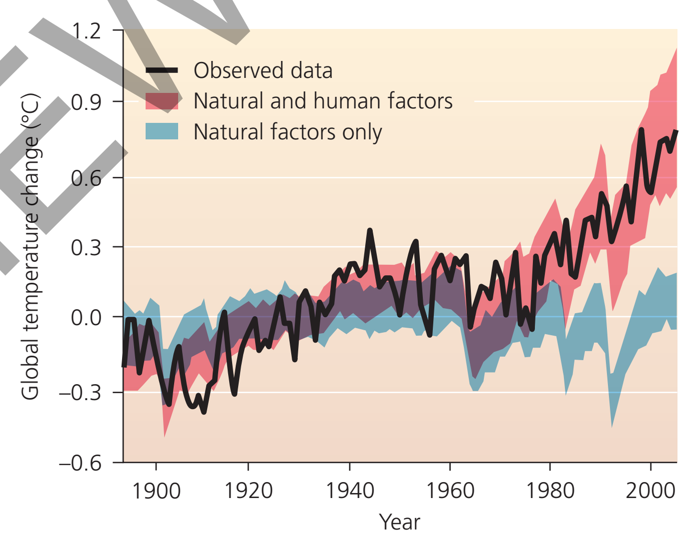
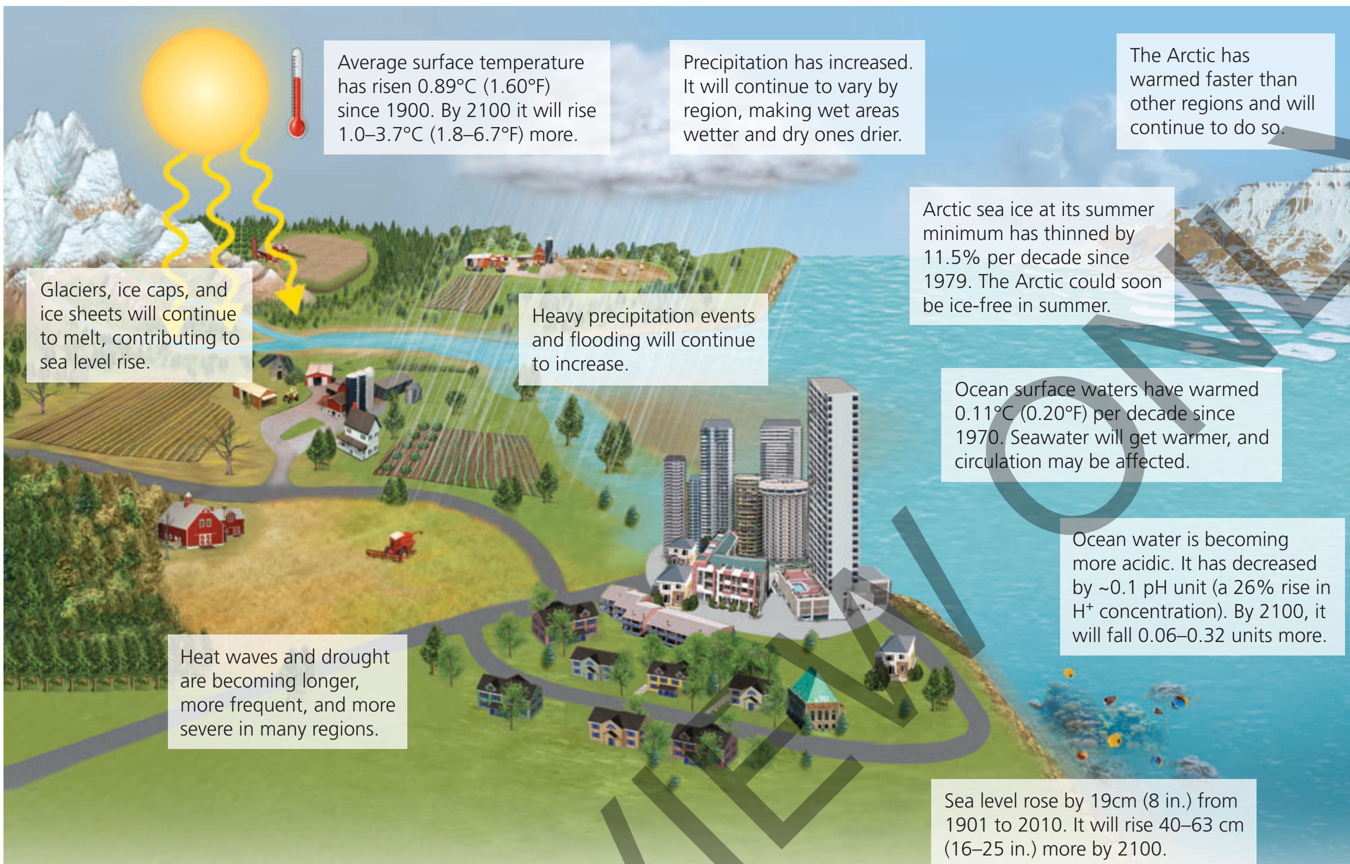


FIGURE 3 Models that incorporate both natural and anthropogenic factors predict observed climate trends best. *Adapted from Melillo, J. M., et al., eds., 2014.* Climate change impacts in the United States: The third national climate assessment. *U.S. Global Change Research Program.*

Current and Future Trends and Impacts

Virtually everyone is noticing changes in the climate these days. Maldives fishermen note the seas encroaching on their home island. Texas ranchers and California farmers suffer multiyear droughts. Florida homeowners struggle to obtain insurance against hurricanes and storm surges. People from New York to Atlanta to Chicago to Los Angeles face one unprecedented weather event after another. Extreme weather events are indeed part of a real pattern backed by a tremendous volume of scientific evidence. Climate change has already had numerous impacts on the physical properties of our planet, on organisms and ecosystems, and on human well-being (**FIGURE 14.8**). If we continue to emit greenhouse gases into the atmosphere, the consequences of climate change will grow more severe.



BIOLOGICAL TRENDS AND IMPACTS

- Species ranges are shifting toward the poles and up in elevation.
- Seasonal timing (such as migration and breeding) is shifting.
- Some species are declining, and many could eventually face extinction.
- Ocean acidification is starting to affect marine life. Coral reefs could disappear, devastating marine ecosystems.
- Forests are being altered by drought, fire, and pest outbreaks.

SOCIAL TRENDS AND IMPACTS

- Ocean acidification could destroy major commercial fisheries.
- Droughts and flooding are leading to agricultural losses.
- Sea level rise will displace people and cause escalating expense.
- More intense storms are causing more property loss and loss of life.
- Farmers and foresters are struggling with altered growing seasons and disturbance regimes.
- Crop yields will likely fall in the dry tropics and subtropics.
- Impacts on biodiversity will cause losses of food, water, and ecosystem goods and services.
- Melting of mountain glaciers will reduce water supplies to millions.
- Economic costs will far outweigh benefits.
- Poorer nations and communities are suffering greater impacts.
- Increased warm-weather health hazards will outweigh decreased cold-weather hazards.

FIGURE 14.8 Current trends and future impacts of climate change are extensive. Shown are major physical, biological, and social trends and impacts (both observed and predicted) as reported by the IPCC. (Mean estimates are shown; the IPCC reports ranges and statistical probabilities as well.) *Data from IPCC, 2013. Fifth assessment report.*

Scientific evidence for climate change is extensive

For years, scientists have studied climate change in enormous breadth, depth, and detail. As a result, researchers have gained a rigorous understanding of most aspects of climate change. To make this vast and growing research knowledge accessible to policymakers and the public, the **Intergovernmental Panel on Climate Change (IPCC)** has taken up the task of reviewing and summarizing it. This international body consists of many hundreds of scientists and governmental representatives. The IPCC was awarded the Nobel Peace Prize in 2007 for its work in informing the world of the trends and impacts of climate change.

In 2013 and 2014, the IPCC released its *Fifth Assessment Report*. By summarizing thousands of scientific studies, this report documents observed trends in surface temperature, precipitation patterns, snow and ice cover, sea levels, storm intensity, and other factors (see Figure 14.8). It also predicts future changes in these phenomena after considering a range of potential scenarios for future greenhouse gas emissions. The report addresses impacts of climate disruption on wildlife, ecosystems, and society. Finally, it discusses strategies we might pursue in response. To learn more, you and your instructor may wish to download the *Fifth Assessment Report* and explore its coverage of recent research findings. A series of three "working group" reports and a synthesis report are publicly accessible online at the IPCC's website.

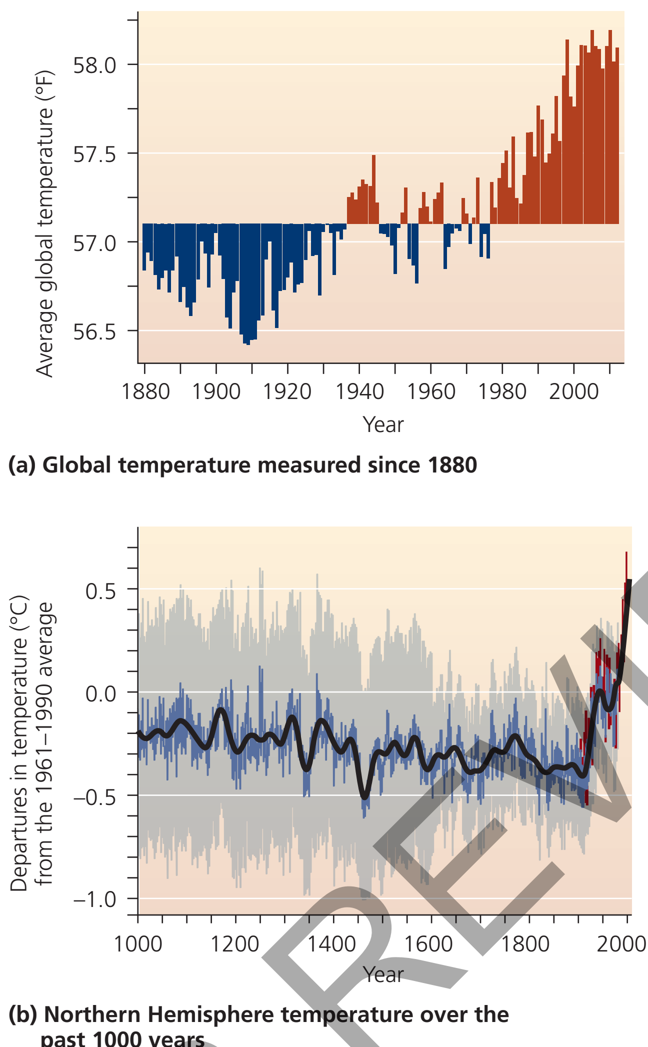


FIGURE 14.9 Global temperatures have risen sharply in the past century. Data from thermometers **(a)** show changes in Earth's average surface temperature since 1880. Since 1976, every single year has been warmer than average. In **(b)**, proxy indicators **(blue line)** and thermometer data **(red line)** together show average temperatures in the Northern Hemisphere over the past 1000 years. The gray-shaded zone represents the 95% confidence range. *Data from (a) Melillo, J.M., et al., eds., 2014.* Climate change impacts in the United States: The third national climate assessment. *U.S. Global Change Research Program; and (b) IPCC, 2001.* Third assessment report.

Temperatures continue to rise

Average surface temperatures on Earth have risen by nearly 0.9°C (1.6°F) in the past 100 years (**FIGURE 14.9**). Most of this increase has occurred since 1975—and just since 2000, we have experienced 13 of the 15 warmest years on record since global measurements began 150 years ago! The decade from 2001 to 2010 was the hottest ever recorded, and since the 1960s each decade has been warmer than the last. If you were born after 1985, you have never in your life lived through a month with average global temperatures lower than the 20th-century average.

In just the past two decades, temperatures in most areas of the United States have risen by more than 1 full degree Fahrenheit (**FIGURE 14.10**).

