Upon completing this chapter, you will be able to:

- Describe Earth's climate system and explain the many factors influencing global climate
- Characterize human influences on the atmosphere and global climate
- Summarize modern methods of climate research
- Outline current and future trends and impacts of global climate change
- Suggest ways we may respond to climate change
A nation of low-lying islands in the Indian Ocean, the Maldives is known for its spectacular tropical setting, colorful coral reefs, and sun-drenched beaches. For visiting tourists it seems to be paradise, and for 370,000 Maldives residents it is home. But residents and tourists alike now fear that the Maldives could soon be submerged by the rising seas that are accompanying global climate change.

Nearly 80% of the Maldives’ land area lies less than 1 m (39 in.) above sea level. In a nation of 1,200 islands whose highest point is just 2.4 m (8 ft) above sea level, rising seas are a matter of life or death. The world’s oceans rose 10–20 cm (4–8 in.) during the 20th century as warming temperatures expanded ocean water and as melting polar ice discharged water into the ocean. According to current projections, sea level will rise another 18–59 cm (7–23 in.) by the year 2100.

Higher seas are expected to flood large areas of the Maldives and cause salt water to contaminate drinking water supplies. Storms intensified by warmer water temperatures will erode beaches, cause flooding, and damage the coral reefs that are so vital to the tourism and fishing industries that drive the nation’s economy. Because of such concerns, the Maldives government recently evacuated residents from several of the lowest-lying islands.

On December 26, 2004, the nation got a taste of what could be in store in the future, when a massive tsunami, or tidal wave, devastated coastal areas throughout the Indian Ocean. The tsunami killed 100 Maldives residents and left 20,000 homeless. Schools, boats, tourist resorts, hospitals,
and transportation and communication infrastructure were damaged or destroyed. The World Bank estimates that direct damage in the Maldives totaled $470 million, an astounding 62% of the nation’s gross domestic product (GDP). Soil erosion, saltwater contamination of aquifers, and other environmental damage will result in still greater long-term economic losses. The tsunami was caused not by climate change, but by an earthquake. Yet as sea levels rise, the damage that such natural events—or ordinary storm waves—can inflict increases considerably.

Maldivian islanders are not alone in their predicament. Other island nations, from the Galapagos to Fiji to the Seychelles, also fear a future of constant vigilance against encroaching seawater. Mainland coastal areas of the world, such as the hurricane-battered coasts of Florida, Louisiana, Texas, the Carolinas, and other states, will face similar challenges. In one way or another, global climate change will affect each and every one of us for the remainder of our lifetimes.

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, climate change may well be the major event of your lifetime and the phenomenon that most shapes your future.

As this chapter was being prepared, the world’s people—particularly those of the United States—were beginning to undergo a revolution in awareness and concern. The 2007 release of the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC; p. 516) made clear to the world the scientific consensus that climate is changing, that we are the cause, and that climate change is already exerting impacts that will become increasingly severe if we do not take action. In 2006–2007, millions of people watched former U.S. Vice President Al Gore’s Oscar-winning film on climate change, *An Inconvenient Truth*, or read his best-selling book of the same title. In April 2007, thousands of U.S. students and citizens staged the first nationwide rallies for action against climate change.

Climate change is the fastest-moving area of environmental science today. New scientific papers that refine our understanding of climate are published every week, and policymakers and businesspeople make headlines with decisions and announcements 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, moisture content, wind, precipitation, barometric pressure, solar radiation, and other characteristics. As we have learned (pp. 477–478), *climate* differs from *weather* in that weather specifies conditions at localized sites over hours or days, whereas climate describes conditions across broader regions over seasons, years, or millennia. *Global climate change* describes trends and variation in Earth’s climate, involving aspects such as temperature, precipitation, and storm frequency and intensity. 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. It is thus only one aspect of global climate change, although warming does in turn drive other components of climate change.

Our planet’s climate varies naturally through time, but the climatic changes taking place today are unfolding at an exceedingly rapid rate. Moreover, scientists agree that human activities, notably fossil fuel combustion and deforestation, are largely responsible. Understanding how and why climate is changing requires understanding how our planet’s climate functions. Thus, we first will survey the fundamentals of Earth’s climate system—a complex and finely tuned system that has nurtured life for billions of years.

The sun and atmosphere keep Earth warm

Three factors exert more influence on Earth’s climate than all others combined. The first is the sun. Without it, Earth would be dark and frozen. The second is the atmosphere. Without it, Earth would be as much as 33°C (91°F) colder on average, and temperature differences between night and day would be far greater than they are. The third is the oceans, which shape climate by storing and transporting 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 18.1).

Greenhouse gases warm the lower atmosphere

As Earth’s surface absorbs solar radiation, the surface increases in temperature and emits infrared radiation (pp. 101–102), radiation with longer wavelengths than visible light. Some atmospheric gases absorb this infrared radiation very effectively. These include water vapor, ozone (O₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄), as well as halocarbons, a diverse group that
includes chlorofluorocarbons (CFCs; * pp. 489–491). Such gases are known as greenhouse gases. After absorbing radiation emitted from the surface, greenhouse gases subsequently re-emit infrared energy of slightly different wavelengths. Some of this re-emitted energy is lost to space, but some travels back downward, warming the atmosphere (specifically the troposphere; * pp. 474–475) and the planet’s surface in a phenomenon known as the greenhouse effect.

The greenhouse effect is a natural phenomenon, and greenhouse gases (with the exception of the anthropogenic halocarbons) have been present in our atmosphere for billions of years. However, human activities have increased the concentrations of many greenhouse gases in the past 250–300 years, thereby enhancing 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 18.1 shows the global warming potentials for several greenhouse gases.

### TABLE 18.1 Global Warming Potentials of Four Greenhouse Gases

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Relative heat-trapping ability (in CO₂ equivalents)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>23</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>296</td>
</tr>
<tr>
<td>Hydrochlorofluorocarbon HFC-23</td>
<td>12,000</td>
</tr>
</tbody>
</table>

Data from Intergovernmental Panel on Climate Change. 2001. Third assessment report. Climate change 2001: The scientific basis.
are expressed in relation to carbon dioxide, which is assigned a global warming potential of 1. Thus, a molecule of methane is 23 times as potent as a molecule of carbon dioxide, and a molecule of nitrous oxide is 296 times as potent as a CO₂ molecule.

**Carbon dioxide is the greenhouse gas of primary concern**

Although carbon dioxide is not the most potent greenhouse gas on a per-molecule basis, it is far more abundant in the atmosphere than gases such as methane and nitrous oxide, so it contributes more to the greenhouse effect. Human activities have boosted Earth’s atmospheric concentration of carbon dioxide from around 280 parts per million (ppm) as recently as the late 1700s to 383 ppm in 2007 (Figure 18.2a). The atmospheric CO₂ concentration is now, by far, at its highest level in over 650,000 years, and likely the highest in the last 20 million years.

What has caused levels of this greenhouse gas to increase so rapidly? As you may recall from our discussion of the carbon cycle in Chapter 7 (p. 188–189), and as we will see further in Chapter 19 (p. 544), most carbon is stored for long periods in the upper layers of the lithosphere. The deposition, partial decay, and compression of organic matter (mostly plants) that grew in wetland or marine areas during the Carboniferous Period (290–354 million years ago; Appendix D) led to the formation of coal, oil, and natural gas in sediments from that time. In the absence of human activity, these carbon reservoirs would be practically permanent. However, over the past two centuries we have burned fossil fuels 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 flux of carbon from lithospheric reservoirs into the atmosphere is the main reason atmospheric carbon dioxide concentrations have increased so dramatically.

At the same time, people have cleared and burned forests to make room for crops, pastures, villages, and cities. Forests serve as sinks (p. 187) for recently active carbon, and their removal reduces the biosphere’s ability to absorb carbon dioxide from the atmosphere. In this way, deforestation has contributed to rising atmospheric CO₂ concentrations.

**Other greenhouse gases add to warming**

Carbon dioxide is not the only greenhouse gas increasing in the atmosphere because of our activities. 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. Since 1750, atmospheric methane concentrations have risen 2.5-fold (Figure 18.2b), and today’s concentration is the highest by far in over 650,000 years.

Human activities have also enhanced 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 18% since 1750 (Figure 18.2c). Ozone concentrations in the troposphere have risen roughly 36% since 1750 because of photochemical smog (pp. 486–488). The contribution of halocarbon gases to global warming has begun to slow because of the Montreal Protocol and subsequent controls (pp. 489–491).

Emissions of greenhouse gases from human activity in the United States consist mostly of carbon dioxide. Even after accounting for the greater global warming potential of molecules of other gases, carbon dioxide’s abundance in our emissions makes it the major contributor to global warming (Figure 18.3).

Water vapor is the most abundant greenhouse gas in our atmosphere and contributes most to the greenhouse effect. Its concentrations vary locally, but its global concentration has not changed over recent centuries, so it is
CHAPTER EIGHTEEN Global Climate Change

Global Climate Change

not viewed as having driven industrial-age climate change. However, as tropospheric temperatures continue to increase, Earth’s water bodies should transfer more water vapor into the atmosphere. Such a positive feedback mechanism (● p. 176) could amplify the greenhouse effect. Alternatively, more water vapor could give rise to increased cloudiness, which might, in a negative feedback loop (● pp. 175–176), slow global warming by reflecting more solar radiation back into space. Depending on whether low- or high-elevation clouds resulted, they might either shade and cool Earth (negative feedback) or else contribute to warming and accelerate evaporation and further cloud formation (positive feedback). Because of feedback loops (see Figure 7.1, ● p. 176), minor modifications of components of the atmosphere can potentially lead to major effects on climate.

Aerosols may exert a cooling effect

Whereas greenhouse gases exert a warming effect on the atmosphere, aerosols (● p. 480), microscopic droplets and particles, can have either a warming or cooling effect. Generally speaking, soot, or black carbon aerosols, can cause warming by absorbing solar energy, but most 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 precipitation (● pp. 491–495). These reactions, along with volcanic eruptions, can also contribute to the formation of a sulfur-rich aerosol haze in the upper atmosphere that reduces the amount of sunlight that reaches Earth’s surface. Aerosols released by major volcanic eruptions can exert short-term cooling effects on Earth’s climate over periods of up to several years (● p. 480).

Radiative forcing expresses change in energy input over time

Scientists have made quantitative estimates of the degree of influence that aerosols, greenhouse gases, and other factors exert over Earth’s energy balance (Figure 18.4). The amount of change in energy that a given factor causes is called its radiative forcing. Positive forcing warms the surface, whereas negative forcing cools it. Scientists’ best estimate is that Earth today compared with the pre-industrial Earth of 1750 is experiencing overall radiative forcing of about 1.6 watts/m². For context, look back at Figure 18.1 and note that Earth is estimated to receive and give off 342 watts/m² of energy. Although 1.6 may seem like a small proportion of 342, it is enough to alter climate significantly.


