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Global Climate Change

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Reforestation project in Ghana. Since deforested soil does not hold water as well as that of established forests, these reforestation workers in Ghana must water plantings by hand until they become established.

Anthropogenic (human-caused) climate change is an established phenomenon. Within the scientific community, the question is no longer whether climate change will occur, but at what rate, with what effects, and what, if anything, we can do about it. The biggest driver of climate change is an increase in atmospheric carbon dioxide (CO_2), which is generated primarily through burning fossil fuels.

Robert Socolow and **Stephen Pacala** of the Princeton University Carbon Mitigation Initiative suggest that somewhere near but below a doubling of atmospheric carbon from preindustrial levels lies the "boundary separating the truly dangerous consequences of emissions from the merely unwise." They propose that to keep future atmospheric carbon below a doubling of the preindustrial level (in the early 1800s, the atmosphere contained 600 billion tons of carbon) would require 7 billion fewer tons generated each year by 2056 than are currently expected.

Many people, seeing the enormity of this challenge, despair of finding a solution. Socolow and Pacala, however, propose that reductions can be thought of in terms of "wedges," each of which would result in a 1-billion-ton-per-year reduction by 2056. A combination of any seven wedges would put us on a path to avoid the critical doubling of CO_2. They identify 15 technologies in five categories, any one of which could serve as one of the seven wedges. Four of these wedges are:

Increase the fuel economy of 2 billion cars from 30 to 60 mpg. Two billion cars are expected to be on the world's roads by 2056, each traveling an average of 10,000 miles per year. If the typical car operates at 60 mpg, there will be 1 billion fewer tons of carbon generated each year than if they operate at 30 mpg.

Install carbon capture and storage at 800 large coal-fired power plants. Currently, the carbon dioxide produced from burning coal is released to the atmosphere. Instead, this carbon could be captured and stored. If 90% of the carbon released each year is captured and stored, 1 billion fewer tons will be released to the atmosphere.

Stop all deforestation. Deforestation worldwide currently releases 2 billion tons of carbon to the atmosphere each year. However, it is expected to slow to 1 billion tons per year without intervention. Thus, to achieve a 1-billion-ton wedge below the expected amount would require either a complete cessation of deforestation or a balance between deforestation and reforestation (see photo).

Add twice today's nuclear energy output to displace coal. Nuclear energy currently accounts for about 17% of the world's electricity. Increasing the amount of nuclear power alone will not affect the amount of carbon dioxide generated. However, replacing existing coal-fired power plants with nuclear power facilities would reduce greenhouse gases. Similarly, we could replace coal with solar or wind power.

In this chapter we examine climate change, which is a truly global challenge. Climate change is perhaps the best example of the systemic nature of environmental problems. The interaction of economics, politics, energy, agriculture, and human values with the natural world has led to climate change. Making changes in economics, politics, energy, agriculture, and human behavior such as those associated with these wedges will be necessary to curb climate change.

In Your Own Backyard

Many communities are preparing to reduce their reliance on gasoline-powered vehicles by preparing infrastructure to charge electric vehicles and/or fuel hydrogen vehicles. Is either of these being developed near where you live?

Introduction to Climate Change

LEARNING OBJECTIVES

- Explain radiative forcing, greenhouse gases, and the enhanced greenhouse effect.
- Explain how climate models project future climate conditions.
- Describe the importance of extreme and unpredictable climate change.

Several factors cause Earth to have a climate amenable to life as we understand it. These include the amount of energy Earth receives from the sun, the distribution of water around the planet, the location and topography of land masses, the tilt of Earth on its axis, the reflectivity of the surface, and the content of Earth's atmosphere. Of these, most vary over thousands or millions of years. Only two—minor fluctuations in solar intensity and the content of the atmosphere—vary over decades. And of these two, only the content of the atmosphere can account for the changes in temperature scientists have observed over the past few centuries.