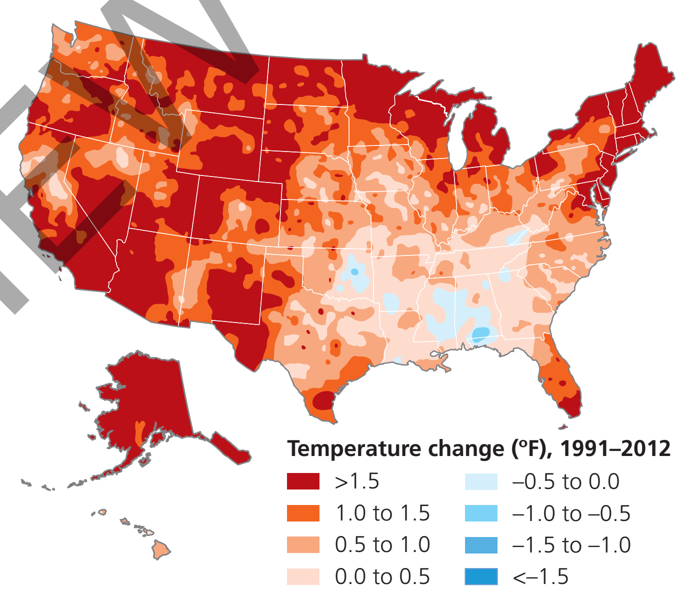


FIGURE 14.10 U.S. temperatures rose between 1991 and 2011. Although some areas of the Southeast cooled slightly, most of the nation warmed by more than 1 degree Fahrenheit (0.6°C). *Data from NOAA National Climatic Data Center as presented in Melillo, J.M., et al., eds., 2014.* Climate change impacts in the United States: The third national climate assessment. *U.S. Global Change Research Program.*

DATA Q By how much did the average temperature rise or fall where you live? How does this compare with changes in other parts of the country?

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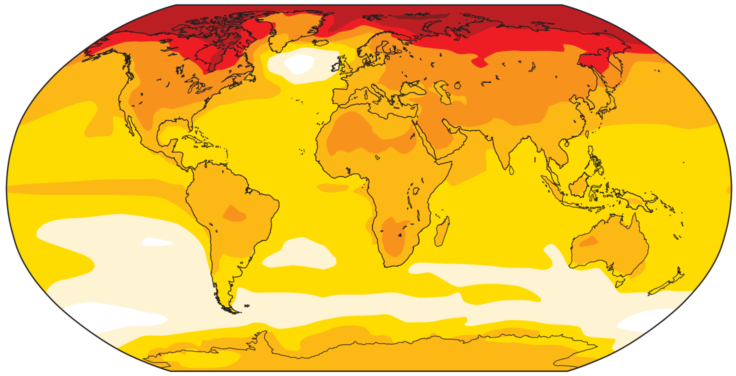


FIGURE 14.11 Surface temperatures are projected to rise for the years 2081–2100, relative to 1986–2005. Landmasses are expected to warm more than oceans, and the Arctic will warm the most. This map was generated using an intermediate emissions scenario with an average global temperature rise of 2.2°C (4.0°F). *Data from IPCC, 2013.* Fifth assessment report. The physical science basis: Contribution of Working Group I.

We can expect global surface temperatures to continue rising because we are still emitting greenhouse gases and because the greenhouse gases already in the atmosphere will continue warming the globe for decades to come. At the end of the 21st century, the IPCC predicts global temperatures will be 1.0–3.7°C (1.8–6.7°F) higher than today's, depending on how well we control our emissions. Unusually hot days and heat waves will become more frequent. Future changes in temperature are predicted to vary from region to region in ways that they already have (**FIGURE 14.11**). For example, polar regions will continue to experience the most intense warming.

Precipitation is changing, too

A warmer atmosphere speeds evaporation and holds more water vapor, and precipitation has increased worldwide by 2% over the past century. Yet some regions of the world are receiving less rain and snow than usual while others receive more than usual. In the southwestern United States, droughts have become more frequent and severe, harming agriculture, worsening soil erosion, reducing water supplies, and triggering wildfire. In other regions, heavy rain events have increased, leading to flooding, such as the 2008 floods in Iowa and elsewhere in the U.S. Midwest and the 2011 floods along the Mississippi River that killed dozens of people, left thousands homeless, and inflicted billions of dollars in damage.

Future changes in precipitation (**FIGURE 14.12**) are predicted to intensify regional changes that have already occurred. Many wet areas will receive more rainfall, increasing the risk of flooding, while many dry areas become drier.

Extreme weather is becoming "the new normal"

The sheer number of extreme weather events in recent years—droughts, floods, tornadoes, hurricanes, snowstorms, cold snaps, heat waves—has caught everyone's attention, and weather records are being broken left and right. In the United States, 2012 was the hottest year ever recorded. The nation experienced a freakish heat wave in March, a severe summer drought that devastated agriculture across three-fifths of the country, and Hurricane Sandy, which inflicted over $60 billion in damage.

Scientific data summarized by the U.S. Climate Extremes Index confirm that the frequency of extreme weather events in the United States has been rising since 1970. Scientists are not the only ones to notice this trend. The insurance industry is finely attuned to such patterns, because insurers pay out money each time a major storm, drought, or flood hits. A major German insurer, Munich Re, calculated that since 1980, extreme weather events causing losses have increased by 50% in South America, have doubled in Europe, and have risen by 2.5 times in Africa, 4 times in Asia, and 5 times in North America.

For years, researchers have conservatively stated that although climate trends influence the probability of what the weather may be like on any given day, no particular weather event can be directly attributed to climate change. In the aftermath of Hurricane Sandy, a metaphor spread across the Internet: When a baseball player takes steroids and starts hitting more home runs, you can't attribute any one particular home run to the steroids, but you *can* conclude that steroids are responsible for the increase in home runs. Our greenhouse gas

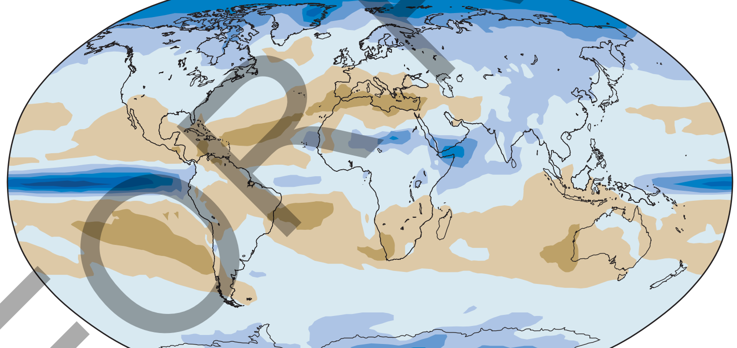


FIGURE 14.12 Precipitation is projected to change for the years 2081–2100, relative to 1986–2005. Browner shades indicate less precipitation; bluer shades indicate more. This map was generated using an intermediate emissions scenario with an average global temperature rise of 2.2°C (4.0°F). *Data from IPCC, 2013.* Fifth assessment report. The physical science basis: Contribution of Working Group I.

emissions are like steroids that are supercharging our climate and increasing the instance of extreme weather events.

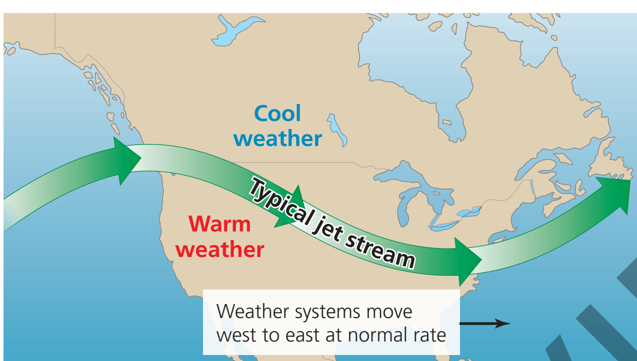
In 2012, research by Jennifer Francis of Rutgers University and Stephen Vavrus of the University of Wisconsin revealed a mechanism that may explain how and why global warming leads to more extreme weather. Because warming has been greatest in the Arctic, this has weakened the intensity of the Northern Hemisphere's polar *jet stream*, a high-altitude air current that blows west-to-east and meanders north and south, influencing the weather across North America and Eurasia. As the jet stream slows down, its meandering loops become longer. These long lazy loops move west to east more slowly, and may get stuck in a north–south orientation for long periods of time. Meteorologists call this an *atmospheric blocking pattern* because it blocks the eastward movement of weather systems (**FIGURE 14.13**). When this happens, a rainy system that would normally move past a city in a day or two may instead be held in place for several days, causing flooding. Or dry conditions over a farming region might last two weeks instead of two days, resulting in drought. Hot spells last longer, and cold spells last longer, too.

Indeed, the record-breaking heat wave of March 2012 resulted after the jet stream became stuck in place (see Figure 14.13b). Atmospheric blocking patterns also were associated with the 2011 drought in Texas, the 2012 wildfires in Colorado, severe wintry weather in the eastern United States in 2014, both floods and heat waves in Europe, and other extreme weather events.

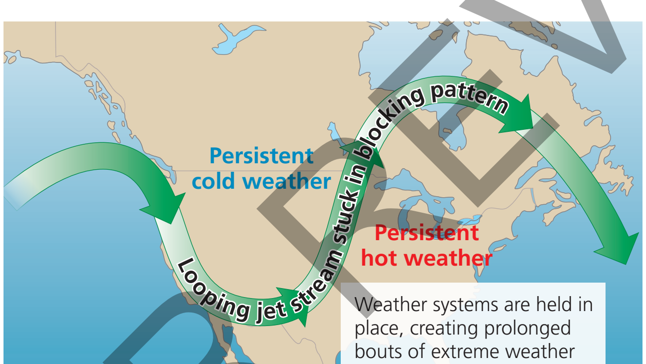
Melting ice has far-reaching effects

As the world warms, mountaintop glaciers are disappearing (**FIGURE 14.14**). Between 1980 and 2012, the World Glacier Monitoring Service estimates that the world's major glaciers on average each lost mass equivalent to 16 m (52 ft) in vertical height of water. Many glaciers on tropical mountaintops have disappeared already. In Glacier National Park in Montana, only 25 of 150 glaciers present at the park's inception remain, and scientists estimate that by 2030 even these will be gone.

Mountains accumulate snow in winter and release meltwater gradually during summer. Over one-sixth of the world's people live in regions that depend on mountain meltwater. As warming temperatures diminish mountain glaciers, summertime water supplies will decline for millions of people, likely forcing whole communities to look elsewhere for water or to move.



(a) Normal jet stream



(b) Jet stream in March 2012

FIGURE 14.13 Changes in the jet stream can cause extreme weather events. When Arctic warming slows the jet stream, it departs from its normal configuration **(a)** and goes into a blocking pattern **(b)** that stalls weather systems in place. The blocking pattern shown here brought record-breaking heat to the eastern United States in March 2012.

(a) Jackson Glacier in 1911

(b) Jackson Glacier in 2009

FIGURE 14.14 Glaciers are melting as global warming proceeds. The Jackson Glacier in Glacier National Park, Montana, retreated substantially between **(a)** 1911 and **(b)** 2009. *Data from World Glacier Monitoring Service.*

Warming temperatures are also melting vast amounts of polar ice. In the Arctic, the immense ice sheet that covers Greenland is melting faster and faster. In Antarctica, coastal ice shelves the size of Rhode Island have disintegrated as a result of contact with warmer ocean water, and recent research suggests that the entire West Antarctic ice shelf may be on its way to unstoppable collapse, creating a 3-m (10-ft) rise in sea level.

Warming is accelerating in the Arctic because as snow and ice melt, darker, less reflective surfaces (such as bare ground and pools of meltwater) are exposed, and Earth's *albedo*, or capacity to reflect light, decreases. As a result, more of the sun's rays are absorbed at the surface, fewer rays reflect back into space, and the surface warms. In a process of positive feedback, this warming causes more ice and snow to melt, which in turn causes more absorption of radiation and more warming (see Figure 2.1b, p. 23).