**Figure 18.4** For each emitted gas or other human impact on the atmosphere since the industrial revolution, we can estimate the warming or cooling effect this has had on Earth’s climate. We express this as radiative forcing, which in this graph is shown as the amount of influence on climate today relative to 1750, in watts per square meter. Red bars indicate positive forcing (warming), and blue bars indicate negative forcing (cooling). Albedo (● p. 521) refers to the reflectivity of a surface. A number of more minor influences are not shown. In total, scientists estimate that human impacts on the atmosphere exert a cumulative radiative forcing of 1.6 watts/m².
The atmosphere is not the only factor that influences climate

Our climate is influenced by factors other than atmospheric composition. Among these are cyclic changes in Earth's rotation and orbit, variation in energy released by the sun, absorption of carbon dioxide by the oceans, and oceanic circulation patterns.

**Milankovitch cycles** During the 1920s, Serbian mathematician Milutin Milankovitch described three types of periodic changes in Earth's rotation and orbit around the sun. These variations, now known as Milankovitch cycles, alter the way solar radiation is distributed over Earth's surface (Figure 18.5). By modifying patterns of atmospheric heating, these cycles trigger long-term climate variation, such as periodic episodes of glaciation.

**Solar output** The sun varies in the amount of radiation it emits, over both short and long time scales. For example, at each peak of its 11–year sunspot cycle the sun may emit solar flares, bursts of energy strong enough to disrupt satellite communications. 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 0.12 watts/m²—less than any of the anthropogenic causes shown in Figure 18.4.

**Ocean absorption** The oceans hold 50 times more carbon than the atmosphere holds, and they absorb carbon dioxide from the atmosphere, both through direct solubility of gas in water, and through uptake by marine phytoplankton for photosynthesis. However, the oceans absorb CO₂ more slowly than we are adding CO₂ to the atmosphere (see Figure 7.12, *p. 188). Thus, carbon absorption by the oceans is slowing global warming but not preventing it. Moreover, recent evidence indicates that this absorption is now decreasing. As ocean water warms, it absorbs less CO₂ because gases are less soluble in warmer water—a positive feedback effect that accelerates warming.

**Ocean circulation** Ocean water exchanges tremendous amounts of heat with the atmosphere, and ocean currents move energy from place to place. In equatorial regions, such as the area around the Maldives, the oceans receive more heat from the sun and atmosphere than they emit. Near the poles, the oceans emit more heat than they receive. Because cooler water is denser than warmer water, the cooling water at the poles tends to sink, and the warmer surface water from the equator moves to take its place. This is one principle underlying global ocean circulation patterns (*pp. 446–447).

One interaction between ocean and atmosphere that influences climate is the El Niño–Southern Oscillation (ENSO), a systematic shift in atmospheric pressure, sea surface temperature, and ocean circulation in the tropical Pacific Ocean. Under normal conditions, prevailing winds blow from east to west along the equator, from a region of high pressure in the eastern Pacific to one of low pressure in the western Pacific, forming a large-scale convective loop, or atmospheric circulation pattern (Figure 18.6a). The winds push surface waters westward, causing water to "pile up" in the western Pacific. As a result, water near Indonesia can be 50 cm (20 in.) higher and 8 °C warmer than water near South America. The westward-moving surface waters allow cold water to rise up from the deep in a nutrient-rich upwelling (*p. 447) along the coast of Peru and Ecuador.

**El Niño** conditions are triggered when air pressure increases in the western Pacific and decreases in the eastern Pacific, causing the equatorial winds to weaken. Without these winds, the warm water that collected in the
La Niña events are the opposite of El Niño events; under these conditions, cold surface waters extend far westward in the equatorial Pacific, and weather patterns are affected in opposite ways.

ENSO cycles are periodic but irregular, occurring every 2–8 years. Scientists are exploring whether globally warming air and sea temperatures may be increasing the frequency and strength of these cycles.

Ocean currents and climate also interact through the thermohaline circulation, a worldwide current system in which warmer, fresher water moves along the surface and colder, saltier water (which is more dense) moves deep beneath the surface (Figure 18.7). In the Atlantic Ocean, warm surface water flows northward from the equator in the Gulf Stream (p. 446–447), carrying heat to high latitudes and keeping Europe warmer than it would otherwise be. As the surface water of this conveyor belt system releases heat energy and cools, it becomes denser and sinks, creating the North Atlantic Deep Water (NADW).

Recently, scientists have hypothesized that interrupting the thermohaline circulation could trigger rapid climate change. If global warming causes much of Greenland’s ice sheet to melt, fresh water runoff into the North Atlantic would dilute surface waters, making them less dense (because fresh water is less dense than salt water). This could potentially stop the NADW formation and shut down the northward flow of warm equatorial water, causing Europe to cool rapidly. This scenario inspired the 2004 blockbuster film The Day After Tomorrow, although the filmmakers chose entertainment value over science and grossly exaggerated the potential impacts. Some data suggest that the thermohaline circulation in this region is already slowing, but other researchers argue that Greenland’s runoff will not be enough to cause a shutdown this century.
Studying Climate Change

To comprehend any phenomenon that is changing, we must study its past, present, and future. Climate scientists monitor present-day climatic conditions, but they also have devised clever means of inferring past change and have developed sophisticated methods to predict future change.

Proxy indicators tell us about the past

To understand how climate is changing today, and to predict future change, scientists must learn what climatic conditions were like thousands or millions of years ago. Environmental scientists have developed a number of methods to decipher clues from the past. **Proxy indicators** are types of indirect evidence that serve as proxies, or substitutes, for direct measurement and that shed light on past climate.

For instance, Earth’s ice caps, ice sheets, and glaciers hold clues to climate history. Over the ages, these huge expanses of snow and ice have accumulated to great depths, preserving within them tiny bubbles of the ancient atmosphere (Figure 18.8). Scientists can examine these trapped air bubbles by drilling into the ice and extracting long columns, or cores. From these ice cores, scientists can determine atmospheric composition, greenhouse gas concentrations, temperature trends, snowfall, solar activity, and even (from trapped soot particles) frequency of forest fires.

By extracting ice cores from Antarctica, scientists have now been able to go back in time 740,000 years, reading Earth’s history across eight glacial cycles (see “The Science behind the Story, pp. 514–515). During 2007–2009, such research is being funded and promoted as part of the International Polar Year, a large international scientific program coordinating research in the Arctic and Antarctic.

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, and as we saw with the study of Easter Island (pp. 8–9), analyzing these materials can illuminate the history of past vegetation. Because climate influences the types of plants that grow in an area, knowing what plants occurred in a location at a given time can tell us much about the climate at that place and time.

Tree rings provide another proxy indicator. The width of each ring of a tree trunk cut in cross-section reveals how much the tree grew in a particular growing season; a wide ring means more growth, generally indicating a wetter year. Long-lived trees such as bristlecone pines can provide records of precipitation and drought going back hundreds or thousands of years. Tree rings are also used to study fire history, since a charred ring indicates that a fire took place in that year. In arid regions such as the U.S. Southwest, packrat middens are a valuable source of climate data. Packrats are rodents that carry seeds and plant parts back to their middens, or dens, in caves and rock crevices sheltered from rain. In an arid-enough location, plant parts may preserve for centuries, allowing researchers to study the past flora of the region.

Researchers gather data on past ocean conditions from coral reefs (pp. 450–451). Living corals take in trace elements and isotope ratios (pp. 92–93) from ocean water as they grow, and incorporate these chemical clues to ocean conditions into growth bands in the structure of the reefs they build.

Proxy indicators often tell us information about local or regional areas, so to get a global perspective scientists need to combine multiple records from various areas. Because the number of available indicators decreases the further back in time we go, estimates of global climate conditions for the recent past tend to be more reliable than those for the distant past.
Direct atmospheric sampling tells us about the present

Studying present-day climate is more straightforward because scientists can measure atmospheric conditions directly. The late Charles Keeling of the Scripps Institution of Oceanography in La Jolla, California, documented trends in atmospheric carbon dioxide concentrations starting in 1958 (Figure 18.9). Keeling collected four air samples from five towers every hour from his monitoring station at the Mauna Loa Observatory in Hawaii. These data show that atmospheric CO₂ concentrations have increased from 315 ppm in 1958 to 383 ppm in 2007. Today Keeling’s colleagues are continuing these measurements, building upon the best long-term dataset we have of direct atmospheric sampling of any greenhouse gas.

Models help us understand climate

To understand how climate systems function and to predict future climate change, scientists simulate climate processes with sophisticated computer programs. Coupled general circulation models (often simply called climate models) are programs that combine what is known about atmospheric circulation, ocean circulation, atmosphere-ocean interactions, and feedback mechanisms to simulate climate processes (Figure 18.10). They couple, or combine, climate influences of the atmosphere and oceans in a single simulation. This requires manipulating vast

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**Figure 18.9** Atmospheric concentrations of carbon dioxide have risen steeply since 1958, when Charles Keeling began collecting these data at the Mauna Loa Observatory in Hawaii. The jaggedness of the upward trend reflects seasonal variation, which is due to the fact that the Northern Hemisphere has more land area and thus more vegetation than the Southern Hemisphere. Thus, more carbon dioxide is absorbed during the northern summer, when Northern Hemisphere plants are more photosynthetically active. Go to graph at www.aw-bc.com/withgott or on the student CD-ROM. Data from National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division, 2007.

**Figure 18.10** Modern climate models incorporate many factors, including processes involving the atmosphere, land, oceans, ice, and biosphere. Such factors are shown graphically here, but the actual models deal with them as mathematical equations in computer simulations.
In the most frigid reaches of our planet, snow falling year after year for millennia compresses into ice and stacks up into immense sheets that scientists can mine for clues to Earth’s climate history. The ice sheets of Antarctica and Greenland trap tiny air bubbles, dust particles, and other proxy indicators (p. 512) of past conditions. By drilling boreholes and extracting ice cores, researchers can tap into these valuable archives.

Recently, researchers drilled and analyzed the deepest core ever. At a remote and pristine site in Antarctica named Dome C, they drilled down 3,270 m (10,728 ft) to bedrock and pulled out more than 800,000 years’ worth of ice. The longest previous ice core (from Antarctica’s Vostok station) had gone back “only” 420,000 years. Ice near the top of these cores was laid down most recently, and ice at the bottom is oldest, so by analyzing ice at intervals along the core’s length, researchers can generate a timeline of environmental change.