Earth's average temperature is based on daily measurements taken at several thousand land-based meteorological stations around the world, as well as data from weather balloons, orbiting satellites, transoceanic ships, and hundreds of sea-surface buoys with temperature sensors. The year 2011 was tied with 2005 as the hottest year since the mid-1880s, and data show that the 20 warmest years in recorded history have occurred since 1990 (**Figure 20.1**). According to the National Oceanic and Atmospheric Administration (NOAA), global temperatures in those years may have been the highest in the last millennium. (Although widespread thermometer records have been assembled only since the mid-19th century, scientists reconstruct earlier temperatures using indirect climate evidence in tree rings, lake and ocean sediments, stalagmites, small air bubbles in ancient ice, and coral reefs.)

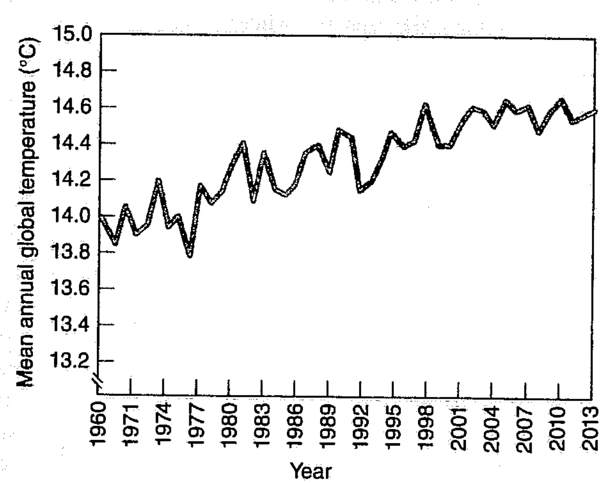


Figure 20.1 Mean annual global temperature, 1960–2013. Data are presented as surface temperatures (°C) for 1960 through 2013. The measurements, which naturally fluctuate, clearly show the warming trend of the last several decades. (The dip in global temperatures in the early 1990s, caused by the eruption of Mount Pinatubo in 1991, is discussed later in the chapter.) (Global Land-Ocean Temperature Index, Goddard Institute of Space Studies, NASA)

Other evidence confirms the increase in global temperature. Several studies have documented that phenological spring in the Northern Hemisphere now comes about six days earlier than it did in 1959, and autumn is delayed five days. (*Phenological spring* is determined by when buds of specific plants open, and autumn, by when leaves of specific trees turn color and fall.) Since 1949, the United States has experienced an increased frequency of extreme heat-stress events, which are very hot, humid days and nights during summer months; medical records indicate that heat-related deaths among the elderly and other vulnerable people increase during these events. In the past few decades, the rate of sea-level rise has increased. For most of the 20th century, the rate of increase was about 1.5 to 2 cm/decade—it is now at about 3 cm/decade. Glaciers worldwide have retreated, and extreme weather events such as severe rainstorms have occurred with increasing frequency in certain regions.

Scientists around the world began researching climate change over a century ago. As the evidence has accumulated, those most qualified to address the issue have concluded that temperatures have increased over the past century, that it is extremely unlikely that natural causes can explain the warming, and that human-produced greenhouse gases are the most plausible explanation for the warming that has occurred. Further, the remainder of this century will experience significant additional climate change, and human activities will be largely responsible for this change.

In response to the growing scientific agreement about both climate change and its human cause, governments around the world, through the United Nations, organized the Intergovernmental Panel on Climate Change (IPCC) in 1988. With input from and review by hundreds of climate experts, the IPCC provides definitive scientific statements about global climate change. The IPCC reviews all the published literature, especially that published over the previous five years, and summarizes the current state of knowledge and uncertainty as they relate to global climate change. The most recent IPCC report (its fifth), issued in 2014, confirmed earlier findings that human-produced air pollutants have caused most of the climate warming observed over the last 50 years. Depending on the assumed **emissions scenario** (a prediction about the amounts, rates, and mix of future greenhouse gases) and on the intensity of the climatic response, the IPCC report projects a 0.2°C (0.4°F) increase in global average temperature in each of the next two decades. By the year 2100, depending on whether and how much we can control greenhouse gas emissions, temperatures are expected to have risen anywhere from 1.8 to 4.0°C (3.2 to 7.2°F). Based on reconstructions of Earth's past climates, such warming would make the Earth warmer during the 21st century than in several tens of millions of years.