As Arctic sea ice disappears, new shipping lanes open up for commerce, and governments and companies are rushing to exploit newly accessible underwater oil and mineral reserves. Russia, Canada, the United States, and other nations are jockeying for position, trying to lay claim to regions of the Arctic as the ice melts.

Warmer temperatures in the Arctic are now also causing *permafrost* (permanently frozen ground) to thaw. As ice crystals within permafrost melt, the thawing soil settles, destabilizing buildings, pipelines, and other infrastructure. When permafrost thaws, it also can release methane that has been stored for thousands of years. Because methane is a potent greenhouse gas, its release acts as a positive feedback mechanism that intensifies climate change.

Rising sea levels may affect hundreds of millions of people

As glaciers and ice sheets melt, increased runoff causes sea levels to rise. Sea levels also are rising because ocean water is warming; water expands in volume as it warms. Worldwide, average sea levels have risen 21 cm (8.3 in.) in the past 130 years (**FIGURE 14.15**), reaching a rate of 3.2 mm/year from 1993 to 2010. These numbers represent vertical rises in water level, and on most coastlines a vertical rise of a few inches means many feet of incursion inland.

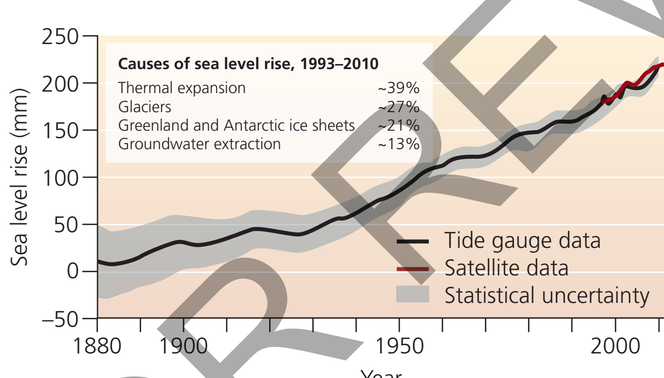


FIGURE 14.15 Global average sea level has risen roughly 210 mm (8.3 in.) since 1880. Sea levels rise because water expands as it warms, glaciers and ice sheets are melting, and groundwater we extract eventually reaches the ocean. *Data from IPCC, 2013.* Fifth assessment report. The physical science basis: Contribution of Working Group I.

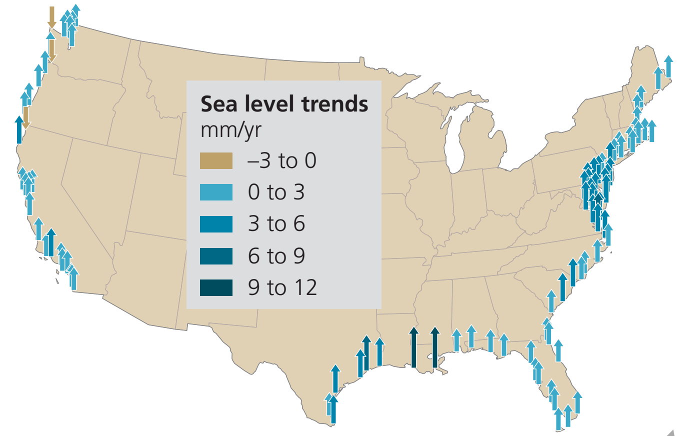


FIGURE 14.16 Sea level is rising at varying rates along the U.S. coast. Rates are highest where land is subsiding along the Gulf Coast and the central Atlantic Seaboard. *Data from National Oceanic and Atmospheric Administration.*

Regions experience differing amounts of sea level change because land may be rising or subsiding naturally, depending on local geological conditions. The Maldives has fared better than many other island nations: It has seen sea levels rise about 3 mm per year since 1990, but most Pacific islands are experiencing greater rises in sea level, some up to 9 mm/year. The United States is experiencing varying degrees of sea level rise (**FIGURE 14.16**), with the East Coast and the Gulf Coast most at risk.

Higher sea levels lead to beach erosion, coastal flooding, intrusion of salt water into aquifers, and greater impacts from storm surges. A *storm surge* is a temporary and localized rise in sea level generated by a storm. The higher that sea level is to begin with, the further inland a storm surge can reach. The impact of storm surges was made painfully clear in 2013 when Typhoon Haiyan struck the Philippines. One of the strongest storms ever recorded, it took 7000 lives and caused over $1.5 billion in damage. In 1987, unusually high waves struck the Maldives and triggered a campaign to build a large seawall around Malé, the nation's capital. "The Great Wall of Malé" is intended to protect buildings and roads by dissipating the energy of incoming waves during storm surges.

In the United States, "Superstorm" Sandy demonstrated the impact that storm surges can have on highly developed metropolitan areas (**FIGURE 14.17**). This massive hurricane battered the eastern part of the nation in October 2012, causing $65 billion in damage and leaving 160 people dead and thousands homeless. In New Jersey, thousands of homes were destroyed, iconic boardwalks were washed away, and coastal communities were inundated with salt water and sand. In New York City, economic activity ground to a halt as tunnels and subway stations flooded and vehicles and buildings suffered damage. A fire broke out amid flooded homes in Queens and destroyed an entire neighborhood.

Like Typhoon Haiyan, Hurricane Sandy was not directly and solely caused by global warming, but in a statistical sense it was facilitated and strengthened by it. Warmer ocean water boosts the chances of large and powerful hurricanes. A warmer atmosphere retains more moisture that a hurricane can dump onto land. A blocking pattern in the jet stream contributed to Sandy's energy. And higher sea levels magnify the damage caused by storm surges.

Seven years before Sandy, the United States was hit by an even costlier storm. Hurricane Katrina slammed into New Orleans and the Gulf Coast in 2005, killing more than 1800 people and inflicting $80 billion in damage. Outside New Orleans today, marshes of the Mississippi River delta continue to disappear as rising seas eat away at coastal vegetation (pp. 248–249). More than 2.5 million ha (1 million acres) of Louisiana's coastal wetlands have vanished since 1940, weakening protection against future storm surges. Around the world, rising seas are eating away at the salt marshes, dunes, mangrove forests, and coral reefs that serve as barriers protecting our coasts.

The IPCC predicts that mean sea level will rise 26–82 cm (10–32 in.) higher by 2100, depending on emissions. It will continue rising after 2100, and some researchers are now using a 1-meter (39-in.) rise scenario to assess risk. More than half of the U.S. population lives in coastal counties, and 4 million Americans live within 1 vertical meter of the high tide line. Researchers recently estimated that a 1-m rise threatens 180 U.S. cities with losing an average of 9% of their land area. Miami, Tampa, New Orleans, and Virginia Beach are most at risk.

Whether sea levels this century rise a full meter or "only" 26 cm, hundreds of millions of people will be displaced or will need to invest in costly efforts to protect against storm surges. Densely populated regions on low-lying river deltas, such as Bangladesh, will be affected. So will storm-prone regions such as Florida; coastal cities such as Houston, Charleston, Boston, and New York City; and areas where land is subsiding, such as the U.S. Gulf Coast. Many islands may need to be evacuated. In the meantime, island nations such as the Maldives and coastal cities such as Tampa are vulnerable to shortages of fresh water as rising seas bring salt water into aquifers.

FIGURE 14.17 Climate change contributes to the power and reach of devastating storms like Hurricane Sandy. The map shows areas in New York City flooded by the storm. The graph shows sea level rise in New York City in the past century. *Map data from* The New York Times *as adapted from federal agencies; graph data from New York City Panel on Climate Change 2010.*

WEIGHING THE ISSUES

Environmental Refugees

The Pacific island nation of Tuvalu has been losing 9 cm (3.5 in.) of elevation per decade to rising seas. Appeals from Tuvalu's 11,000 citizens were heard by New Zealand, which began accepting "environmental refugees" from Tuvalu in 2003. Do you think the rest of the world should grant such environmental refugees international status and assume some responsibility for taking care of them? Do you think a national culture can survive if its entire population is relocated? Think of the tens of thousands of refugees from Hurricane Katrina. How did their lives and culture fare in the wake of that tragedy?

Acidifying oceans imperil marine life

As carbon dioxide concentrations in the atmosphere rise, the oceans absorb more CO_2. So far, the oceans have absorbed roughly one-quarter of the CO_2 we have added to the atmosphere. This is altering ocean chemistry, making seawater more acidic—a phenomenon referred to as **ocean acidification** (pp. 258–259).

Ocean acidification threatens marine animals such as corals, clams, oysters, mussels, and crabs, which pull carbonate ions out of seawater to build their exoskeletons of calcium carbonate. As seawater becomes more acidic, carbonate ions become less available, and calcium carbonate begins to dissolve, jeopardizing the existence of these animals.

Global ocean chemistry has already decreased by 0.1 pH unit, which corresponds to a 26% rise in hydrogen ion concentration. Initial impacts on corals and oysters are already apparent (**FIGURE 14.18**). By 2100, scientists predict that seawater will decline in pH by another 0.06–0.32 units—very possibly enough to destroy most of our planet's living coral reefs (p. 258). Such destruction could be catastrophic for marine biodiversity and fisheries, because so many organisms depend on coral reefs for food and shelter. Indeed, ocean acidification and the potential loss of marine life threaten to become one of the most far-reaching impacts of global climate change.

Coral reefs face two additional risks from climate change: Warmer waters contribute to deadly coral bleaching (p. 258), and stronger storms physically damage reefs. All these factors concern residents of places like the Maldives or south Florida. In each of these places, coral reefs provide habitat for fish consumed locally and exported for profit, offer snorkeling and scuba diving sites for tourism, and protect coastlines from erosion by reducing wave intensity.

FIGURE 14.18 Ocean acidification threatens the oyster industry. Since 2005, acidified seawater has killed billions of larval oysters in Washington and Oregon, jeopardizing the region's once-thriving industry. Scientists are helping producers find ways to respond, but many in the industry fear acidification will wreak havoc with many shellfish.

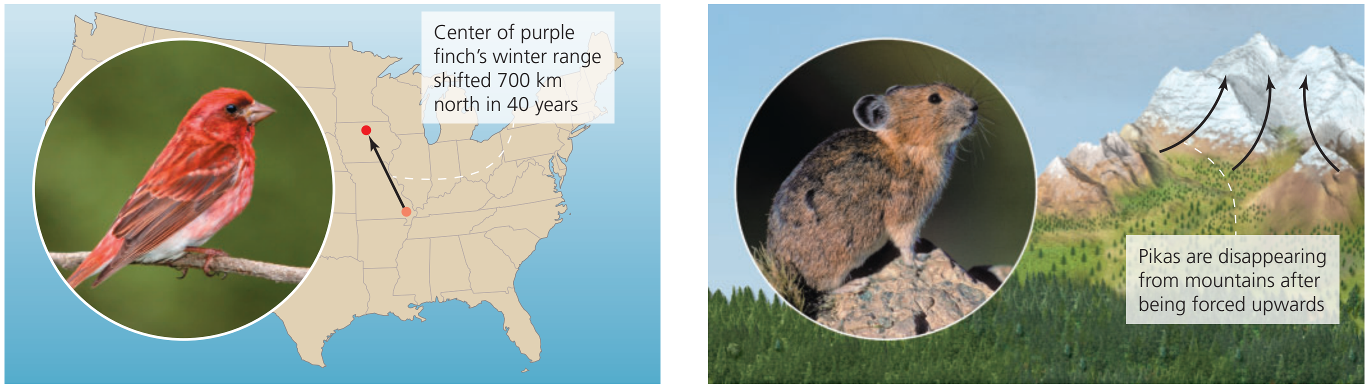
Climate change affects organisms and ecosystems

As the developing crisis with marine life shows, changes in Earth's physical systems have consequences for living things. Organisms are adapted to their environments, so changes to those environments affect them. As global warming proceeds, it is modifying biological phenomena that rely on temperature. In the spring, plants are now leafing out earlier, insects are hatching earlier, birds are migrating earlier, and animals are breeding earlier. These shifts can create mismatches in seasonal timing. For example, European birds known as great tits had evolved to raise their young when caterpillars peak in abundance. Now caterpillars are peaking earlier, but the birds have been unable to adjust, and fewer young birds are surviving.