Dome C, a high summit of the Antarctic ice sheet, is one of the coldest spots on the planet, with an annual mean temperature of −54.5°C (−65.1°F). The Dome C ice core was drilled by the European Project for Ice Coring in Antarctica (EPICA), a consortium of researchers from 10 European nations. Antarctic operations are expensive and logistically complicated, ice-drilling requires powerful technology, and the analysis requires a diverse assemblage of experts. When the team published a research paper detailing its data in the journal Nature in 2004, the paper had 56 authors.

That landmark paper reported data across 740,000 years. The researchers obtained data on surface air temperature by measuring the ratio of deuterium isotopes (pp. 91, 93) to normal hydrogen in the ice, because this ratio is temperature-dependent (see top panel of figure). And by examining the density of dust particles, they could tell when arid and/or windy climates sent more dust aloft.

In 2005, two followup papers in the journal Science reported analyses of greenhouse gas concentrations from the EPICA ice core. By analyzing air bubbles trapped in the ice, the researchers quantified atmospheric concentrations of carbon dioxide, methane, and nitrous oxide from across 650,000 years.

One finding from the EPICA studies was expected—yet important. The researchers documented that temperature swings in the past were tightly correlated with concentrations of carbon dioxide (see middle panel of figure), as well as methane and nitrous oxide. This bolstered the scientific consensus that greenhouse gas emissions are causing Earth to warm today.

Also clear and expected from the data was that temperature varied with swings in solar radiation due to Milankovitch cycles (p. 510). The complex interplay of these cycles produced periodic temperature fluctuations on Earth resulting in periods of glaciation (when temperate regions of the planet were covered in ice) as well as warm interglacial periods. The Dome C ice core spanned eight glacial cycles.

In addition, the EPICA data demonstrate that by increasing greenhouse gas concentrations since the industrial revolution, we have brought them well above the highest levels they reached naturally across 650,000 years. Today’s carbon dioxide concentration (383 ppm in 2007) is too recent to show up in the ice core, but is far above previous maximum values (of ~300 ppm) shown in the middle panel of the figure. Present-day concentrations of methane and nitrous oxide are likewise the highest in 650,000 years. These data show that we as a society have brought ourselves deep into uncharted territory.

Other findings from the ice core are not easily explained. Intriguingly, the earlier glacial cycles are of a different character than the more recent cycles (see figure). For the most recent cycles, the Dome C core confirmed what the Vostok data had shown:

Glacial periods were long, whereas interglacial periods were brief, with a rapid rise and fall of temperature. Interglacials thus appear on a graph of
temperature through time as tall thin spikes. However, older glacial cycles revealed by the Dome C core look different: The glacial and interglacial periods were of more equal duration, and the warm extremes of interglacials were not as great.

This change in the nature of glacial cycles through time had been noted before by researchers working with oxygen isotope data from the fossils of marine organisms (bottom panel of figure). But why glacial cycles should be so different before and after the 450,000-year mark, no one knows.

Today polar scientists are searching for a site that might provide an ice core stretching back more than 1 million years. For at that time, data from marine isotopes tell us that glacial cycles switched from a periodicity of roughly 41,000 years (conforming to the influence of planetary tilt), to intervals of about 100,000 years (more similar to orbital changes). An ice core that captures cycles on both sides of the 1-million-year divide might help clarify the influence of Milankovitch cycles, or perhaps offer other explanations.

The intriguing patterns revealed by the Dome C ice core show that we still have plenty to learn about our complex climate history. However, the clear relationship between greenhouse gases and temperature evident in the EPICA data confirm that we would do well to address our society’s greenhouse emissions.

Deuterium isotope data from the EPICA ice core reveal changes in surface temperature across 740,000 years (top panel). High peaks indicate warm interglacial periods, and low troughs indicate cold glacial periods. Data from the previous Vostok ice core are shown for comparison. Atmospheric carbon dioxide concentrations (middle panel) from the EPICA ice core rise and fall in tight correlation with temperature. These datasets are consistent with oxygen-18 isotope data from the marine record (bottom panel), an independent proxy indicator for global temperature.

Current and Future Trends and Impacts

Evidence that climate conditions have changed worldwide since industrialization is now overwhelming and indisputable. Climate change in recent years has already had numerous effects on the physical properties of our planet, on organisms and ecosystems, and on human well-being. If we continue to emit greenhouse gases into the atmosphere, the impacts of climate change will only grow more severe.

The IPCC summarizes evidence of climate change and predicts future impacts

In recent years, it seems that virtually everyone is detecting climatic changes around us. A fisherman in the Maldives notes the seas encroaching on his home island. A rancher in west Texas suffers a multi-year drought. A homeowner in Florida finds it impossible to obtain insurance against the hurricanes and storm surges that increasingly threaten. New Yorkers, Bostonians, Chicagoans, and Los Angelinos marvel over one freakish weather event after another. Are all these impressions part of a real pattern, and is there solid scientific evidence to confirm that climate is indeed already changing?

Over the past century, and particularly in recent years, a wide variety of data sets have shown significant trends in climate conditions. The most thoroughly reviewed and widely accepted synthesis of scientific information concerning climate change is a series of reports issued by the Intergovernmental Panel on Climate Change (IPCC). This international panel of scientists and government officials was established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization.

In 2007 the IPCC released its Fourth Assessment Report, which represents the consensus of scientific climate research from around the world. This report summarizes many thousands of scientific studies, and it documents observed trends in surface temperature, precipitation patterns, snow and ice cover, sea levels, storm intensity, and other factors. 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 current and future climate change on wildlife, ecosystems, and human societies. Finally, it discusses possible strategies we might pursue in response to climate change. Figure 18.12 summarizes a selection of the IPCC report’s major observed and predicted trends and impacts.

The IPCC report is authoritative but, like all science, deals in uncertainties. Its authors have therefore taken great
### Major Trends and Impacts of Climate Change, from IPCC Fourth Assessment Report, 2007

<table>
<thead>
<tr>
<th>Global physical indicators</th>
<th>Regional physical indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth’s average surface temperature increased 0.74°C (1.33°F) in the past 100 years, and will rise 1.8–4.0°C (3.2–7.2°F) in the 21st century.</td>
<td>Arctic areas warmed fastest. Future warming will be greatest in the Arctic and greater over land than over water.</td>
</tr>
<tr>
<td>Eleven of the years from 1995 to 2006 were among the 12 warmest on record.</td>
<td>Summer Arctic sea ice thinned by 7.4% per decade since 1978.</td>
</tr>
<tr>
<td>Atmospheric water vapor increased since at least the 1980s.</td>
<td>Average Northern Hemisphere temperatures of the past 50 years were the highest in at least 1,300 years.</td>
</tr>
<tr>
<td>Oceans absorbed &gt;80% of heat added to the climate system, and warmed to depths of at least 3,000 m (9,800 ft).</td>
<td>Thawing decreased area of Arctic permafrost in spring by 15% since 1900.</td>
</tr>
<tr>
<td>Glaciers, snow cover, ice caps, ice sheets, and sea ice will continue melting, contributing to sea-level rise.</td>
<td>Precipitation increased in e. North America, e. South America, n. Europe, and n. and c. Asia since 1900.</td>
</tr>
<tr>
<td>Sea level rose by an average of 17 cm (7 in.) in the 20th century, and will rise 18–59 cm (7–23 in.) in the 21st century.</td>
<td>Precipitation decreased in the Sahel, the Mediterranean, s. Africa, and parts of s. Asia since 1900.</td>
</tr>
<tr>
<td>Ocean water became more acidic by about 0.1 pH unit, and will decrease in pH by 0.14–0.35 units more by century’s end.</td>
<td>Precipitation will generally increase at high latitudes and decrease at subtropical latitudes, often making wet areas wetter and dry ones drier.</td>
</tr>
<tr>
<td>Storm surges increased, and will increase further.</td>
<td>Heavy precipitation events increased over most land areas.</td>
</tr>
<tr>
<td>Sea level rise will worsen coastal erosion and degrade wetlands.</td>
<td>Droughts became longer, more intense, and more widespread since the 1970s, especially in the tropics and subtropics.</td>
</tr>
<tr>
<td>Carbon uptake by terrestrial ecosystems will likely peak by the mid-21st century and then weaken or reverse, amplifying climate change.</td>
<td>Droughts and flooding will increase, leading to agricultural losses.</td>
</tr>
<tr>
<td>Timber production may rise slightly in the near-term, but will vary by region.</td>
<td>Over most land areas, cold and frost days decreased and will continue to decrease while hot days and heat waves increased and will continue to increase.</td>
</tr>
<tr>
<td>Impacts on biodiversity will cause losses of food, water, and other ecosystem goods and services.</td>
<td>Hurricanes intensified in the North Atlantic since 1970, and will continue to intensify.</td>
</tr>
<tr>
<td>Sea-level rise will displace people from islands and coastal regions.</td>
<td>The thermohaline circulation will slow, but will not shut down and chill Europe in the 21st century.</td>
</tr>
<tr>
<td>Melting of mountain glaciers will reduce water supplies to millions of people.</td>
<td>Antarctica will continue accumulating snow, but may also continue losing ice around its edges.</td>
</tr>
<tr>
<td>Economic costs will outweigh benefits as climate change worsens; costs could average 1–5% of GDP globally for 4°C (7.2°F) of warming.</td>
<td>Species ranges are shifting toward the poles and upward in elevation, and will continue to shift.</td>
</tr>
<tr>
<td>Poorer nations and communities suffer more from climate change, because they rely more on climate-sensitive resources and have less capacity to adapt.</td>
<td>The timing of seasonal phenomena (such as migration and breeding) is shifting, and will continue to shift.</td>
</tr>
<tr>
<td>Human health will suffer as increased warm-weather health hazards outweigh decreased cold-weather health hazards.</td>
<td>About 20–30% of species studied so far will face extinction risk if temperature rises more than 1.5–2.5°C (2.7–4.5°F).</td>
</tr>
</tbody>
</table>

**FIGURE 18.12** Climate change has had numerous consequences already and is predicted to have many more. Listed here are some of the main observed and predicted trends and impacts described in the Intergovernmental Panel on Climate Change’s Fourth Assessment Report. For simplicity, this table expresses mean estimates only; the IPCC report provides ranges of estimates as well. 1Certainty level 566–90% probability of being correct. 2Certainty level 580% probability of being correct. 3Certainty level 590–99% probability of being correct. 4Certainty level 5>99% probability of being correct. 5Certainty level 550% probability of being correct. Data from the Intergovernmental Panel on Climate Change (IPCC). 2007. Fourth assessment report.
Temperature increases will continue

The IPCC report concludes that average surface temperatures on Earth increased by an estimated 0.74°C (1.33°F) in the century from 1906 to 2005 (Figure 18.13), with most of this increase occurring in the last few decades. Eleven of the years from 1995 to 2006 were among the 12 warmest on record since global measurements began 150 years earlier. The numbers of extremely hot days and heat waves have increased, whereas the number of cold days has decreased.