The fifth IPCC report also projected that it is very likely that higher maximum temperatures and more hot days will be experienced over nearly all land areas. A similar level of confidence exists for projections of higher minimum temperatures, fewer frost days, fewer cold days, an increase in the heat index, and more intense precipitation events over many areas.

THE CAUSES OF GLOBAL CLIMATE CHANGE

Carbon dioxide (CO_2) and certain other trace gases, including methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs), and tropospheric ozone (O_3), are accumulating in the atmosphere as a result of human activities (**Table 20.1**). Tropospheric ozone (O_3) has also increased and while estimates vary, it has probably increased by about 50% since the middle of the 18th century). All of these are **greenhouse gases,** or gases that absorb radiated heat from the sun, thereby increasing the temperature of the atmosphere. Additional, but minor, greenhouse gases include carbon tetrachloride, methyl chloroform, chlorodifluoromethane (HCFC-22), sulfur hexafluoride, trifluoromethyl sulfur pentafluoride, fluoroform (HFC-23), and perfluoroethane.

reenhouse gas A gas that absorbs infrared adiation; carbon dioxide, methane, nitrous ɪxide, chlorofluorocarons, and tropospheric ɪne are all greenhouse gases.

The concentration of atmospheric carbon dioxide grew from about 288 **parts per million (ppm)** approximately 200 years ago (before the Industrial Revolution began) to 400 ppm in 2014 (**Figure 20.2**). Burning carbon-containing fossil fuels—coal, oil, and natural gas—accounts for most of the human contribution to total carbon dioxide. Land conversion, such as when tracts of tropical forests are logged or burned, also releases CO_2 and causes an increase in the atmospheric CO_2 concentration.

Not only does the burning of vegetation release CO_2 into the atmosphere, but it also reduces the capacity of the biosphere to remove and store carbon in roots and tree trunks by photosynthesis. Scientists estimate that without aggressive efforts to reduce carbon emissions, during the second half of the 21st century the concentration of atmospheric CO_2 will reach or exceed double what it was in the 1700s.

infrared radiation Radiation that has wavelengths longer ɪan that of visible light but shorter than that ɟf radio waves; most of the energy absorbed by Earth is radiated as frared radiation, which greenhouse gases can absorb.

Because these gases absorb **infrared radiation**—that is, radiated heat from the sun—higher greenhouse gas concentrations lead to warming and global climate change. This occurs because the absorption of heat slows its eventual reradiation into space, thereby warming the lower atmosphere.

radiative forcing The pacity of a gas to affect the balance of energy that enters and leaves Earth's atmosphere; measured in units of power per unit area, sually watts per square meter (W/m²).

The capacity of various gases to affect the balance of energy entering and leaving the atmosphere is referred to as **radiative forcing.** A major fraction of the trapped heat is transferred to the ocean and raises its temperature as well, although the ocean's large heat capacity means that it will take many decades for enough warming to occur to reestablish the energy balance. This retention of heat in the atmosphere is a natural phenomenon that has made Earth habitable for its millions of species. However, as human activities increase the atmospheric concentration of greenhouse gases, the atmosphere and ocean will continue to warm, and the overall global temperature will rise. Carbon dioxide accounts for 60% of the increased radiative forcing and heat retention caused by greenhouse gases.