Biologists are also recording spatial shifts in the ranges of organisms, as plants and animals move toward the poles or upward in elevation (i.e., toward cooler areas) as temperatures warm (**FIGURE 14.19**). Some organisms will not be able to cope and could face extinction. Trees may not be able to shift their distributions fast enough. Rare species may be forced out of preserves and into developed areas where they cannot survive. Animals and plants adapted to mountainous environments may be forced uphill until there is nowhere left to go.

Effects on plant communities comprise an important component of climate change, because by drawing in carbon dioxide for photosynthesis, plants act as reservoirs for carbon. If an atmosphere richer in CO_2 enhances plant growth, then plants might in turn remove more CO_2 from the air. However, if climate change decreases plant growth (through drought, fire, or disease, for instance), then carbon flux to the atmosphere could increase. Large-scale outdoor experiments are revealing complex answers, showing that extra CO_2 can both augment and diminish plant growth.

In regions where precipitation and stream flow increase, erosion and flooding will pollute and alter aquatic systems. In regions where precipitation decreases, lakes, ponds, wetlands, and streams will shrink. The many impacts of climate change on ecological systems will diminish the ecosystem goods and services our societies depend on, from food to clean air to drinking water.



(a) Birds are moving north

(b) Pikas are being forced upslope

FIGURE 14.19 Animal populations are shifting toward the poles and upward in elevation. Fully 177 of 305 North American bird species have shifted their winter ranges significantly northward in the past 40 years, according to a 2009 analysis of Christmas Bird Count data by National Audubon Society researchers. The purple finch **(a)** has shown the greatest shift; its center of abundance moved 697 km (433 mi) north. Mountain-dwelling animals such as the pika **(b)**, a unique mammal of western North America, are being forced upslope (into more limited habitat) as temperatures warm. Many pika populations in the Great Basin have disappeared from mountains already.

Climate change affects society

Drought, flooding, storm surges, and sea level rise are already taking a toll on the lives and livelihoods of millions of people. However, climate change will have still more consequences. These include impacts on agriculture, forestry, health, and economics.

Agriculture For some crops in the temperate zones, moderate warming may slightly increase production as growing seasons lengthen. Added carbon dioxide for photosynthesis may or may not boost yields, and research indicates that crops can become less nutritious when supplied with more CO_2. If rainfall continues to shift in space and time, intensified droughts and floods will likely cut into agricultural productivity (**FIGURE 14.20**). Considering all factors, the IPCC predicts that global crop yields will increase somewhat—but beyond a rise of 3°C (5.4°F), it expects crop yields to decline. It also expects crop production to fall in seasonally dry tropical and subtropical regions where drought and shorter growing seasons will worsen hunger in many developing nations.

FIGURE 14.20 Drought induced by climate change decreases crop yields. Withered corn fields like this one in Illinois were a common sight in 2012, when the U.S. government declared 1000 counties across 26 states to be disaster areas due to drought.

Forestry In the forests that provide our timber and paper products, enriched atmospheric CO_2 may spur greater growth, but drought, fire, and disease may eliminate these gains. Forest managers increasingly find themselves battling catastrophic fires, invasive species, and insect and disease outbreaks. Catastrophic fires are caused in part by decades of fire suppression (p. 196) but are also promoted by longer, warmer, drier fire seasons. Milder winters and hotter, drier summers are promoting outbreaks of bark beetles that are destroying millions of acres of trees (p. 197).

Health As climate change proceeds, we will face more heat waves—and heat stress can cause death. A 1995 heat wave in Chicago killed at least 485 people, and a 2003 heat wave in Europe killed 35,000 people. A warmer climate also exposes us to other health problems:

- Respiratory ailments from air pollution as hotter temperatures promote photochemical smog (p. 291)
- Expansion of tropical diseases, such as malaria and dengue fever, into temperate regions as disease vectors (such as mosquitoes) spread toward the poles
- Disease and sanitation problems when floods overcome sewage treatment systems
- Injuries and drowning as storms become more frequent or intense

Economics People will experience a variety of economic costs and benefits from the impacts of climate change, but on the whole researchers predict that costs will outweigh benefits. Climate change is also expected to widen the gap between rich and poor because poorer people lack the wealth and technology that help people adapt to change, and because poorer people rely more on resources (such as local food and water) that are sensitive to climate disruption.

From a variety of studies, the IPCC has estimated that climate change may cost 1–5% of GDP on average globally, with poor nations losing proportionally more than rich nations. Economists have proposed societal costs of anywhere from $10 to $350 per ton of carbon. The *Stern Review on the Economics of Climate Change*, commissioned by the British government, concluded that climate change could cost us 5–20% of GDP by the year 2200, but that investing just 1% of GDP starting now could enable us to avoid these future costs. A 2014 report titled *Risky Business* detailed hundreds of billions of dollars in likely damages from climate change. This report was issued by a politically diverse team of leading businesspeople and finance experts, chaired by former New York City Mayor Michael Bloomberg, former hedge fund manager Tom Steyer, and former Treasury Secretary Henry Paulson. Regardless of the precise numbers, economists are concluding that investing money now to fight climate change will save us a great deal more money in the future.

Impacts vary by region

Each of us will experience the impacts of climate change differently, depending on where we live. Temperature changes have been greatest in the Arctic (**FIGURE 14.21**). Here, ice sheets are melting, sea ice is thinning, storms are increasing, and altered conditions are posing challenges for people and wildlife. As sea ice melts earlier, freezes later, and recedes from shore, it becomes harder for Inuit people and for polar bears alike to hunt the seals they each rely on for food. Permafrost is thawing, destabilizing buildings. As the strong Arctic warming melts ice caps and ice sheets, it contributes to sea level rise globally.

For the United States, impacts are assessed by the U.S. Global Change Research Program, which Congress created to coordinate federal climate research. Its 2014 *National Climate Assessment* summarizes current research, observed trends, and predicted future impacts of climate change on the United States. This report shows that average U.S. temperatures have increased by 0.7–1.1°C (1.3–1.9°F) since record keeping began in 1895, with the vast majority of this rise occurring just since 1970. Temperatures are predicted to rise by another 1.7–5.6°C (3–10°F) by the end of this century (**FIGURE 14.22**). Extreme weather events have become more frequent, and the costs they impose on farmers, city-dwellers, coastal communities, and taxpayers across the country are escalating.

Impacts vary regionally, and each U.S. region will face its own challenges (**FIGURE 14.23**). Winter and spring precipitation is projected to decrease in the South but increase in the North. Drought may strike in some regions and flooding in others. Sea level rise will affect the Atlantic and Gulf Coasts more than the West Coast. You can learn more about the predictions for your own region by consulting this publicly accessible report online.

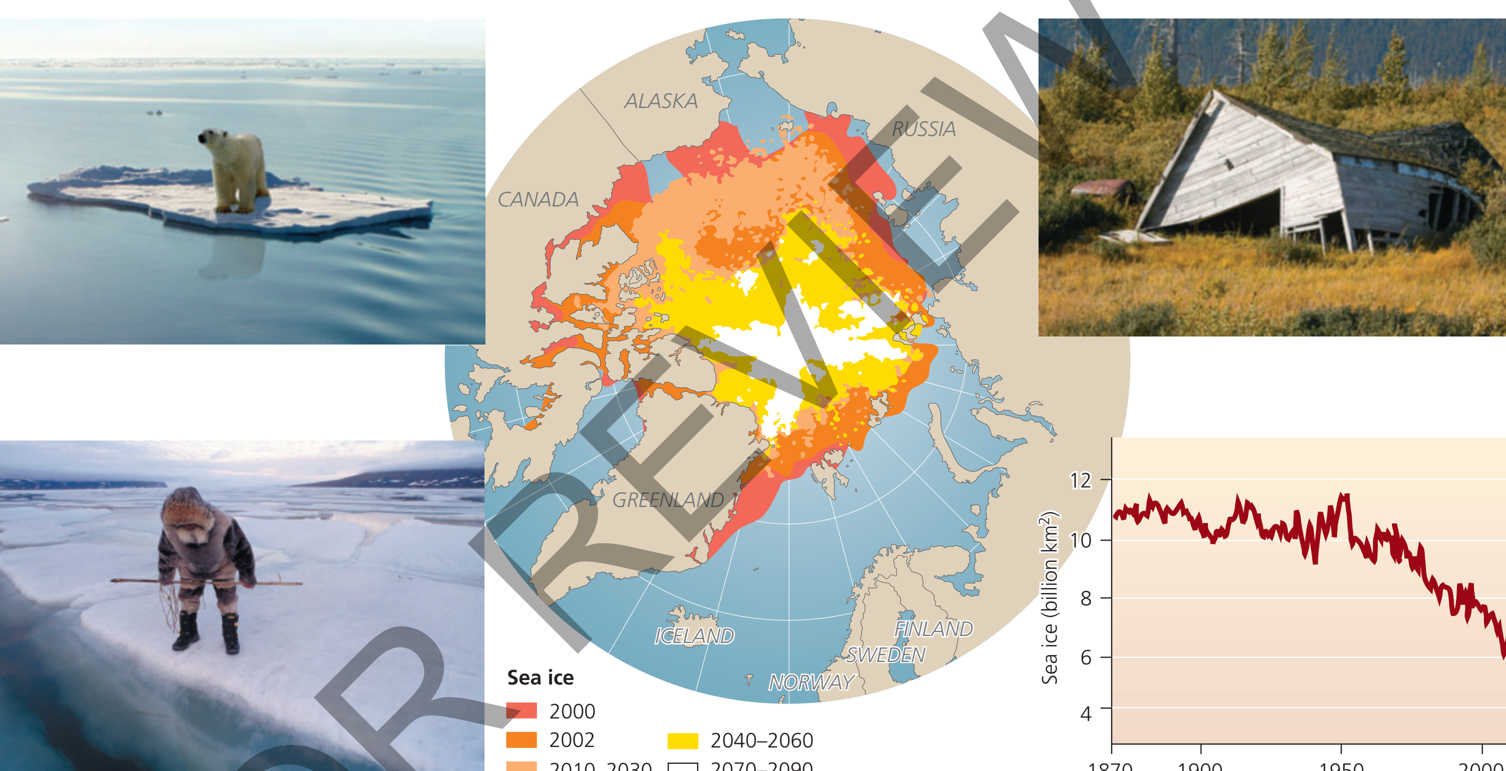


FIGURE 14.21 The Arctic has borne the brunt of climate change. As sea ice melts, it recedes from large areas. The map shows mean minimum summer extent of sea ice for the recent past, present, and future. The graph shows declines in sea ice averaged from six data sets. Inuit people find it difficult to hunt and travel in their traditional ways. Polar bears starve because they are less able to hunt seals. Structures are damaged as permafrost thaws beneath them. *Map data from National Center for Atmospheric Research and National Snow and Ice Data Center.*