Temperature changes are greatest in the Arctic (Figure 18.14). 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. Thin sea ice is dangerous for people to travel and hunt upon, and in recent years, polar bears have been dying of exhaustion and starvation as they try to swim long distances between ice floes. Permafrost (permanently frozen ground) is thawing in the Arctic, destabilizing countless buildings. The strong Arctic warming is contributing to sea-level rise by melting ice caps and ice sheets.

In December 2005, a group representing North America's Inuit people sent a legal petition to the Inter-American Commission on Human Rights, demanding that the United States restrict its greenhouse gas emissions, which the Inuit maintained were destroying their way of life in the Arctic. After a year, the Commission dismissed the petition with a terse three-sentence letter. Do you think Arctic-living people deserve some sort of compensation from industrialized nations whose emissions have caused climate change that has disproportionately affected the Arctic? Do you think climate change can be viewed as a human rights issue? What ethical issues, if any, do you think climate change presents? How could these best be resolved?

In the future, we can expect average surface temperatures on Earth to rise roughly 0.2°C (0.4°F) per decade for the next 20 years, according to IPCC analysis. If we were to cease greenhouse gas emissions today, temperatures would still rise 0.1°C (0.2°F) per decade because of the time lag from gases already in the atmosphere that have yet to exert their full influence. At the end of the 21st century, the IPCC predicts global temperatures will be 1.8–4.0°C (3.2–7.2°F) higher than today’s, depending upon the emission scenario. Unusually hot days and...
Heat waves will become more frequent. Temperature change is predicted to vary from region to region in ways that parallel regional differences already apparent (Figure 18.15).

Sea surface temperatures are also increasing as the oceans absorb heat added to the climate system. The record number of hurricanes and tropical storms in 2005—Katrina and 27 others—left many people wondering whether global warming was to blame. Are warmer ocean temperatures spawning more hurricanes, or hurricanes that are more powerful or long-lasting? Scientists are not yet sure, but recent analyses of storm data suggest that warmer seas may not be increasing the number of storms, but likely are increasing the power of storms, and possibly their duration.

Changes in precipitation vary by region

A warmer atmosphere holds more water vapor, but changes in precipitation patterns have been complex, with some regions of the world receiving more precipitation than usual and others receiving less. In regions from the African Sahel to the southwestern United States, droughts have become more frequent and severe, harming agriculture, promoting soil erosion, reducing drinking water supplies, and encouraging forest fires. Meanwhile, in both dry and humid regions, heavy rain events have increased, contributing to flooding, such as the 2002 flood in the Czech Republic, which killed 16 people, left 30,000 homeless, and inflicted $2.8 billion in damage.
Precipitation changes are predicted to vary among regions in ways that parallel regional differences seen over the past century (Figure 18.16). In general, precipitation will increase at high latitudes and decrease at low and middle latitudes, magnifying differences in rainfall that already exist and worsening water shortages in many developing countries of the arid subtropics. In many areas, heavy precipitation events will become more frequent, increasing the risk of flooding.

Melting ice and snow have far-reaching effects

As the world warms, mountaintop glaciers are disappearing (Figure 18.17). Since 1980, the World Glacier Monitoring Service estimates, major glaciers have lost an average of 9.6 m (31.5 ft) in vertical thickness. Many glaciers on tropical mountaintops have disappeared already. In Glacier National Park in Montana, only 27 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 the winter and release meltwater gradually during the summer. Throughout high-elevation areas of the world, however, warming temperatures will continue to melt mountain glaciers, posing risks of sudden floods as ice dams burst, and reducing summertime water supplies to millions of people. Over one-sixth of the world’s people live in regions supplied by mountain meltwater, and some of these people are already beginning to face water shortages. If this water vanishes during drier months, whole communities will be forced to look elsewhere for water, or to move.

Warming temperatures are also reducing snow cover at high latitudes and melting the immense ice sheets of the Arctic. Recent research reveals that melting of the Greenland ice sheet is accelerating (see “The Science behind the Story,” pp. 522–523). At the other end of the world, in Antarctica, ice shelves the size of Rhode Island...
have disintegrated as a result of contact with warmer ocean water, but increased precipitation has supplied the continent with enough extra snow to compensate for the loss of ice around its edges.

One reason warming is accelerating in the Arctic is that as snow and ice melt, darker, less-reflective surfaces 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 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.

Near the poles, snow cover, permafrost, and ice sheets are projected to decrease, and sea ice will continue to shrink in both the Arctic and Antarctic. Some emission scenarios show Arctic sea ice disappearing completely by the late 21st century, creating new shipping lanes for commerce (and likely a rush to exploit underwater oil and mineral reserves that may exist in Arctic waters).

Rising sea levels will affect hundreds of millions of people

As glaciers and ice sheets melt, increased runoff into the oceans causes sea levels to rise. Sea levels also are rising because ocean water is warming, and water expands in volume as its temperature increases. In fact, recent sea-level rise has resulted primarily from the thermal expansion of seawater. Worldwide, average sea levels rose an estimated 17 cm (6.7 in.) during the 20th century (Figure 18.18). Sea rise by an estimated 1.8 mm/year from 1961–2003 and 3.1 mm/year from 1993–2006. Note that all these numbers represent vertical rises in water level, and on most coastlines a vertical rise of a few inches means many feet of horizontal incursion inland.

Higher sea levels lead to beach erosion, coastal flooding, intrusion of saltwater into aquifers, and other impacts. In 1987, unusually high waves struck the Maldives and triggered a campaign to build a large seawall around Male, the nation’s capital. Known as “The Great Wall of Male,” the seawall is intended to protect buildings and roads by dissipating the energy of incoming waves during storm surges. A storm surge is a temporary and localized rise in sea level brought on by the high tides and winds associated with storms. The higher that sea level is to begin with, the further inland a destructive storm surge can reach. “With a mere 1-meter rise [in sea level],” Maldives’ President Maumoon Abdul Gayoom warned in 2001, “a storm surge would be catastrophic, and possibly fatal to the nation.”

The Maldives is not the only nation with such concerns. In fact, among island nations, the Maldives has fared better than many others. It saw sea level rise about 2.5 mm per year throughout the 1990s, but most Pacific islands are experiencing greater changes. Regions experience differing amounts of sea level change because land elevations may be rising or subsiding naturally, depending on local geological conditions.

In the United States, 53% of the population lives in coastal areas. Vulnerability to storm surges became tragically apparent in 2005 when Hurricane Katrina struck New Orleans and the Gulf Coast, followed shortly thereafter by Hurricane Rita (Figure 18.19).

The levees surrounding New Orleans that Katrina’s floodwaters breached are now repaired, but large portions of the city will always remain below sea level. Areas that are now 2.1 m (7 ft) below sea level may be as much as 3.3 m (10 ft) below sea level by 2100 as the land subsides and sea level rises. Outside the city, marshes of the Mississippi River delta are being lost rapidly, as dams upriver hold back silt that used to maintain the delta, as land subsides because of petroleum extraction, and as rising seas eat away at coastal vegetation. Approximately 2.5 million ha (1 million acres) of Louisiana wetlands have become open water since 1940, and continued wetland loss will deprive New Orleans of protection against future storm surges.

At the end of the 21st century, the IPCC predicts mean sea level to be 18–59 cm (7–23 in.) higher than today’s, depending upon the emission scenario. However, these estimates do not take into account findings on accelerated ice melting in Greenland, because that research (see “The Science behind the Story, • pp. 522–523) is so new that it has not yet been incorporated into climate models. If Greenland’s melting continues to accelerate, then sea levels will rise more quickly.

Rising sea levels will force hundreds of millions of people to choose between moving upland or investing in costly protections against high tides and storm surges.
PART TWO  Environmental Issues and the Search for Solutions

Outlet glaciers melting into Scoresby Sund, Greenland’s largest fjord

Scientists have known for years that the Arctic is bearing the brunt of global warming and that the massive ice sheet covering Greenland is melting around its edges. But data from 1993 to 2003 showed Greenland’s ice loss accounting for only 4–12% of global sea level rise, about 0.21 mm/yr. And as authors of the IPCC’s Fourth Assessment Report used results from climate models to predict Greenland’s future contributions to sea-level rise, the models told them to expect more of the same.

However, some brand-new research hadn’t made it into the models. Scientists studying how ice moves were learning that ice sheets can collapse more quickly than expected and that Greenland’s ice loss is accelerating. As a result, they said, the IPCC report underestimates the likely speed and extent of future sea level rise.

Greenland’s ice sheet is massive, averaging nearly a mile deep and covering as much area as Texas, California, Michigan, and Minnesota combined. If the entire ice sheet were to melt, global sea level would rise by a whopping 7 m (23 ft).

The ice sheet gains mass by accumulating snow during cold weather, which becomes packed into ice over time. It loses mass as surface ice melts in warm weather, generally at the periphery, where ice is thinnest or contacts seawater. If melting and runoff outpace accumulation, then the ice sheet shrinks.

But researchers are now learning that the internal physical dynamics of how ice moves may be more important. These dynamics can speed the flow of immense amounts of ice in outlet glaciers downhill toward the coast, where eroding ice sloughs off and melts into the sea.

The first good indication of this process came in 2002 when a team led by Jay Zwally of NASA’s Goddard Space Flight Center in Maryland noted that ice in outlet glaciers flows more quickly during warm months, when pools of meltwater form on the surface. In a paper published in the journal Science in 2002, Zwally’s group proposed that meltwater leaks down through crevasses and vertical tunnels called moulins to the bottom of the glacier. There, the water runs downhill in a layer between bedrock and ice, lubricating the bedrock surface and enabling the ice to slide downhill like a car hydroplaning on a wet road. In addition, the meltwater weakens ice on its way down and warms the base of the glacier, melting some of it to create more water (see the figure).

Other scientists proposed an additional mechanism: Warming ocean water melts ice shelves along the coast, depriving outlet glaciers of the buttressing support that holds them in place. Without a floating ice tongue at its terminus, a glacier slides into the ocean more readily.

These physical dynamics represent positive feedback, researchers said; once global warming initiates these processes, they encourage further melting. As such, they said, we should expect that Greenland’s melting will accelerate.