Because CO_2 and other gases slow the loss of heat generated by the incoming solar radiation in a manner parallel to how the glass enclosure reduces energy loss in a greenhouse, the natural trapping of heat in the atmosphere is often referred to as the **greenhouse effect**, and the gases that absorb infrared radiation are called greenhouse gases. Greenhouse gases accumulating in

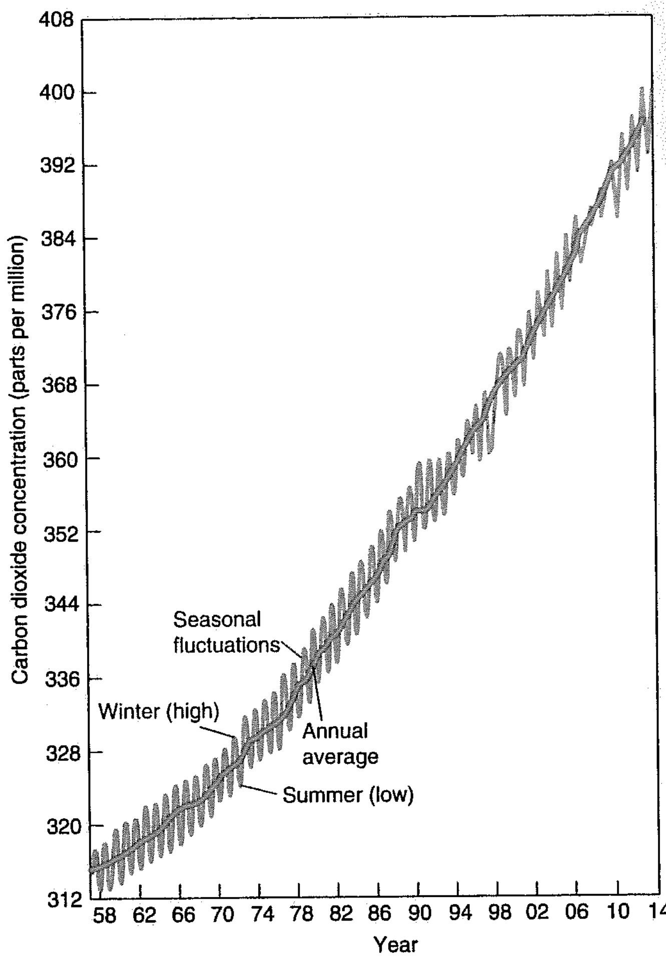


Figure 20.2 Carbon dioxide (CO_2) in the atmosphere, 1958–2014. The annual mean concentration of atmospheric CO_2 has increased steadily since 1958, when measurements began at the Mauna Loa Observatory in Hawaii. This location was selected because it is far from urban areas where factories, power plants, and motor vehicles that emit CO_2 might bias the measurements. The seasonally varying concentrations are highest in the Northern Hemisphere's winter, when plants are not actively growing and absorbing CO_2, and lowest in summer, when plants are growing and absorbing CO_2. Did CO_2 increase by the same amount between 1960 and 1970 as between 2004 and 2014? (Dave Keeling and Tim Whorf, Scripps Institution of Oceanography, La Jolla, CA)

Table 20.1 Increases in Selected Atmospheric Greenhouse Gases, Preindustrial Times to the Present

Gas	*Estimated Preindustrial Concentration**	*2014 Concentration*
Carbon dioxide	288 ppm**	401 ppm
Methane	848 ppb***	1874 ppb
Nitrous oxide	285 ppb	324 ppb
Chlorofluorocarbon-12	0 ppt****	531 ppt
Chlorofluorocarbon-11	0 ppt	238 ppt

*The preindustrial value is for the 17th and 18th centuries. There have been significant variations, as, for example, over the course of the ice ages.
**ppm = parts per million.
***ppb = parts per billion.
****ppt = parts per trillion.
Source: Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory (historical estimates), NOAA Annual Greenhouse Gas Index (2014 data).

the atmosphere as a result of human activities are thus causing an **enhanced greenhouse effect (Figure 20.3)**.