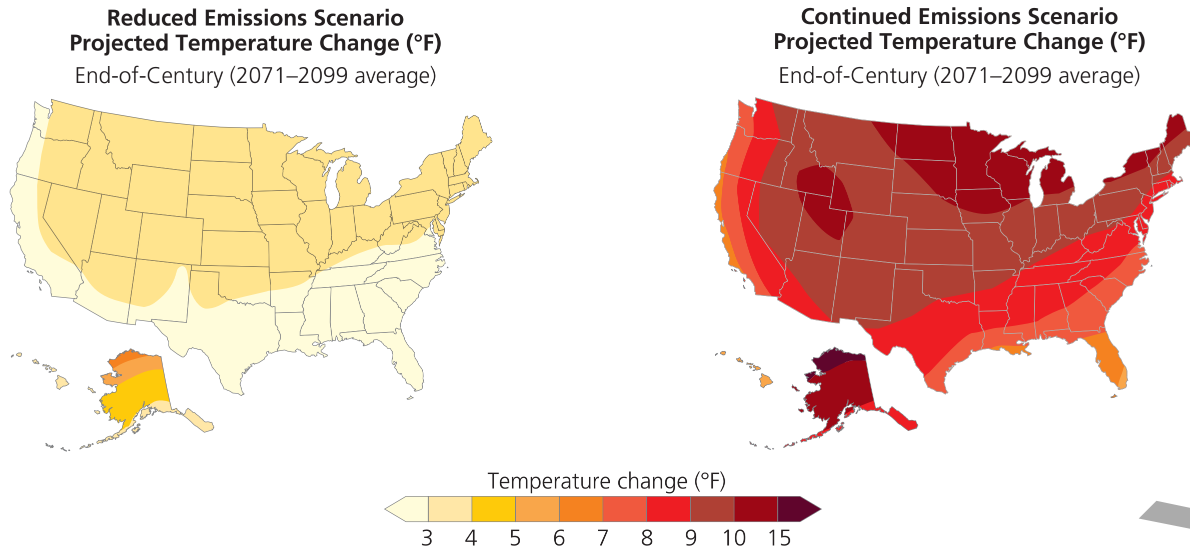


FIGURE 14.22 Average temperatures across the United States are predicted to rise further by the end of this century. Even in a scenario of sharply reduced emissions **(left)**, temperatures are predicted to rise by 3–4°F. In a scenario of business-as-usual emissions **(right)**, temperatures are predicted to rise by 7–11°F. *Data from Melillo, J. M., et al., eds., 2014.* Climate change impacts in the United States: The third national climate assessment. *U.S. Global Change Research Program.*

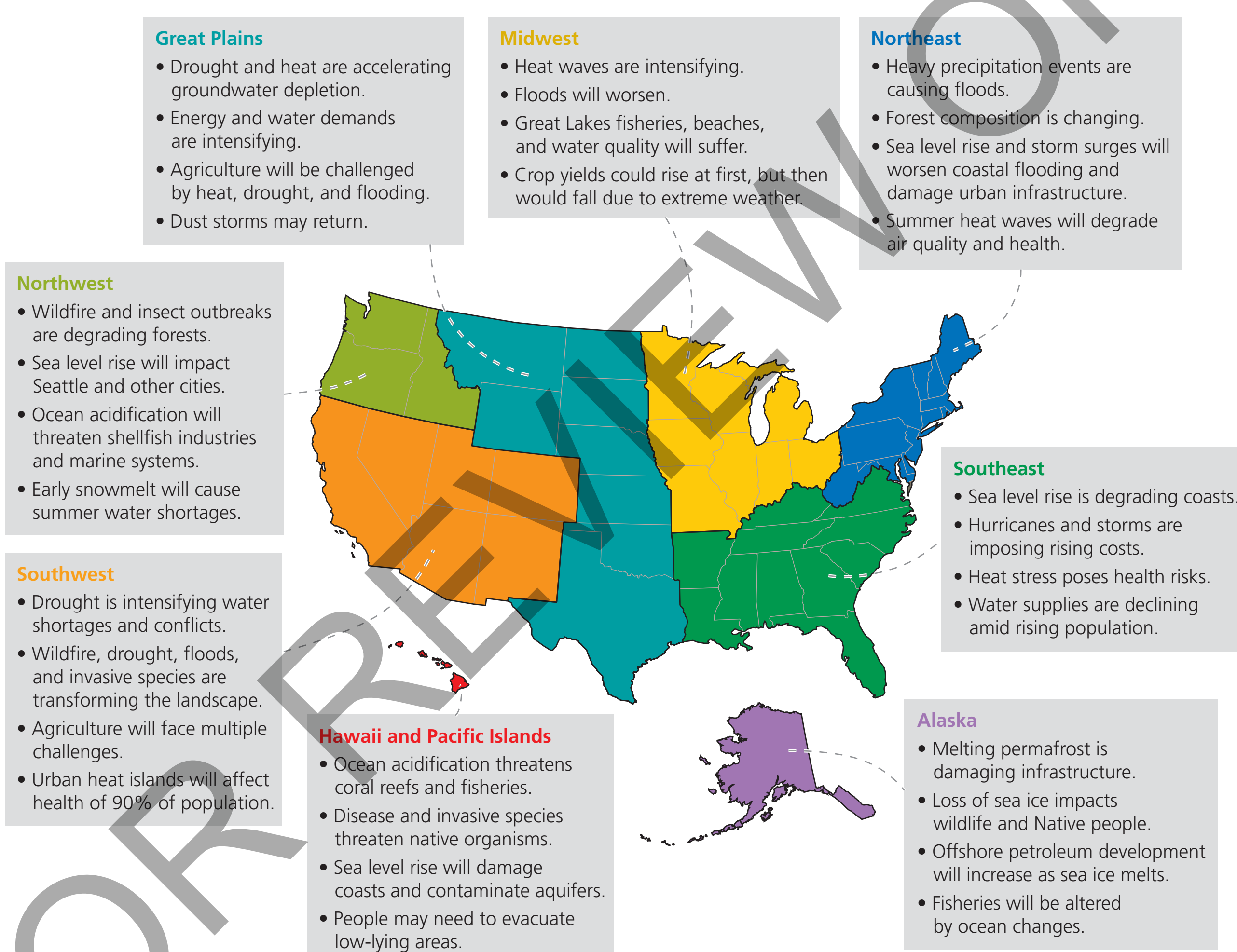


FIGURE 14.23 Impacts of climate change will vary by region. Shown are a few of the most important impacts scientists expect for each region by the end of the century. *Data from Melillo, J. M., et al., eds., 2014.* Climate change impacts in the United States: The third national climate assessment. *U.S. Global Change Research Program.*

FAQ **What's with the "global warming pause"? Has global warming stopped?**

In recent years, the rate at which global temperatures are rising has slowed considerably. Mean temperatures from 1998 to 2012 rose less than one-sixth as much as in the preceding 14-year period, and at only one-third to one-half the rate they rose from 1951 to 2012. This so-called "pause" or "hiatus" in global warming has led many opponents of emissions reduction to declare that we no longer need to worry about climate change.

Everyone would like to believe that climate change is no longer occurring. However, scientists studying the situation are concluding that the pause is a temporary result of natural short-term variation, brought about by several coinciding factors: (1) a phase of the Interdecadal Pacific Oscillation (p. 308) in which the ocean absorbs more heat from the atmosphere than usual, (2) several volcanic eruptions that spread cooling aerosols through the atmosphere, and (3) decreasing irradiance from the sun during a downswing in the solar cycle. On top of this, various ozone-depleting substances that have been restricted by the Montreal Protocol (p. 294) happen to be greenhouse gases, and their reduction since 1987 has helped to slow climate change. Scientists predict that as natural cycles shift back into phases that intensify warming instead of dampening it, we can expect temperatures to swing upward more rapidly in coming years.

Are we responsible for climate change?

Scientists agree that today's global warming is due to the well-documented recent increase in greenhouse gases in our atmosphere, and that this results primarily from burning fossil fuels for energy and secondarily from the loss of carbon-absorbing vegetation due to deforestation.

Yet despite the overwhelming evidence for climate change and its impacts, many people, especially in the United States, have long tried to deny that it is happening. Most of these "climate skeptics" or "climate change deniers" now admit that the climate is changing but still express doubt that we are the cause. Public debate over climate change has been fanned by corporate interests, spokespeople from think tanks, and a handful of scientists funded by fossil fuel industries, all of whom have aimed to cast doubt on the scientific consensus. Their views have been amplified by the U.S. news media, which seeks to present two sides to every issue, even when evidence does not equally support the arguments of each side.

However, as the evidence has mounted and as the economic and societal costs of climate change have grown more apparent, more and more policymakers, corporate executives, military leaders, national security experts, heads of business and industry, and everyday citizens have concluded that climate change is escalating and is causing impacts to which we must begin to respond.

Responding to Climate Change

From this point onward, our global society will be focusing on how best to respond to the challenges of climate change. The good news is that everyone—not just leaders in government and business, but everyday people, and especially today's youth—can play a part in this all-important search for solutions.

Shall we pursue mitigation or adaptation?

We can respond to climate change in two fundamental ways. One is to pursue actions that reduce greenhouse gas emissions, so as to lessen the severity of climate change. This strategy is called **mitigation** because the aim is to mitigate the problem; that is, to alleviate it or reduce its severity. Examples of mitigation include improving energy efficiency, switching to clean renewable energy sources, preserving forests, recovering landfill gas, and promoting farm practices that protect soil quality. The sooner we begin reducing emissions, the lower the level at which they will peak, and the less we will alter climate (**FIGURE 14.24**).

We can also pursue strategies to cushion ourselves from the impacts of climate change. This strategy is called **adaptation** because the goal is to adapt to change. Erecting a seawall like the Maldives' Great Wall of Malé is an example of adaptation. Other examples include restricting coastal development; adjusting farming practices to cope with drought; and modifying water management practices to deal with reduced river flows, glacial outburst floods, or salt contamination of groundwater.

We need to pursue adaptation because even if we were to halt all our emissions right now, the greenhouse gas pollution already in the atmosphere would continue driving global warming, with temperature rising an estimated 0.6°C (1.0°F)

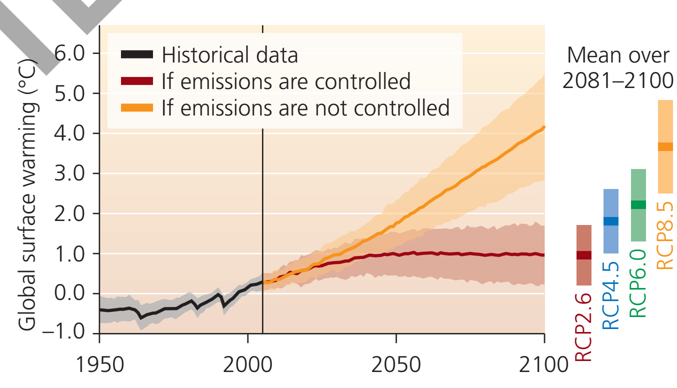


FIGURE 14.24 **The sooner we stabilize our emissions, the less climate change we will cause.** The red line shows temperature change we can expect if we strongly limit our carbon emissions. The orange line shows the change expected if we fail to control emissions effectively. Vertical bars show means and ranges of year-2100 temperatures for these two scenarios and two other intermediate ones studied by the IPCC. Predictions are based on a large number of climate models. *Data from IPCC, 2013.* Fifth assessment report. The physical science basis: Contribution of Working Group I.

more by the end of the century. Because we will face this change no matter what we do, it is wise to develop ways to minimize its impacts.

Yet we also need to pursue mitigation, because if we do nothing to diminish climate change, it will eventually overwhelm any efforts we might make to adapt. We will spend the remainder of our chapter examining approaches for the mitigation of climate change.

We are developing solutions in electricity generation and transportation

The generation of electricity produces nearly 40% of U.S. carbon dioxide emissions, and transportation accounts for 35%.

Electricity generation From cooking to heating to lighting, much of what we do each day depends on electricity. Fossil fuel combustion generates two-thirds of U.S. electricity, and coal accounts for most of the resulting emissions. We can reduce electricity use by encouraging conservation and efficiency (pp. 354–356). Power producers can capture excess heat from electricity generation and put it to use (cogeneration; p. 355). Firms can manufacture and consumers can adopt energy-efficient appliances, lighting, windows, ducts, insulation, and heating and cooling systems. In addition, each of us can make lifestyle choices to lower electricity consumption.