Several research groups soon attempted to measure the rates of

FIGURE 18.19  In a world of higher sea levels and stronger storms, rescues like this one from the floodwaters of Hurricane Katrina’s storm surge in coastal Mississippi in 2005 could become more frequent.
Densely populated regions on low-lying river deltas, such as Bangladesh, will be most affected. So will storm-prone regions such as Florida and Charleston, and areas where land is subsiding, such as the U.S. Gulf Coast. Many Pacific islands will need to be evacuated, and some nations such as Tuvalu and the Maldives fear for their very existence. In the meantime, the Maldives is likely to suffer from shortages of fresh water because rising seas threaten to bring salt water into the nation's wells, just as the 2004 tsunami did. The contamination of groundwater and soils by seawater threatens not only island nations like the Maldives but also coastal areas such as the Tampa, Florida, region, which depend on small lenses of fresh water that float atop saline groundwater.

The researchers found that the physical dynamics of ice movement were responsible for the loss of 56 km³ of ice in 1996, 92 km³ in 2000, and 167 km³ in 2005. The 2005 amount is equivalent to 44 trillion gallons of water, enough to supply the New York City metro area for over a century.

They also determined that the physical dynamics of ice flow accounted for two-thirds of total ice loss. The other third was due to runoff outpacing snow accumulation, and this too was accelerating. Including these amounts showed that Greenland lost a grand total of 91 km³ of ice in 1996, 138 km³ in 2000, and 224 km³ in 2005. This last amount exceeds all the water consumed in the United States in an entire year.

Clearly, ice losses were accelerating quickly. Rignot and Kanagaratnam calculated that Greenland's contribution to sea level rise increased from 0.23 mm/yr in 1996 to 0.57 mm/yr in 2005. Scientists will now be keeping a close eye on Greenland's ice sheet to see whether it continues to discharge water more and more quickly. If it does, climate modelers will have several years in which to incorporate into their models the new and evolving understanding of the physical dynamics of ice—just in time for the next IPCC report scheduled for 2013.

Weighing the Issues

Environmental Refugees

Citizens of the Maldives see an omen of their future in the Pacific island nation of Tuvalu, which 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 these environmental refugees in 2003. 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 are their lives and culture faring in the wake of that tragedy?
Maldives residents also worry about damage to the marine ecosystems that are critical for their economy, including coral reefs (pp. 450–451). Coral reefs provide habitat for important food fish that are consumed locally and exported; offer snorkeling and scuba diving sites for tourism; and reduce wave intensity, protecting coastlines from erosion. Around the world, rising seas will eat away at the coral reefs, mangrove forests, and salt marshes that serve as barriers protecting our coasts (pp. 450–453).

Climate change poses two additional threats to coral reefs: warmer waters are causing coral bleaching (pp. 450–451), and enhanced CO₂ concentrations in the atmosphere are changing ocean chemistry. As ocean water absorbs atmospheric CO₂, it becomes more acidic, which impairs the growth of coral and other organisms whose exoskeletons consist of calcium carbonate. The oceans have already decreased by 0.1 pH unit (a fairly large amount; pp. 94–96), and are predicted to decline in pH by 0.14–0.35 more units over the next 100 years.

**Climate change affects organisms and ecosystems**

The many changes in Earth’s physical systems have direct consequences for life on our planet. Organisms are adapted to their environments, so they are affected when those environments are altered. As global warming proceeds, it modifies temperature-dependent biological phenomena. For instance, in the spring, birds are migrating earlier, insects are hatching earlier, and animals are breeding earlier. Plants are leafing out earlier, too—an effect confirmed by satellite photography that records whole landscapes “greening up” each year.

These changes in seasonal timing are expected to continue, and they are having complex effects. For instance, European birds known as great tits time their breeding cycle so that their young hatch and grow at the time of peak caterpillar abundance. However, as plants leaf out earlier and insects emerge earlier, research shows that great tits are not breeding earlier. As a result of the mismatch in timing, fewer caterpillars are available when young birds need them, and fewer birds survive. Although some organisms will no doubt adapt to such changes in seasonal timing, research so far shows that in most cases mismatches occur.

Biologists also have recorded spatial shifts in the ranges of organisms, with plants and animals moving toward the poles or upward in elevation (i.e., toward cooler regions) as temperatures warm. As these trends continue, some organisms will not be able to cope, and as many as 20–30% of all plant and animal species could be threatened with extinction, the IPCC estimates. Trees may not be able to shift their distributions fast enough. Animals adapted to montane environments may be forced uphill until there is nowhere left to go (as we saw with Monteverde’s organisms in Chapter 5). Rare species finding refuge in protected preserves may be forced out of preserves into developed areas, making such refuges far less effective tools for conservation.

These changes will greatly affect species interactions, and scientists foresee major modifications in the structure and function of communities and ecosystems. 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 diminish, affecting aquatic organisms, as well as human health and well-being. Acidification of the oceans may pose major threats for corals and other marine animals. Given that corals will likely also suffer increased bleaching from thermal stress, the world’s coral reefs are expected to decline substantially. This would reduce marine biodiversity significantly, because so many other organisms depend on living coral reefs for food and shelter.

Effects on plant communities comprise an important component of climate change, because by drawing in CO₂ for photosynthesis, plants act as sinks for carbon. If climate change increases vegetative growth, this could help mitigate carbon emissions, in a process of negative feedback. However, if climate change decreases plant growth (through drought or fire, for instance), then positive feedback could increase carbon flux to the atmosphere. The many impacts on ecological systems will reduce the ecosystem goods and services we receive from nature and that our societies depend on, from food to clean air to drinking water.

**Climate change exerts societal impacts**

Human society has begun to feel impacts of climate change. Damage from drought, flooding, hurricanes, storm surges, and sea level rise, as discussed above, has already taken a toll on the lives and livelihoods of millions of people. However, climate change will have even more consequences for human populations, including impacts on agriculture, forestry, economics, and health.

**Agriculture** For farmers, earlier springs require earlier crop planting. For some crops in the temperate zones, production may increase slightly with moderate warming, because growing seasons become longer and because more carbon dioxide is available to plants for photosynthesis. However, rainfall will shift in space and time, and in areas where droughts and floods become more severe, these will cut into agricultural productivity. Overall, global crop yields are predicted to increase somewhat, but beyond a rise of 3° C (5.4° F), the IPCC expects crop yields to decline. In seasonally dry tropical and subtropical regions, growing seasons may be shortened, and harvests may be more susceptible to drought and crop failure. Thus, scientists
predict that crop production will fall in these regions even with minor warming. This would worsen hunger in many of the world’s developing nations.

Weighing Issues | Agriculture in a Warmer World
The IPCC predicts that slight warming could shift agricultural belts toward the poles and marginally increase global crop production. Locate the nations of Russia, Canada, and Argentina on a world map, and hypothesize how such a poleward shift of agriculture might affect these nations. Now locate India, Nigeria, and Ethiopia, and hypothesize how the shift might affect them. Given that many developing nations near the equator are already suffering from food shortages and soil degradation, what effects do you think that global warming may have? If climate change magnifies inequities between developed and developing nations, what could we do to alleviate this problem?

Forestry | Forest managers increasingly find themselves having to battle insect and disease outbreaks, invasive species, and catastrophic fires, which are mostly caused by decades of fire suppression (p. 343) but are also promoted by longer, warmer, drier fire seasons. For timber and forest products, enriched atmospheric CO₂ may spur greater growth in the near term, but this will vary substantially from region to region. Other climatic effects such as drought may eliminate these gains. For instance, droughts brought about by a strong El Niño in 1997–1998 allowed immense forest fires to destroy millions of hectares of rainforest in Indonesia, Brazil, Mexico, and elsewhere.

Health | As a result of climate change, we will face more heat waves—and heat stress can cause death (Figure 18.20), especially among older adults. A 1995 heat wave killed at least 465 people in Chicago, for example, and one killed 35,000 people in Europe in 2003. In addition, a warmer climate exposes us to other health problems:

- Respiratory ailments from air pollution, as hotter temperatures promote formation of photochemical smog (pp. 486–488)
- Expansion of tropical diseases, such as dengue fever, into temperate regions as vectors of infectious disease (such as mosquitoes) move toward the poles
- Disease and sanitation problems when floods overcome sewage treatment systems
- Injuries and drowning if storms become more frequent or intense
- Hunger-related ailments as human population grows and demands on agricultural systems increase

Figure 18.20 Climate models—in this case, the Canadian and Hadley models (a)—provide projections of the heat index (a product of temperature and humidity) for July across the United States for the coming century. The Canadian model predicts that the July heat index will be 14°C (25°F) hotter across much of the southeastern United States. Past and projected mortality rates attributed to hot weather (b) are shown for several U.S. cities.

Health hazards from cold weather will decrease, but researchers feel that the increase from warm-weather hazards will more than offset these gains.

**Economics** People will experience a variety of economic costs and benefits from the many impacts of climate change, but on the whole researchers predict that costs will outweigh benefits, and that this gap will widen as climate change grows more severe. Climate change will also widen the gap between rich and poor, both within and among nations. Poorer people have less wealth and technology with which to adapt to climate change, and poorer people rely more on resources (such as local food and water) that are particularly sensitive to climatic conditions.

From a wide variety of economic studies, the IPCC estimated that climate change will cost 1–5% of GDP on average globally, although poor nations would lose more proportionally than rich nations. Economists trying to quantify damages from climate change by measuring the “social cost of carbon” (i.e., external costs; p. 42) have proposed costs of anywhere from $10 to $350 per ton of carbon. The highest profile economic study to date has been the *Stern Review* commissioned by the British government (see “The Science behind the Story, Chapter 2, pp. 44–45). This study maintained that climate change could cost us roughly 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. Regardless of the precise numbers, many economists and policymakers are concluding that spending money now to mitigate climate change will save us a great deal more in the future.

All these physical, biological, and social impacts of climate change are consequences of the warming effect of our greenhouse gas emissions (Figure 18.21). We are

![Figure 18.21](image-url)
bound to experience further consequences, but by addressing the root causes of anthropogenic climate change now, we can still prevent the most severe future impacts.

**Impacts will vary regionally**

All future impacts of climate change are subject to regional variation, so the way each of us experiences these impacts over the coming decades will vary tremendously, depending on where we live.

For the United States, potential impacts were analyzed by the U.S. Global Change Research Program (USGCRP), which Congress created in 1990 to coordinate federal climate research. In 2000–2001, this program issued a comprehensive report highlighting the past and future effects of global climate change on the United States, where average temperatures increased by 0.6°C (1.0°F) during the 20th century.

To develop its predictions (Table 18.2), the report used coupled general circulation models (*p. 513*). These models allowed scientists to present graphical depictions summarizing the predicted impacts of climate change on particular geographic areas (Figure 18.22). For instance, climate models predicted that forest communities should in general shift northward and upward in elevation. Although some forest types will likely decline, others, including oak-hickory and oak-pine forests, may expand in the eastern United States (Figure 18.23). The report also predicted that of 16 crops in the United States, yields of 13 would increase and only 1 (potatoes) would decrease.