The levels of the other trace gases associated with global climate change are also rising. Every time you drive your car, the combustion of gasoline in the car's engine releases CO_2 along with other pollution-creating gases. Decomposition of carbon-containing organic material by anaerobic bacteria in moist places as varied as rice paddies, sanitary landfills, and the intestinal tracts of cattle and other large animals (humans included) is a major source of methane (CH_4). Various industrial processes, land use conversion, and the use of fertilizers produce nitrous oxide. CFCs are refrigerants released into the atmosphere from old, leaking refrigerators and air conditioners. CFC emissions have decreased, but the very long lifetime of emissions in the past—from a variety of sources including aerosol spray cans and foam insulation—means that they will continue to contribute to future climate change. Over the past decade, CFC concentrations in the atmosphere have begun to decrease. Water vapor, which is also a greenhouse gas, exerts a **positive feedback** on the climate that amplifies warming. Warmer temperatures cause greater evaporation from the ocean and a higher concentration of atmospheric water vapor, which, in turn, causes warmer air and ocean temperatures, causing further evaporation.

Although current rates of fossil-fuel combustion and deforestation are high, causing the CO_2 level in the atmosphere to increase markedly, scientists think the warming trend will be slower than the increasing level of CO_2 might indicate. The reason is that it requires more heat to raise the temperature of the ocean than of the air (recall that water has a high heat capacity). In addition, the atmosphere is well mixed, while the ocean is stratified, so the ocean takes longer than the atmosphere to absorb heat. For this reason, climate scientists expect that ocean warming will be more pronounced in the 21st century than it was in the 20th century, and recent ocean surface temperature data confirm this prediction.

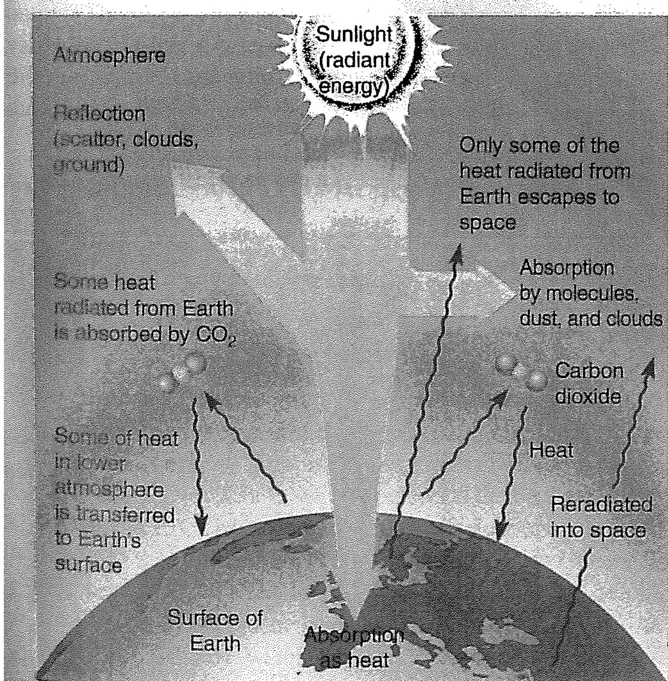


Figure 20.3 Enhanced greenhouse effect. The buildup of carbon dioxide (CO_2) and other greenhouse gases absorbs some of the outgoing infrared (heat) radiation, warming the atmosphere. Some of the heat in the warmed atmosphere is transferred back to Earth's surface, warming the land and ocean. The percent of incoming radiation absorbed is increasing, while the percent reflected is decreasing.

ENVIRONEWS ON CAMPUS

The President's Climate Commitment

At the time this book went to press, the executive officers of 684 colleges and universities had signed the "President's Climate Commitment." This commitment, as laid out in the "Commitment Text" provided on the organization's website, requires any signatory institution to take several steps, including the following:

- Complete a comprehensive inventory of greenhouse gas emissions.
- Make climate neutrality and sustainability a part of the educational experience for all students.
- Set a target date for achieving carbon neutrality.
- Provide regular policy and informational updates.