We can also reduce greenhouse gas emissions by switching to cleaner energy sources. Natural gas generates the same amount of energy as coal, with half the emissions. Cleaner still are alternatives to fossil fuels, including nuclear power (Chapter 15), as well as bioenergy, hydropower, geothermal power, solar power, and wind power (Chapter 16).

While our society transitions to clean energy alternatives, we are also trying to capture emissions before they leak to the atmosphere. **Carbon capture** refers to technologies or approaches that remove carbon dioxide from emissions. The next step is **carbon storage** (also called **carbon sequestration**), in which the carbon is sequestered, or stored, under pressure in deep salt mines, depleted oil and gas deposits, or other underground reservoirs (see Figure 15.18, p. 351). However, we remain a long way from developing adequate technology and secure storage space to accomplish this without leakage—and it is questionable whether we will ever be able to store enough carbon to make a sizeable dent in our emissions.

Transportation The typical automobile is highly inefficient; only 14% of the energy from fuel we pump into our gas tanks actually moves our cars down the road (**FIGURE 14.25**). More aerodynamic designs, increased engine efficiency, and improved tire design can help make our vehicles more fuel-efficient (p. 355). Indeed, many nations use vehicles that are more fuel-efficient than those of the United States, and recent government mandates are now improving fuel efficiency in American vehicles (p. 356). New technology is also bringing us alternatives to the traditional combustion-engine automobile. These include electric vehicles, gasoline-electric hybrid vehicles (p. 355), hydrogen fuel cells (p. 385), and alternative fuels such as compressed natural gas and biodiesel (p. 383).

We also can make lifestyle choices that reduce our reliance on cars. Some people are choosing to live nearer to their workplaces. Others use mass transit such as buses, subway trains, and light rail. Still others bike or walk to work. Making automobile-based cities and suburbs more friendly to pedestrian and bicycle traffic and improving people's access to mass transit stand as central challenges for city and regional planners (pp. 412–415).

We will need multiple strategies

Advances in agriculture, forestry, and waste management can help us mitigate climate change. In agriculture, sustainable management of cropland and rangeland enables soil to store more carbon. New techniques reduce methane emission from rice cultivation and from cattle and manure. In forest management, preserving forests, reforesting cleared areas, and pursuing sustainable forestry practices (p. 197) all help to absorb carbon from the air. Waste managers are cutting emissions by generating energy from waste in incinerators (p. 394); capturing methane seeping from landfills (p. 394); and encouraging recycling, composting, and reuse of materials and products (pp. 395–397).

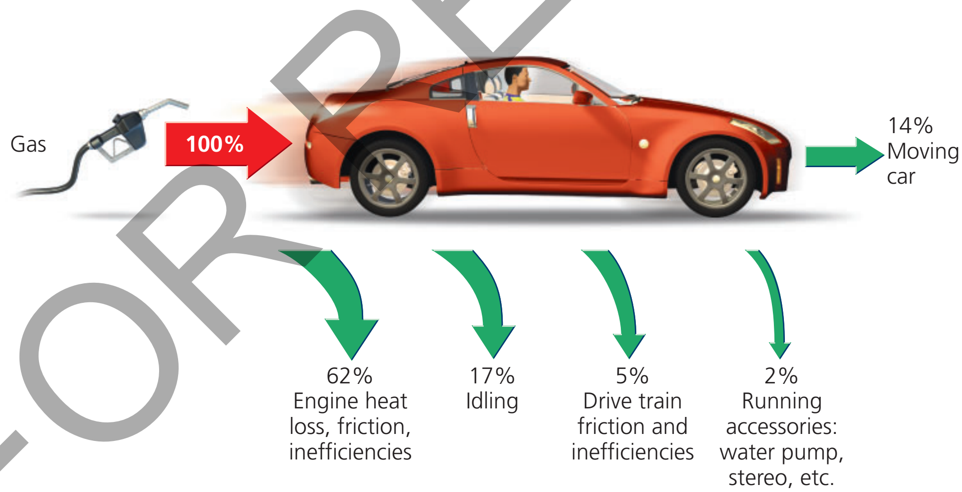


FIGURE 14.25 Conventional automobiles are fuel-inefficient. Only about 13–14% of the energy from a tank of gas actually moves the typical car down the road. Nearly 85% of useful energy is lost, primarily as heat. *Data from U.S. Department of Energy.*

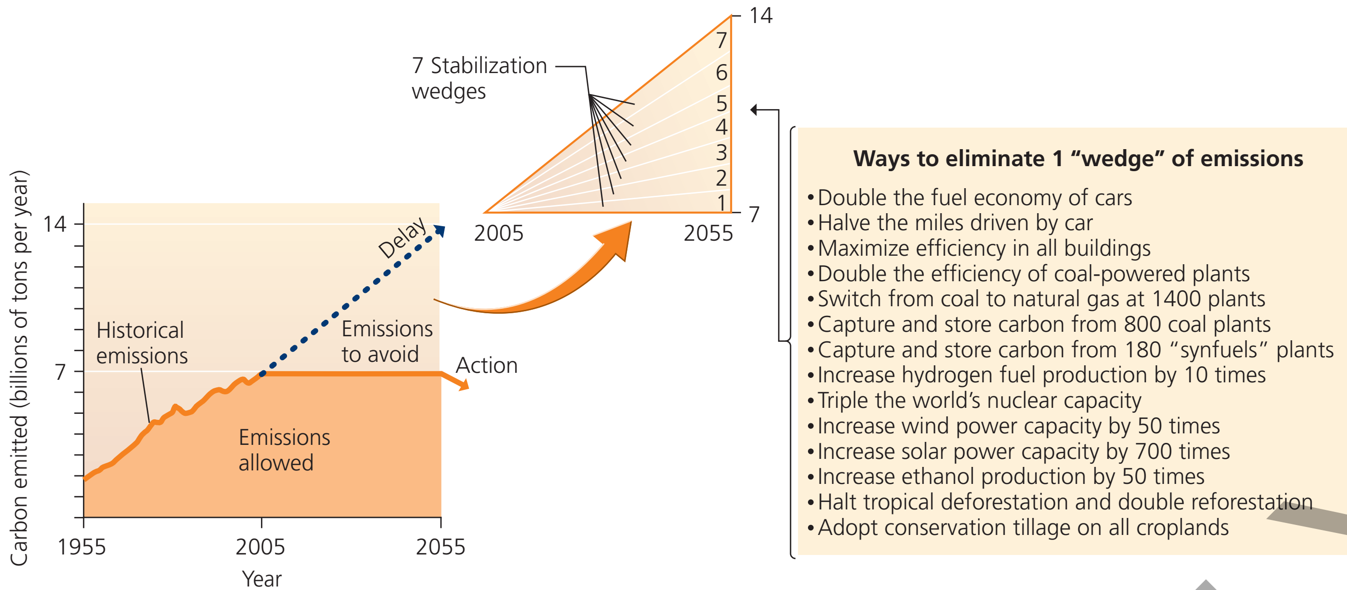


FIGURE 14.26 We can stabilize emissions by breaking this large job into smaller steps. Stephen Pacala and Robert Socolow began with a standard graph showing the doubling of CO_2 emissions that scientists expect to occur from 2005 to 2055. They added a flat line to represent the trend if emissions were held constant and then separated the graph into emissions allowed (below the line) and emissions to be avoided (the triangular area above the line). They then divided this "stabilization triangle" into seven equal-sized wedges. Each "stabilization wedge" represents 1 billion tons of CO_2 emissions in 2055 to be avoided. Finally, they identified a series of strategies, each of which could take care of one wedge. If we accomplish just 7 of these strategies, we could halt our growth in emissions for the next half-century. *Adapted from Pacala, S., and R. Socolow, 2004. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies.* Science *305: 968–972. Reprinted by permission of AAAS and the author.*

We should not expect to find a single "magic bullet" for mitigating climate change. Reducing emissions will require steps by many people and institutions across many sectors of our economy. However, most reductions can be achieved using current technology, and we can begin implementing changes right away. For society to reduce emissions, environmental scientists Stephen Pacala and Robert Socolow advise that we follow some age-old wisdom: When the job is big, break it into smaller parts. Pacala and Socolow have identified 15 strategies (**FIGURE 14.26**) that could each eliminate 1 billion tons of carbon per year by 2050 if deployed at a large scale. Achieving just 7 of these 15 aims would stabilize our emissions. If we achieve more, then we reduce emissions.

What role should government play?

Even if people agree on strategies and technologies to reduce emissions, they may disagree on what role government should play to encourage those strategies and technologies: Should it mandate change through laws and regulations? Should it impose no policies at all and hope that private enterprise will develop solutions on its own? Should it take the middle ground and design policies that give private entities financial incentives to reduce emissions? This debate has been vigorous in the United States and Canada, where many business leaders and politicians have opposed all government action to address climate change, fearing that emissions reductions will impose economic costs on industry and consumers.

In 2007, the U.S. Supreme Court ruled that carbon dioxide was a pollutant that the Environmental Protection Agency (EPA) could regulate under the Clean Air Act (p. 284). When Barack Obama became president, he instead urged that Congress craft laws to address emissions. In 2009, the House of Representatives passed legislation to create a **cap-and-trade** system (p. 111) in which industries and utilities would compete to reduce emissions for financial gain, and under which emissions were mandated to decrease 17% by 2020. However, legislation did not pass in the Senate. As a result, responsibility for addressing emissions passed to the EPA, which is now phasing in emissions regulations on industry and utilities, hoping to spur energy efficiency retrofits and renewable energy use at a pace that minimizes political opposition (p. 293).

In 2013 President Obama announced that because of legislative gridlock, he would take steps to address climate change using his executive authority. His "climate action plan" urged the EPA to speed its regulation of new power plants and to begin regulating existing power plants. It also aimed to jumpstart renewable energy development, modernize the electric grid, finance clean coal and carbon storage efforts, improve automotive fuel economy, protect and restore forests, and encourage energy efficiency.

The Kyoto Protocol sought to limit emissions

Climate change is a global problem, so the world's policymakers have tried to tackle it with international treaties. In 1992, most nations signed the **U.N. Framework Convention on Climate Change**, which outlined a plan to reduce greenhouse gas emissions to 1990 levels by the year 2000 through a voluntary approach. Emissions kept rising, however, so nations forged a binding treaty to *require* emissions reductions. Drafted in 1997 in Kyoto, Japan, the **Kyoto Protocol** mandated signatory nations, by the period 2008–2012, to reduce emissions of six greenhouse gases to levels below those of 1990. The treaty took effect in 2005 after Russia became the 127th nation to ratify it.

The United States was the only developed nation not to ratify the Kyoto Protocol. U.S. leaders objected to how it required industrialized nations to reduce emissions but did not require the same of rapidly industrializing nations such as China and India. Proponents of the Kyoto Protocol countered that the differential requirements were justified because industrialized nations created the current problem and therefore should take the lead in resolving it.

As of 2011 (the most recent year with full international data), nations that signed the Kyoto Protocol had decreased their emissions by 9.3% from 1990 levels (**FIGURE 14.27**). However, much of this reduction was due to economic contraction in Russia and former Soviet-Bloc nations following the breakup of the Soviet Union. When these nations are factored out, the remaining signatories showed a 3.2% *increase* in emissions. Nations not parties to the accord, including China, India, and the United States, increased their emissions still more.