The USGCRP report reached conclusions broadly similar to those of the internationally accepted IPCC assessment reports, but climate scientists say the USGCRP report was suppressed once the George W. Bush administration came to power. Climate change has been a politically divisive issue because any decision to move away from a fossil fuel economy challenges many entrenched and powerful interests.

### Are we responsible for climate change?

The IPCC's 2007 report concluded conservatively that it is greater than 90% likely that most of the global warming recorded over the past half century is due to the well-documented increase in greenhouse gas concentrations in our atmosphere. Scientists agree that this increase in greenhouse gases results primarily from our combustion of fossil fuels for energy and secondarily from land use changes, including deforestation and agriculture.

By the time the IPCC's *Fourth Assessment Report* came out, many scientists had already become concerned enough to put themselves on record urging governments to address climate change. In June 2005, as the leaders of the “G8” industrialized nations met, the national academies of science from 11 nations (Brazil, Canada, China, France, Germany, India, Italy, Japan, Russia, the United Kingdom, and the United States) issued a joint statement urging these political leaders to take action. Such a broad consensus statement from the
world’s scientists was virtually unprecedented, on any issue. The statement read, in part:

The scientific understanding of climate change is now sufficiently clear to justify nations taking prompt action. It is vital that all nations identify cost-effective steps that they can take now, to contribute to substantial and long-term reduction in net global greenhouse gas emissions. . . . A lack of full scientific certainty about some aspects of climate change is not a reason for delaying an immediate response that will, at a reasonable cost, prevent dangerous anthropogenic interference with the climate system.

Despite broad consensus among scientists and most national governments that climate change is a pressing issue, public discussion of climate change in the United States remained mired in an outdated debate over whether the phenomenon was real and whether humans were to blame. The debate was fanned largely by “greenhouse skeptics,” a handful of scientists typically backed by funding from Exxon-Mobil and other corporations in the fossil fuel and auto industries. These people aimed to cast doubt on the scientific consensus, and their views were amplified by the American news media, which seeks to present two sides to every issue, even when the sides’ arguments are not equally supported by evidence.

Today that debate is largely over, and most Americans accept that our fossil fuel consumption is altering the planet that our children will inherit. The tide turned with the 2007 release of the IPCC report, the broad popularity of Al Gore’s 2006 movie and book, *An Inconvenient Truth* (Figure 18.24), grassroots activism, and action by political leaders at the state and local levels.

In a public opinion poll taken by the *New York Times* and CBS News in April 2007, 84% of respondents viewed human activity as contributing to global warming, and 78% of respondents supported immediate action to curb global warming. Fifteen percent of respondents rated global warming as “the most important” environmental problem, up from only 2% a decade earlier. More than half said global warming was “a very serious problem and should be one of the highest priorities for government leaders,” whereas only 9% thought it was not serious or did not need addressing.

As a result of this shift in public perception, and in response to demand from their shareholders, many corporations and industries began offering support for reductions in greenhouse gas emissions. Strikingly, these advocates included some of the titans of industry in our fossil-fuel based economy who previously had worked to block action on climate change. Companies joining together in the U.S. Climate Action Partnership to ask government leaders to “quickly enact strong national
legislation to require significant reductions of greenhouse gas emissions included Alcoa, BP America, ConocoPhillips, Dow Chemical, Duke Energy, DuPont, General Electric, General Motors, Pacific Gas and Electric, and Shell. These giants of the American economy thereby joined ranks with the insurance industry, which years earlier had grown concerned with climate change as it foresaw increased payouts for damage due to coastal storms, drought, and floods.

Responding to Climate Change

Today we possess a newly broad consensus that climate change is a clear and present challenge to our society. How precisely we should respond to climate change is a difficult question, however, and one we will likely be wrestling with for decades.

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, in order to lessen the severity of future climate change. This strategy is called mitigation because the aim is to mitigate, or alleviate, the problem. The second type of response is to accept that climate change is happening and to pursue strategies to minimize its impacts on us. This strategy is called adaptation because the goal is to adapt to change by finding ways to cushion oneself from its blows.

Erecting a seawall like Maldives residents did with the Great Wall of Male is an example of adaptation, using technology and engineering. The people of Tuvalu also adapted, but with a behavioral choice—some chose to leave their island and make a new life in New Zealand (see “Weighing the Issues,” p. 523). Other examples of adaptation 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.

In contrast, mitigation strategies center on reducing greenhouse gas emissions by improving energy efficiency, switching to clean and renewable energy sources, encouraging farm practices that protect soil quality, recovering landfill gas, and preventing deforestation.

Many environmental advocates have criticized adaptation strategies, because they view them as escapist—a way of sidestepping the hard work that must be done to protect future generations from climate change. However, adaptation and mitigation are not mutually exclusive approaches; a person or a nation can pursue both.

Indeed, both approaches are necessary. Adaptation is needed because even if we were to halt all our emissions now, global warming would continue until the planet’s systems reach a new equilibrium, with temperature rising an estimated 0.6° C (1.0° F) 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.

Mitigation is necessary because if we do nothing to slow down climate change, it will eventually overwhelm any efforts at adaptation we could make. To leave a sustainable future for our civilization and to safeguard the living planet that we know, we will need to pursue mitigation. Moreover, the faster we begin reducing our emissions, the lower the level at which they will peak, and the less we will alter climate (Figure 18.25). We will spend the remainder of our chapter examining approaches for the mitigation of climate change.

Electricity generation is the largest source of U.S. greenhouse gases

The generation of electricity produces the largest portion (40%) of U.S. carbon dioxide emissions (Figure 18.26). From cooking and heating to the clothes we wear, much of what we own and do depends on electricity. Fossil fuel combustion generates 69% of U.S. electricity, and coal alone accounts for 50%, along with most of the greenhouse gas emissions. Reducing the volume of fossil fuels we burn to generate electricity would lessen greenhouse gas emissions, as would decreasing electricity consumption. There are two ways to reduce the amount of fossil
fuels we use: (1) encouraging conservation and efficiency (\textit{\small pp. 565–568}) and (2) switching to cleaner and renewable energy sources (Chapters 20 and 21).

**Conservation and efficiency** Conservation and efficiency in energy use can arise from new technologies, such as high-efficiency lightbulbs and appliances, or from individual ethical choices to reduce electricity consumption. The U.S. Environmental Protection Agency (EPA) offers technological solutions through its Energy Star Program, which rates household appliances, lights, windows, fans, office equipment, and heating and cooling systems by their energy efficiency. For instance, replacing an old washing machine with an Energy Star washing machine can cut your CO$_2$ emissions by 200 kg (440 lb) annually. Replacing standard lightbulbs with compact fluorescent lights reduces energy use for lighting by 40%. Energy Star homes use highly efficient windows, ductwork, insulation, and heating and cooling systems to reduce energy use and emissions by as much as 30%. Such technological solutions are popular, and they can be profitable for manufacturers while also saving consumers money.

Consumers can also opt for lifestyle choices. For nearly all of human history, people managed without the electrical appliances that most of us take for granted today. It is possible for each of us to choose to use fewer greenhouse-gas-producing appliances and technologies and to take practical steps to use electricity more efficiently.

**Sources of electricity** We can also reduce greenhouse gas emissions by altering the types of energy we use. Among fossil fuels, natural gas burns more cleanly than oil, and oil is cleaner-burning than coal. Using natural gas instead of coal produces the same amount of energy with
roughly one-half the emissions (● p. 58). Moreover, approaches to boost the efficiency of fossil fuel use, such as cogeneration (● pp. 566–567) produce fewer emissions per unit energy generated.

Currently, interest in carbon capture and carbon sequestration or storage is intensifying. Carbon capture refers to technologies or approaches that remove carbon dioxide from power plant emissions. Successful carbon capture technology would allow plants to continue using fossil fuels while cutting greenhouse gas pollution. The carbon would then be sequestered, or stored, somewhere—perhaps underground under pressure in locations where it will not seep out. However, we are still a long way from developing adequate technology and secure storage space to accomplish this, and some experts doubt that we will ever be able to sequester enough carbon to make a dent in our emissions.

Technologies and energy sources that generate electricity without using fossil fuels represent another means of reducing greenhouse gas emissions. These include nuclear power (● pp. 575–588), hydroelectric power (● pp. 595–598), geothermal energy (● pp. 617–620), photovoltaic cells (● pp. 609–610), wind power (● pp. 612–617), and ocean energy sources (● pp. 620–621). These energy sources give off no emissions during their use (but some in the production of their infrastructure). We will examine these clean and renewable energy sources in detail in Chapters 20 and 21.

Transportation is the second largest source of U.S. greenhouse gases

Can you imagine life without a car? Most Americans probably can’t—a reason why transportation is the second-largest source of U.S. greenhouse emissions. One-third of the average American city—including roads, parking lots, garages, and gas stations—is devoted to use by the nation’s 220 million registered automobiles. The average American family makes 10 trips by car each day, and governments across the nation spend $200 million per day on road construction and repairs.

Unfortunately, the typical automobile is highly inefficient. Close to 85% of the fuel you pump into your gas tank does something other than move your car down the road. According to the U.S. Department of Energy, only about 13–14% of the fuel energy actually moves the vehicle and its occupants from point A to point B (Figure 18.27). Although more aerodynamic designs, increased engine efficiency, and improved tire design could help reduce these losses, gasoline-fueled automobiles may always remain somewhat inefficient.

Automotive technology The technology exists to make our vehicles more fuel-efficient than they currently are. Indeed, the vehicles of many nations are more fuel-efficient than those of the United States. Raising fuel efficiency (● pp. 565–566) for American-made vehicles will require government mandate and/or consumer demand, and as gasoline prices rise, demand for more fuel-efficient automobiles will intensify.

Advancing technology is also bringing us alternatives to the traditional combustion-engine automobile. These include hybrid vehicles that combine electric motors and gasoline-powered engines for greater efficiency (● pp. 566–567). They also include fully electric vehicles, alternative fuels such as compressed natural gas and biodiesel (● pp. 591–592), and hydrogen fuel cells that use oxygen and hydrogen and produce only water as a waste product (● pp. 622–625).

Driving less and using public transportation People can also opt to make lifestyle choices that reduce their reliance on cars. For example, some people are choosing to live nearer to their workplaces. Others use mass transit such as buses, subway trains, and light rail. Still others

![Figure 18.27](image-url)

Conventional automobiles are extremely inefficient. Almost 85% of useful energy is lost, and only 14% actually moves the car down the road.
bike or walk to work or for their errands (Figure 18.28). Unfortunately, reliable and convenient public transit is not yet available in many U.S. communities. Making automobile-based cities and suburbs more friendly to pedestrian and bicycle traffic and improving people’s access to public transportation stand as central challenges for city and regional planners (● pp. 370–373).