Many schools have made substantial progress toward their goals. For example, Bowdoin College in New Brunswick, Maine, expects to be carbon-neutral by 2020. You can check whether your school is part of this commitment at presidentsclimatecommitment.org, and, if so, what progress it has made to date.

POLLUTANTS THAT COOL THE ATMOSPHERE

One of the complications that makes the rate and extent of global climate change difficult to predict is that other air pollutants, known as atmospheric aerosols, tend to cool the atmosphere in what is called the **aerosol effect**. Aerosols, which come from both natural and human sources, are tiny particles so small they remain suspended in the troposphere for days, weeks, or months. Because sulfate particles are efficient at scattering radiation, a sulfate-laden haze tends to cool the planet by reflecting some of the incoming sunlight back into space, away from Earth.

aerosol effect Atmospheric cooling that occurs where and when aerosol pollution is the greatest.

Temperature observations indicate that sulfur-laden haze has significantly moderated warming in some of the industrialized parts of the world. By contrast, sooty aerosols generally absorb radiation, so they tend to warm the planet. In the atmosphere, complex mixtures of aerosols make the actual aerosol effect on the climate relatively uncertain, although it will likely exert an overall cooling influence.

The sulfur dioxide emissions that produce sulfur-laden haze come mainly from the stacks of the same power plants that are responsible for much of the CO_2 emissions. In addition, volcanic eruptions inject sulfur-containing particles into the atmosphere. The explosion of Mount Pinatubo in the Philippines in June 1991 was the largest volcanic eruption in the 20th century. The force of this eruption injected massive amounts of sulfur into the stratosphere (the layer of the atmosphere above the troposphere), where the particles stay aloft longer (up to a few years) than do the aerosols emitted into the troposphere. Because a sulfur-laden layer in the stratosphere reduces the amount of sunlight that reaches Earth's surface (although not the total amount that reaches the planet), this eruption caused a temporary period of global cooling. Compared to the rest of the 1990s, 1992 and 1993 global temperatures were relatively cool (see Figure 20.1).

Overall, the effect of the greenhouse gas increase is considerably more potent than that of the sulfur-laden haze. The increased concentrations of some greenhouse gases will persist in the atmosphere for years to hundreds of years, whereas human-produced sulfur emissions remain for only days, weeks, or months. And carbon dioxide and other greenhouse gases warm the planet 24 hours a day, whereas sulfur haze cools the planet only during the daytime. In addition, because sulfur emissions are a respiratory irritant and cause acid deposition (see Chapter 19), most nations are trying to reduce their sulfur emissions, not maintain or increase them.

MODELING THE FUTURE CLIMATE

Many interacting factors, such as winds, clouds, ocean currents, and albedo (a measure of reflectivity; ice has a higher **albedo** than does asphalt; see Chapter 4), affect the complex climate system, each exerting its influence on the climate. Because interactions among the atmosphere, ocean, and land are too complex and too large to construct in a testing laboratory, climate scientists develop simulation models using powerful computers to test how the Earth system works. Such models use well-established physical laws along with approximations for treating small-scale features of the climate to represent the effects of competing processes and thereby to describe Earth's climate system in numerical terms (**Figure 20.4**). Models can be used to explore and analyze past climate events and, in the most advanced models, to project future warming and suggest the consequences (what-if scenarios) of warming on the biosphere and its life-support systems.

A climate model is only as good as its representation of the physical laws and processes. Global climate change models have been refined in recent years and are now capable of representing many features of the current climate and the climate of the last few centuries. However, limitations do remain, particularly in the representation of clouds and changes that are likely to occur as the climate changes. If global climate change leads to more low-lying clouds, they would reflect some of the incoming sunlight and decrease the amount of warming, acting as **negative feedback**.