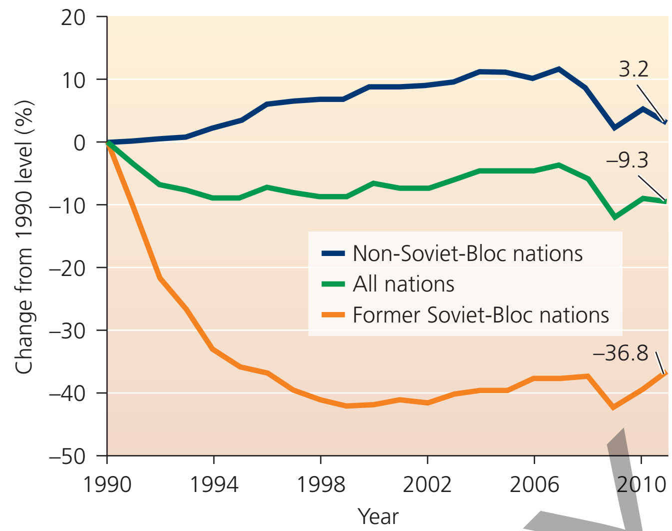
International climate negotiations seek a way forward

In recent years, representatives of the world's nations have met at a series of conferences, trying to design a treaty to succeed the Kyoto Protocol. Delegates from European nations and small island nations have generally taken the lead, while China, India, and the United States have been reluctant to make commitments.

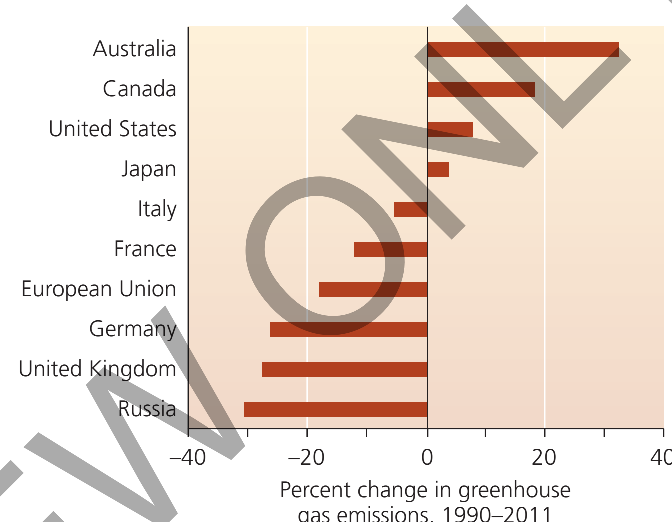
A contentious 2009 conference in Copenhagen, Denmark, ended without specific targets or solid commitments. The process got back on track in Cancún, Mexico, in 2010, where developed nations promised to pay developing nations to assist mitigation and adaptation efforts. Nations also broadly agreed on a plan, nicknamed *REDD* (p. 192), to help tropical nations reduce forest loss. Developed nations agreed to transfer clean energy technology to developing nations, and China and India agreed in principle to emission targets and international monitoring. However, most of these plans and promises have not yet come to pass.

In Durban, South Africa, in 2011, negotiators failed to design a new treaty. Instead, nations agreed to a "road map" toward a legally binding international deal in 2015, which would come into force only after 2020. This plan was reaffirmed at the 2012 conference in Doha, Qatar, and the 2013 conference in Warsaw, Poland. In Doha, negotiators also extended the Kyoto Protocol until 2020. However, a number of nations backed out of this Kyoto extension, and the treaty now applies to only about 15% of the world's emissions.

Most scientists reacted with disappointment and alarm at having to wait until 2020 for a meaningful agreement, warning that this is creating a "lost decade" during which climate change is intensifying.



(a) Emissions through time since the Kyoto Protocol



(b) Changes in emissions since the Kyoto Protocol

FIGURE 14.27 The Kyoto Protocol produced mixed results. Nations ratifying it decreased their emissions of six greenhouse gases by 9.3% by 2011 **(a)**, but this was largely because of unrelated economic contraction in the former Soviet-Bloc countries. A selection of major nations **(b)** shows varied outcomes in reducing emissions. The United States did not ratify the Protocol, Australia joined it late, and Canada left early. Values do not include influences of land use and forest cover. *Data from U.N. Framework Convention on Climate Change, 2014.*

DATA **Q** In part (b), compare the nations whose emissions have increased with those whose emissions have decreased. What difference(s) do you note between these two groups that might explain why their emissions differ?

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Will emissions cuts hurt the economy?

Many U.S. policymakers oppose mandates to reduce emissions out of fear that they will hamper economic growth. China and India have resisted emissions cuts under the same assumption. This is understandable, given that our current economies depend so heavily on fossil fuels. Yet nations such as Germany, England, and France have reduced their emissions since 1990 while enhancing their economies and providing their citizens high standards of living. Wealthy nations from Denmark to New Zealand to Hong Kong to Switzerland to Sweden emit fewer than half the greenhouse gases per person as the United States does.

Indeed, the United States reduced its carbon dioxide emissions 11% from 2007 to 2013. This occurred as a result of efficiency measures, a shift from coal to natural gas, and a recession that caused fossil fuel use to decline temporarily. Despite the recession, the U.S. economy grew during this period overall, demonstrating that cutting emissions need not hinder economic growth.

In fact, the United States and other wealthy industrialized nations are the nations most likely to *gain* economically from major energy transitions, because they are best positioned to invent, develop, fund, and market new technologies to power the world in a post-fossil-fuel era. Germany, Japan, and China have realized this and are now leading the world in production, deployment, and sales of solar energy technology (**FIGURE 14.28**). If the United States does not act more assertively to develop energy technologies for the future, then the future could belong to nations like China, Germany, and Japan.

FIGURE 14.28 China is racing to become the world's leader in renewable energy technology. Here, workers at a Chinese factory produce photovoltaic solar panels.

States and cities are advancing climate change policy

In the absence of legislative action at the federal level to address climate change, state and local governments across the United States are advancing policies to limit emissions. Mayors from over 1000 cities have signed the U.S. Mayors Climate Protection Agreement, committing their cities to pursue policies to "meet or beat" Kyoto Protocol guidelines. Former New York City Mayor Michael Bloomberg launched a panel on climate change in 2008, and this helped prepare the city to tackle challenges soon posed by Superstorm Sandy.

A number of U.S. states have enacted targets or mandates for renewable energy production, seeking to boost alternatives to fossil fuels. The boldest state-level action so far has come in California. In 2006 that state's legislature worked with Governor Arnold Schwarzenegger to pass the Global Warming Solutions Act, which seeks to cut California's greenhouse gas emissions 25% by the year 2020. This law established a cap-and-trade program for carbon emissions and followed earlier efforts in California to mandate higher fuel efficiency for automobiles.

Action is also being taken by nine northeastern states in the Regional Greenhouse Gas Initiative. In this effort, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont run a cap-and-trade program for power plant emissions. From 2005 to 2012, these states cut their CO_2 emissions from power plants by 40%, even as their economies grew. It is estimated that investment of the auction proceeds will save more than $2 billion in energy costs and eliminate 8 million tons of CO_2 emissions.

Market mechanisms can be used to address climate change

Emissions trading programs (p. 111) seek to harness the economic efficiency of market capitalism to control pollution by allowing business, industry, or utilities flexibility in how they do so. Supporters of emissions trading argue that this approach provides the fairest, least expensive, and most effective method of reducing emissions. Polluters choose how to cut their emissions and are given financial incentives for reducing emissions below the legally required amount (**FIGURE 14.29**). Cap-and-trade programs are intended to be self-sustaining. The price of permits fluctuates freely in the market, creating the same kinds of financial incentives as any other commodity that is bought and sold. As an example of how a cap-and-trade program works, consider the Regional Greenhouse Gas Initiative:

1. Each state decided what polluting sources it would require to participate.
2. Each state set a cap on the total CO_2 emissions it would allow, equal to its 2009 level.
3. Each state distributed to each polluter one permit for each ton it emits, up to the amount of the cap.
4. Each state is lowering its cap progressively—10% by 2018.
5. Sources with too few permits to cover their pollution must reduce emissions, buy permits from other sources, or pay for carbon offsets (p. 328). Sources with excess permits may sell them.
6. Any source emitting more than its permitted amount faces penalties.

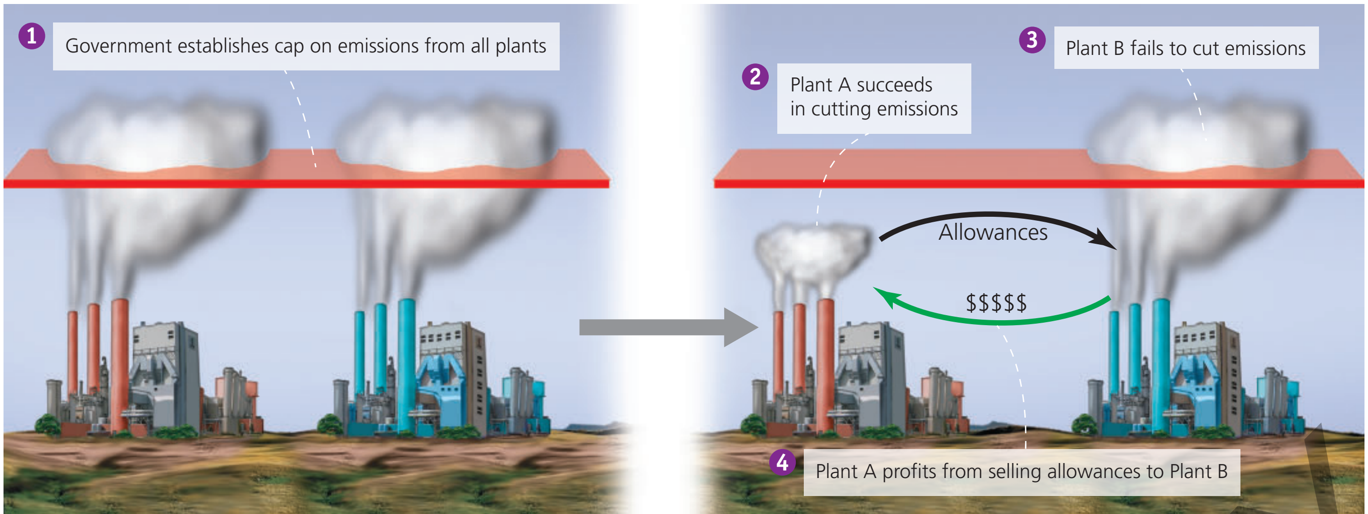

FIGURE 14.29 A cap-and-trade emissions trading system harnesses the efficiency of market capitalism to achieve the goal of reducing emissions. In such a system, 1 government first sets an overall cap on emissions. As polluting facilities respond, some will have better success reducing emissions than others. In this figure, 2 Plant A succeeds in cutting its emissions well below the cap, whereas 3 Plant B fails to cut its emissions at all. As a result, 4 Plant B pays money to Plant A to purchase allowances that Plant A is no longer using. Plant A profits from this sale, and the government cap is met, reducing pollution overall. Over time, the cap can be progressively lowered to achieve further emissions cuts.

The world's largest cap-and-trade program is the European Union Emission Trading Scheme. This market began in 2005, but investors soon realized that national governments had allocated too many permits to their industries. The overallocation gave companies little incentive to reduce emissions, so permits lost their value, and prices in the market took a nosedive. Europeans partly addressed these problems by making emitters pay for permits and setting emissions caps across the entire European Union while expanding the program. In the long run, permits will retain value and an emissions trading market will work only if government policies are in place to limit emissions.

Carbon taxes are another option

As the world's carbon trading markets show mixed results early in their growth, some economists, scientists, and policymakers are saying that cap-and-trade systems are not effective enough, don't work quickly enough, or leave too much to chance. Many of these critics would prefer that governments enact a **carbon tax** instead. In this approach, governments charge polluters a fee for each unit of greenhouse gases they emit. This gives polluters a financial incentive to reduce emissions. Carbon taxes have been introduced in over 20 nations. In the United States, Boulder, Colorado, taxes electricity consumption and Montgomery County, Maryland, taxes power plants.