In a 2002 study, the American Public Transportation Association (APTA) concluded that increasing the use of public transportation is the single most effective strategy for conserving energy and reducing pollution. Already, public transportation in the United States reduces fossil fuel consumption by 855 million gallons of gas (45 million barrels of oil) each year, the APTA estimates. Yet according to the study, if U.S. residents increase their use of public transportation to the levels of Canadians (7% of daily travel needs) or Europeans (10% of daily travel needs), the United States could substantially cut its air pollution, its dependence on imported oil, and its contribution to climate change.

We can reduce emissions in other ways as well

Other pathways toward mitigating climate change include advances in agriculture, forestry, and waste management. In agriculture, sustainable land management that protects the integrity of soil on cropland and rangeland enables soil to store more carbon. Techniques have also been developed to reduce the emission of methane from rice cultivation and from cattle and their manure, and to reduce nitrous oxide emissions from fertilizer. We can also grow renewable biofuels, and this is an active area of current research (● p. 590–591).

In forest management, the rapid reforestation of cleared areas helps restore forests, which act as reservoirs that pull carbon from the air. Sustainable forestry practices and preserving existing forests can help to reverse the carbon dioxide emissions resulting from deforestation.

Waste managers are doing their part to cut greenhouse emissions by recovering methane seeping from landfills (● pp. 638–639), treating wastewater (● pp. 435–438), and generating energy from waste in incinerators (● pp. 637–638). Individuals, communities, and waste haulers also help reduce emissions by encouraging recycling, composting, and the reduction and reuse of materials and products (● pp. 639–644).

We will need to follow multiple strategies to reduce emissions

We should not expect to find a single magic bullet for mitigating climate change. Instead, reducing emissions will require many steps by many people and institutions across many sectors of our economy. The good news is that most reductions can be achieved using current technology and that we can begin implementing these changes right away.

Environmental scientists Stephen Pacala and Robert Socolow argue that “humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century.” They advise that we follow some age-old wisdom: When the job is big, break it into small parts. Pacala and Socolow propose that we adopt a portfolio of strategies, each one feasible in itself, that could together stabilize our CO₂ emissions at current levels (Figure 18.29).

Pacala and Socolow began with graphs that predicted a doubling of emissions over the next 50 years and asked: What would we need to do to hold our emissions flat instead and to avoid the additional future emissions represented by the triangular area of the graph above the flat trend line? The researchers subdivided their so-called stabilization triangle into 7 equal wedges, like slices of a pie. To eliminate one wedge, a strategy would need to reduce emissions equivalent to 1 billion tons of carbon per year 50 years in the future. Pacala and Socolow identify not just 7, but 15, strategies (listed in Figure 18.29) that could each take care of one wedge if developed and deployed at a large scale.

In the long term, the stabilization-wedge approach will not be enough. To stop climate change, we will need to reduce emissions (as opposed to stabilizing them), and this may require us to develop new technology, further change our lifestyles, and/or reverse our population
CHAPTER EIGHTEEN
Global Climate Change

533

Historical emissions

Delay

2005

Ways to eliminate 1 “wedge” of emissions

- Double the fuel economy of cars
- Halve the miles driven by car
- Maximize efficiency in all buildings
- Double the efficiency of coal-powered plants
- Switch from coal to natural gas at 1,400 plants
- Capture and store carbon from 800 coal plants
- Capture and store carbon from 180 “synfuels” plants
- Increase hydrogen fuel production by 10 times
- Triple the world’s nuclear capacity
- Increase wind power capacity by 50 times
- Increase solar power capacity by 700 times
- Increase ethanol production by 50 times
- Halt tropical deforestation and double reforestation
- Adopt conservation tillage on all croplands

14

1

7 Stabilization wedges

2005

2055

FIGURE 18.29 Pacala and Socolow began with a standard graph (left) of predicted carbon emissions from CO₂ showing the doubling of 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 separated the graph into emissions allowed (below the line) and emissions to be avoided (the triangular area above the flat line). They then divided this “stabilization triangle” into seven equal-sized portions, which they called “stabilization wedges” (center). Each stabilization wedge represents 1 billion tons of CO₂ emissions in 2055 to be avoided. Finally, they identified 15 strategies (box at right), each of which could take care of 1 wedge. If we accomplish just 7 of these 15 strategies, we could halt our growth in emissions for the next half century.


growth. However, there is plenty we can do in the meantime to mitigate climate change simply by scaling up the technologies and approaches for emissions reductions that we already have developed.

Shall we use government mandates or market incentives?

How quickly and successfully we translate our science and technology into practical solutions for reducing emissions depends largely on the policies we urge our leaders to pursue and on how government and the market economy interact. As we saw in Chapter 3 and in numerous instances throughout this book, governmental command-and-control policy has been vital in safeguarding environmental quality and promoting human well-being. However, government mandates are often resisted by industry, and market incentives can sometimes be more effective in driving change.

With climate change policy, we are in the midst of a dynamic period of debate and experimentation. At all levels—international, national, state, regional, and local—policymakers, industry, commerce, and citizens are searching for ways to employ government and the market to reduce emissions in ways that are fair, economically palatable, effective, and enforceable.

We began tackling climate change by international treaty


By the late 1990s, it was clear that a voluntary approach was not likely to succeed. For example, from 1990 to 2006, U.S. greenhouse emissions increased by 17.9%. However, certain other nations demonstrated that economic vitality does not require ever-increasing emissions. For instance, Germany has the third most technologically advanced economy in the world and is a leading producer of iron, steel, coal, chemicals, automobiles, machine tools, electronics, textiles, and other goods—yet it managed between 1990 and 2004 to reduce its greenhouse gas emissions by 17.2%. In the same period, the United Kingdom cut its emissions by 14.3%.

After watching the seas rise and observing the failure of most industrialized nations to cut their emissions, nations of the developing world—the Maldives among them—helped initiate an effort to create a binding international
treaty that would require all signatory nations to reduce their emissions. This effort led to the Kyoto Protocol.

The Kyoto Protocol seeks to limit emissions

An outgrowth of the FCCC drafted in 1997 in Kyoto, Japan, the Kyoto Protocol mandates signatory nations, by the period 2008–2012, to reduce emissions of six greenhouse gases to levels below those of 1990 (Table 18.3). The treaty took effect in 2005 after Russia became the 127th nation to ratify it.

The United States has continued to refuse to ratify the Kyoto Protocol. U.S. leaders have called the treaty unfair because it requires industrialized nations to reduce emissions but does not require the same of rapidly industrializing nations such as China and India, whose greenhouse emissions have risen over 50% in the past 15 years. Proponents of the Kyoto Protocol say the differential requirements are justified because industrialized nations created the current problem and therefore should take the lead in resolving it. The refusal of the United States to join international efforts to curb greenhouse emissions has generated resentment among its allies and has undercut the effectiveness of these efforts.

Because resource use and per capita emissions are far greater in the industrialized world, governments and industries there often feel they have more to lose economically from restrictions on emissions. Ironically, industrialized nations are also the ones most likely to gain economically, because they are best positioned to invent, develop, and market new technologies to power the world in a post-fossil-fuel era.

As of 2004 (the most recent year with full international data), nations that signed the Kyoto Protocol had decreased their emissions by 3.3% from 1990 levels. However, much of this reduction was due to economic contraction in Russia and nations of the former Soviet Bloc following the breakup of the Soviet Union. When these nations are factored out, the remaining signatories showed an 11.0% increase in emissions from 1990 to 2004.

Kyoto Protocol critics and supporters alike acknowledge that even if every nation complied with the treaty, greenhouse gas emissions would continue to increase—albeit more slowly than they would without the treaty. Nations are now looking ahead and negotiating over what will come next to supersede Kyoto.

States and cities are advancing climate change policy

In the absence of action to address climate change by the George W. Bush administration and the U.S. Congress, numerous state and local governments across the United States are responding to popular sentiment and advancing policies to limit greenhouse emissions. By mid-2007, mayors from over 600 cities from all 50 U.S. states (representing 22% of the U.S. population) had signed on to the U.S. Mayors Climate Protection Agreement, led by Seattle Mayor Greg Nickels. Under this agreement, mayors commit their cities to pursue policies to "meet or beat" Kyoto Protocol guidelines and to urge their states and the federal government to take action as well.

At the state level, the boldest action so far has come from California, where in 2006 California’s legislature worked with governor Arnold Schwarzenegger to pass the Global Warming Solutions Act, which aims to cut the state’s greenhouse gas emissions 25% by the year 2020. This law is the first state legislation with penalties for noncompliance, and followed earlier efforts in California to mandate higher fuel efficiency for automobiles.

Bold action was also taken by 10 northeastern states that launched the Regional Greenhouse Gas Initiative (RGGI) in 2007. In this effort, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont have set up a cap-and-trade program for carbon emissions from power plants. This emissions trading program (\* pp. 79–82) is one example of how a government-sponsored and mandated plan can engage the market economy to achieve public policy goals.

### Table 18.3 Emissions Reductions Required and Achieved

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<tr>
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<tbody>
<tr>
<td>Russia</td>
<td>0.0%</td>
<td>−32.0%‡</td>
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<tr>
<td>Germany</td>
<td>−21.0%</td>
<td>−17.2%</td>
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<tr>
<td>United Kingdom</td>
<td>−12.5%</td>
<td>−14.3%</td>
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<td>France</td>
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<tr>
<td>Italy</td>
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<td>Japan</td>
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<tr>
<td>United States</td>
<td>−7.0%</td>
<td>+15.8%</td>
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<tr>
<td>Canada</td>
<td>−6.0%</td>
<td>+26.6%</td>
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*Percentage decrease in emissions (carbon-equivalents of six greenhouse gases) from 1990 to period 2008–2012, as mandated under Kyoto Protocol.
†Actual percentage change in emissions (carbon-equivalents of six greenhouse gases) from 1990 to 2004. Negative values indicate decreases; positive values indicate increases. Values do not include influences of land use and forest cover.
‡Russia’s substantial decrease was due mainly to economic contraction following the breakup of the Soviet Union.
Market mechanisms are being used to address climate change

As we first discussed in Chapter 3 (pp. 79–82), permit trading programs represent a way to harness the economic efficiency of the free market to achieve policy goals while allowing business, industry, or utilities flexibility in how they meet those goals. Supporters of permit trading programs argue that they provide the fairest, least expensive, and most effective method of achieving emissions reductions. Polluters get to choose how to reduce their emissions and are given financial incentives for reducing emissions below the legally required amount. We will likely discover how successful these ventures are over the next decade as various carbon trading programs get up and running around the world.