The downside of a carbon tax is that polluters pass the cost along to consumers by charging higher prices for the products or services they sell. Proponents of carbon taxes have responded by proposing an approach called **fee-and-dividend**. In this approach, funds from the carbon tax, or "fee," are transferred as a tax refund, or "dividend," given to taxpayers. This way, if polluters pass their costs along to consumers, those consumers will be reimbursed. In theory, the system should provide polluters a financial incentive to reduce emissions while imposing no financial burden on taxpayers and no drag on the economy. The fee-and-dividend approach is a type of **revenue-neutral carbon tax**, because there is no net transfer of revenue from taxpayers to the government. For this reason, the approach is gaining broad political appeal.

The Canadian province of British Columbia introduced a revenue-neutral carbon tax in 2008. In the five years that followed, the province reduced its emissions by 10% as fuel consumption declined 17% and the province's economy grew. The tax began at \$10 per ton of CO_2-equivalent, was gradually raised to \$30, and has been gathering over a billion dollars a year. The tax revenues replace revenues from personal income taxes and corporate taxes, which are lowered by the same amount. Thus, rather than receiving a dividend check, citizens see a decline in their income taxes. The end result so far has been that emissions are lower, the economy remains just as strong, and taxpayers are happy to have lower income taxes.

WEIGHING THE ISSUES

Cap-and-Trade or a Carbon Tax?

What advantages and disadvantages do you see in using a cap-and-trade system to reduce greenhouse gas emissions? What pros and cons do you see in using carbon taxes to achieve this goal? What do you think of the idea of a revenue-neutral carbon tax? If you were a U.S. senator, what type of policy would you support in order to address emissions in the United States, and why?

Offsets help achieve carbon-neutrality

Emissions trading programs generally allow participants to buy **carbon offsets**, voluntary payments intended to enable another entity to help reduce the emissions that one is unable to reduce. The payment thus offsets one's own emissions. For example, a coal-burning power plant could pay a reforestation project to plant trees that will soak up as much carbon dioxide as the coal plant emits. Or a university could fund clean renewable energy projects to make up for fossil fuel energy the university uses.

Carbon offsets are popular among utilities, businesses, universities, governments, and individuals trying to achieve **carbon-neutrality**, a condition in which no net carbon is emitted. In principle, carbon offsets are a powerful idea, but rigorous oversight is needed to make sure that offset funds achieve what they are intended for—and that offsets fund only emissions cuts that would not occur otherwise.

Businesses and corporations seeking to make their practices more sustainable also can find ways to reduce their carbon footprints directly. An excellent example is Pearson Education, the publisher of your textbook! In 2009 Pearson achieved carbon-neutrality after a concerted two-year effort. Pearson reduced its energy consumption and carbon footprint directly by 12% by upgrading buildings for energy efficiency, designing more efficient computer servers, reducing the number of vehicles in its fleets, increasing the proportion of hybrid vehicles, and cutting back on employee business travel while enhancing the use of video conferencing. Pearson eliminated a further 47% of its emissions by purchasing clean renewable energy instead of fossil fuel energy and by installing large solar panel arrays at two of its sites in New Jersey and a wind turbine at a Minnesota site. To offset the remaining 41% of its emissions, the company is funding a number of programs to preserve forest and replant trees in various areas of the world, from England to Costa Rica.

Should we engineer the climate?

What if all our efforts to reduce emissions are not adequate to rein in climate change? As climate change becomes more severe, some scientists and engineers are reluctantly considering drastic steps to alter Earth's climate in a last-ditch attempt to reverse global warming—an approach called **geoengineering** (**FIGURE 14.30**).

One geoengineering approach would be to suck carbon dioxide out of the air. We might enhance photosynthesis in natural systems by planting trees or by fertilizing ocean phytoplankton with nutrients such as iron. A more high-tech method would be to design "artificial trees," structures that chemically filter CO_2 from the air. A different approach would be to block sunlight before it reaches Earth, thereby cooling the planet. We might deflect sunlight by injecting sulfates or other fine dust particles into the stratosphere, by seeding clouds with seawater, or by deploying fleets of reflecting mirrors on land, at sea, or in orbit in space.

Scientists were long reluctant even to discuss the notion of geoengineering. The potential methods are technically daunting, would take years or decades to develop, and might

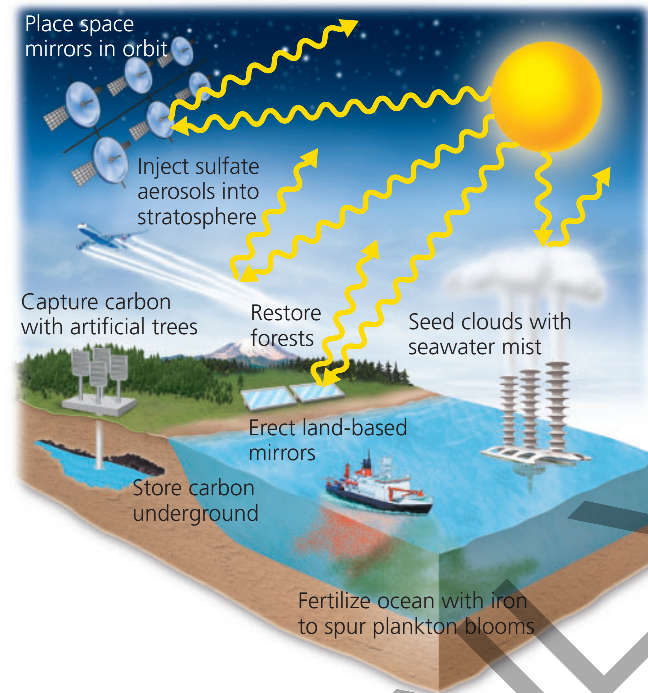

FIGURE 14.30 Geoengineering proposals seek to use technology to remove carbon dioxide from the air or reflect sunlight away from Earth. However, most geoengineering ideas would take years to develop, may not work well, or might cause undesirable side effects. Thus, they are not a substitute for reducing emissions.

pose unforeseen risks. Blocking sunlight does not reduce greenhouse gases, so ocean acidification would continue. And any method would work only as long as society has money and ability to maintain it. Moreover, many experts are wary of promulgating hope for easy technological fixes, lest politicians lose incentive to try to reduce emissions. However, as climate change intensifies, scientists are beginning to assess the risks and benefits of geoengineering, so that we can be ready to take action if climate change becomes severe enough to justify it.

You can address climate change

Government policies, corporate actions, international treaties, technological innovations—and perhaps even geoengineering—will all play roles in addressing climate change. But in the end the most influential factor may be the collective decisions of millions of regular people. Just as we each have an ecological footprint (p. 4), we each have a **carbon footprint** that expresses the amount of carbon we are responsible for emitting. To reduce emissions, each of us can take steps in our everyday lives—from choosing energy-efficient appliances, to eating less meat, to deciding where to live and how to get to work.

College students are vital to driving the personal and societal changes needed to reduce carbon footprints and address climate change. Today a groundswell of interest is sweeping across campuses, and many students are pressing their administrations to seek carbon-neutrality or to divest from fossil fuel investments and promote renewable energy (pp. 18, 422). College students have played a role in many grassroots events and organizations, including 350.org's International Day of Climate Action on October 24, 2009. This event—kicked off by the Maldives' underwater cabinet meeting—featured 5200 events in 181 nations and was deemed "the most widespread day of political action in the planet's history."

Global climate change may be the biggest challenge we face, but halting it would be our biggest victory. With concerted action, there is still time to avert the most severe impacts. Through outreach, education, innovation, and lifestyle choices, we have the power to turn the tables on climate change and help bring about a bright future for humanity and our planet.

Conclusion

Many factors influence Earth's climate, and human activities have come to play a major role. Climate change is well underway, and further greenhouse gas emissions will intensify global warming and cause increasingly severe and diverse impacts. Sea level rise and other consequences of global climate change will affect locations worldwide from the Maldives to Bangladesh to Alaska to New York to Florida. As scientists and policymakers come to better understand anthropogenic climate change and its environmental, economic, and social consequences, more and more of them are urging immediate action. Reducing greenhouse gas emissions and taking other steps to mitigate and adapt to climate change represent the foremost challenges for our society in the coming years.

Testing Your Comprehension

1. What is the fate of solar radiation after it reaches Earth? How do greenhouse gases warm the lower atmosphere?
2. Why is carbon dioxide considered the main greenhouse gas? Why are carbon dioxide concentrations increasing in the atmosphere?
3. What evidence do scientists use to study the ancient atmosphere? Describe what a proxy indicator is, and give two examples.
4. Has simulating climate change with computer programs been effective in helping us predict climate? Briefly describe how these programs work.
5. List three major trends in climate that scientists have documented so far. Now list three future trends that they predict, along with their potential consequences.
6. Describe how rising sea levels, caused by global warming, can create problems for people. How is climate change affecting marine ecosystems?
7. How might a warmer climate affect agriculture? How is it affecting distributions of plants and animals? How might it affect human health?
8. What are the largest two sources of greenhouse gas emissions in the United States? How can we reduce these emissions?
9. What roles have international treaties played in addressing climate change? Give two specific examples.
10. List two economic market-based approaches for reducing greenhouse gas emissions. Discuss advantages and disadvantages of each approach.

Seeking Solutions

1. Some people argue that we need "more proof" or "better science" before we commit to changes in our energy economy. How much certainty do you think we need before we take action regarding climate change? How much certainty do you need in your own life before you make a major decision? Should nations and elected officials follow a different standard? Do you feel that the precautionary principle (pp. 155, 220) is an appropriate standard in the case of global climate change? Why or why not?
2. Suppose that you have decided to make your own lifestyle carbon-neutral. You plan to begin by making a 25% reduction in the emissions for which you are responsible. What are the first three actions you would take to achieve your goal?
3. How might your campus reduce its greenhouse gas emissions? Develop three concrete proposals for ways to reduce emissions on your campus that you feel would be effective and feasible. How would you present these proposals to campus administrators to gain their support?
4. **THINK IT THROUGH** You have been appointed as the U.S. representative to an international conference to negotiate terms of an emissions reduction treaty to replace the Kyoto Protocol in 2020. The U.S. government has instructed you to take a leading role in designing the new treaty and to engage constructively with other nations' representatives while protecting America's economic and political interests. What type of agreement will you try to shape? Describe at least three components that you would propose or agree to, and at least one that you would oppose.

5. **THINK IT THROUGH** You have just been elected governor of a medium-sized U.S. state. Citizens want you to take bold action to reduce greenhouse gas emissions—but they do not want prices of gasoline or electricity to rise. Industries in your state are wary of emissions reductions being required of them but are willing to explore ideas with you. The state legislature will support your efforts as long as you remain popular with voters. The state to your west has just passed ambitious legislation mandating steep emissions cuts. The state to your east has joined a regional emissions trading consortium. The state to your north has just established a revenue-neutral carbon tax. What actions will you take in your first year as governor, and why? What effects would you expect each action to have?

Calculating Ecological Footprints

Global climate change is something to which we all contribute, because fossil fuel combustion plays such a large role in supporting the lifestyles we lead. Conversely, as individuals, each one of us can help to address climate change through personal decisions and actions in how we live our lives. Several online calculators enable you to calculate your own personal carbon footprint, the amount of carbon emissions for which you are responsible. Go to http://www.nature.org/greenliving/carboncalculator/, take the quiz, and enter the relevant data in the table.

	Carbon footprint (tons per person per year)
World average	
U.S. average	
Your footprint	
Your footprint with three changes (see question 3)	

1. How does your personal carbon footprint compare to that of the average U.S. resident? How does it compare to that of the average person in the world? Why do you think your footprint differs in the ways it does?
2. As you took the quiz and noted the impacts of various choices and activities, which one surprised you most?
3. Think of three changes you could make in your lifestyle that would lower your carbon footprint. Now take the footprint quiz again, incorporating these three changes. Enter your resulting footprint in the table. By how much did you reduce your yearly emissions?
4. What do you think would be an admirable yet realistic goal for you to set as a target value for your own footprint? Would you choose to purchase carbon offsets to help reduce your impact? Why or why not?

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