As an example of how a cap-and-trade emissions trading program can work, consider the planned approach for the Regional Greenhouse Gas Initiative:

1. Each state decides what polluting sources it will require to participate in the program.
2. Each state sets a cap on the total CO₂ emissions it will allow.
3. Each state distributes to each emissions source one permit for each ton they emit, up to the amount of the cap.
4. Sources with too few permits to cover their emissions must find ways to reduce their emissions, buy permits from other sources, or pay for credits through a carbon offset project. Sources with excess permits may keep them or sell them.
5. Any source emitting more than its permitted amount will face penalties.

Once up and running, it is hoped that the system will be self-sustaining. The price of a permit is meant to fluctuate freely in the market, creating the same kinds of financial incentives as any other commodity that is bought and sold in our capitalist system.

The world’s first emissions trading program for greenhouse gas reduction (operating since 2003) is the Chicago Climate Exchange, which now boasts over 120 corporations, institutions, and municipalities in North America and Brazil. This legally binding trading system imposes a 6% reduction on overall emissions by 2010.

The world’s largest cap-and-trade program is the European Union Emission Trading Scheme, which began on January 1, 2005. All EU member states participate, and each submits for approval a national allocation plan that conforms to the nation’s obligations under the Kyoto Protocol. This market got off to a successful start, and carbon prices reached 30 euros per ton in early 2006. However, when investors determined that national governments had allocated too many emissions permits to their industries, the price of carbon fell. The over-allocation gave companies little incentive to reduce emissions, so permits lost their value. By early 2007, prices in the market had tanked to below 0.30 euros. This drop is roughly equivalent to a stock valued at $40 falling to less than 40 cents.

Proponents of emissions trading chalk up the freefall in the European market as a learning experience. Europeans will have the chance to correct their allocations and revive their market beginning in 2008 as the program enters its next phase, when it expands to include more greenhouse gases, more emissions sources, and additional members.

Carbon offsets are in vogue

Emissions trading programs have allowed participants who cannot or will not adequately reduce their own emissions to use carbon offsets instead. A carbon offset is a voluntary payment to another entity intended to enable that entity to reduce the greenhouse emissions that one is unable or unwilling to reduce on its own. The payment thus offsets one’s own emissions. For instance, a coal-burning power plant could pay a reforestation project to plant trees that will soak up as much carbon as the coal plant emits. Or a university could fund the development of clean and renewable energy projects to make up for fossil fuel energy the university uses.

Carbon offsets are fast becoming popular among utilities, businesses, universities, governments, and individuals trying to achieve carbon-neutrality, a state in which no net carbon is emitted. For time-stressed people with enough wealth, offsets represent a simple and convenient way to reduce one’s emissions without investing in efforts to change one’s habits. For example, you can go to the website of the company TerraPass, calculate your emissions for travel by car or plane, or for your home or campus dorm, and purchase offsets for those emissions. Your money funds renewable energy and efficiency projects, and you can advertise your donation with bumper stickers and decals.

In principle, carbon offsets seem a great idea, but in practice they often fall short. Without rigorous oversight to make sure that the offset money actually accomplishes what it is intended for, carbon offsets risk being no more than a way for wealthy consumers to assuage a guilty conscience. Efforts to create a transparent and enforceable offset infrastructure are ongoing. If these efforts succeed, then carbon offsets could become an effective and important key to mitigating climate change.
You can reduce your own carbon footprint

Carbon offsets, emissions trading schemes, national policies, international treaties, and technological innovations will all play roles in mitigating climate change. But in the end the most influential factor may be the collective decisions of millions of regular people. In our everyday lives, each one of us can take steps to approach a carbon-neutral lifestyle by reducing greenhouse emissions that result from our decisions and activities. Just as we each have an ecological footprint (p. 6), we each have a carbon footprint that expresses the amount of carbon we are responsible for emitting.

You can apply many of the strategies discussed in this chapter in your everyday life—from deciding where to live and how to get to work to choosing appliances. You will encounter still more solutions in our discussions of energy sources, conservation, and renewable energy in Chapters 19–21 and elsewhere throughout this book.

Global climate change may be the biggest challenge facing us and our children. Fortunately, it is still early enough that, with concerted action, we can avert the most severe impacts. Taking immediate, resolute action is the most important thing that we, personally and as a society, can do.

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 increase 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 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 actions to mitigate and adapt to climate change represents the foremost challenge for our society in the coming years.

You should now be able to:

Describe Earth’s climate system and explain the many factors influencing global climate

- Earth’s climate changes naturally over time, but it is now changing rapidly because of human influence. (p. 506)
- The sun provides most of Earth’s energy and interacts with the atmosphere, land, and oceans to drive climate processes. (pp. 506, 510–511)
- Earth absorbs about 70% of incoming solar radiation and reflects about 30% back into space. (pp. 506–507)
- Greenhouse gases such as carbon dioxide, methane, water vapor, nitrous oxide, ozone, and halocarbons warm the atmosphere by absorbing infrared radiation and re-emitting infrared radiation of different wavelengths. (pp. 506–509)
- Milankovitch cycles influence climate in the long term. (p. 510)

Characterize human influences on the atmosphere and global climate

- Increased greenhouse gas emissions enhance the greenhouse effect. (pp. 507–509)
- By burning fossil fuels, clearing forests, and manufacturing halocarbons, humans are increasing atmospheric concentrations of many greenhouse gases. (pp. 508–509)
- Human input of aerosols into the atmosphere exerts a variable but slight cooling effect. (p. 509)

Summarize modern methods of climate research

- Geologic records, such as cores through ice or sediments, reveal information about past climatic conditions. (pp. 512, 514–515)
- Direct atmospheric sampling tells us about current composition of the atmosphere. (p. 513)
- Coupled general circulation models serve to predict future changes in climate. (pp. 513–516)

Outline current and future trends and impacts of global climate change

- The IPCC has comprehensively synthesized current climate research, and its periodic reports represent the consensus of the scientific community. (pp. 516–518)
- Temperatures on Earth have warmed by an average of 0.74° C (1.33° F) over the past century and are predicted to rise 1.8–4.0° C (3.2–7.2° F) over the next century. (pp. 518–519)
- Changes in precipitation vary by region. (pp. 519–520)
- Sea level has risen an average of 17 cm (7 in.) over the past century. (pp. 521–523)
- Other impacts include melting of glaciers and polar ice, frequency of extreme weather events, impacts on
agriculture, forestry, and health, and effects on plants and animals. (pp. 520–528)

- Climate change and its impacts will vary regionally. (p. 527)
- Despite some remaining uncertainties, the scientific community feels that evidence for humans’ role in influencing climate is strong enough to justify governments taking action to reduce greenhouse emissions. (pp. 527–528)

Suggest ways we may respond to climate change

- Both adaptation and mitigation are necessary for responding to climate change. (p. 529)
- Conserving electricity, improving efficiency of energy use, and switching to clean and renewable energy sources will help reduce fossil fuel consumption and greenhouse emissions. (pp. 529–531)

TESTING YOUR COMPREHENSION

1. What happens to solar radiation after it reaches Earth? How do greenhouse gases warm the lower atmosphere?

2. Why is carbon dioxide considered the main greenhouse gas? How could an increase in water vapor create either a positive or negative feedback effect?

3. How do scientists study the ancient atmosphere?

4. Has simulating climate change with computer programs been effective in helping us predict climate? How do these programs work?

5. List five major trends in climate that scientists have documented so far. Now list five future trends or impacts that they are predicting.

6. Describe how rising sea levels, caused by global warming, can create problems for people. How may climate change affect 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? In what ways can we reduce these emissions?

9. What roles have international treaties played in addressing climate change? Give two specific examples.

10. Describe one market-based approach for reducing greenhouse emissions. Explain one reason it may work well and one reason it may not work well.

SEEKING SOLUTIONS

1. To determine to what extent current climate change is the result of human activity versus natural processes, which type(s) of scientific research do you think is (are) most helpful? Why?

2. Some people argue that we need “more proof,” or “better science” before we commit to substantial changes in our energy economy. How much “science,” or certainty, do you think we need before we should 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 believe that the precautionary principle (● pp. 277, 405) is an appropriate standard in the case of global climate change? Why or why not?

3. Describe several ways in which we can reduce greenhouse gas emissions from transportation. Which approach do you think is most realistic, which approach do you think is least realistic, and why?

4. Imagine that you would like to make your own lifestyle carbon-neutral and that you aim to begin by reducing the emissions you are responsible for by 25%. What actions would you take first to achieve this reduction?

5. THINK IT THROUGH You have been appointed as the United States representative to an international conference to negotiate terms of a treaty to take hold after the Kyoto Protocol ends. All nations recognize that the Kyoto Protocol was not fully effective, and most are committed to creating a stronger agreement. The U.S.
6. **THINK IT THROUGH** You have just been elected governor of a medium-sized U.S. state. Polls show that the public wants you to take bold action to reduce greenhouse gas emissions. However, polls also show that the public does not want prices of gasoline or electricity to rise very much. Carbon-emitting industries in your state are wary of emissions reductions being required of them, but are willing to explore ideas with you. Your state legislature will support you in your efforts as long as you remain popular with voters. The state to your west has just passed ambitious legislation mandating steep greenhouse gas emissions reductions. The state to your east has just joined a new regional emissions-trading consortium. What actions will you take in your first year as governor?

### INTERPRETING GRAPHS AND DATA

We burn fossil fuels to generate electricity, to power vehicles for transportation, and as primary energy sources (non-electricity uses, mostly for heating) in homes, businesses, and industry. For each of these uses, the accompanying graph shows trends in the emission of carbon dioxide from fossil fuel combustion in the United States.

1. Calculate the approximate percentage changes in CO₂ emissions from transportation; electricity generation; and residential, commercial, and industrial primary energy use (mostly heating) between 1980 and 2006.
2. Between 1980 and 2006, U.S. population increased by 32% and the inflation-adjusted U.S. gross domestic product (GDP) more than doubled. What quantitative conclusions can you draw from these data about CO₂ emissions per capita? About CO₂ emissions per unit of total economic activity? Create a graph and sketch a trend line of CO₂ emissions per capita from 1980 to 2006. Now sketch a trend line of CO₂ emissions per unit of total economic activity from 1980 to 2006.
3. Imagine you are put in charge of designing a strategy to reduce U.S. emissions of CO₂ from fossil fuel combustion. Based on the data presented here, what approaches would you recommend, and how would you prioritize these? Explain your answers.

### 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 contribute to mitigating global climate change through personal decisions and actions that affect the way 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 one of these, at http://www.carbonfootprint.com, follow the link for the U.S. version, take the quiz, and enter the relevant data in the table.
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 from these in the ways it does?

2. 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?

3. Now take the quiz again, trying to make enough changes to reduce your footprint to the level at which we could halt climate change. Do you think you could achieve such a footprint? 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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