On the other hand, if global climate change leads to a greater number of high, thin cirrus clouds, they would only reflect a little more solar radiation but would trap a lot more infrared radiation, intensifying the warming (i.e., serving as a positive feedback

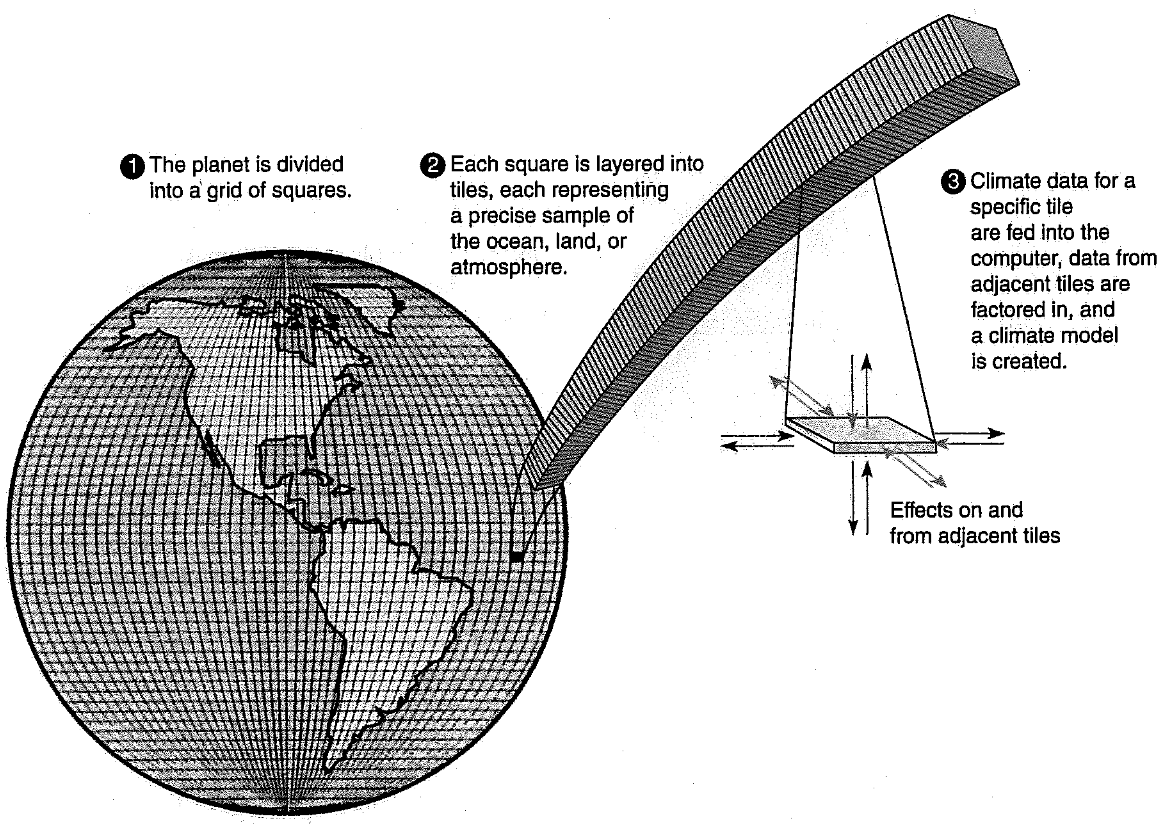


Figure 20.4 Building a climate model. Climate models typically cover the planet's surface with many hundreds to thousands of latitude-longitude tiles, much like the tiles of a mosaic. At each location, the tiles are piled atop each other, creating stacks of a few dozen tiles extending up into the upper atmosphere and down into the ocean depths. The model's program considers how hour-by-hour (or even minute-by-minute) changes in sunlight, temperature, air pressure, currents or winds, and water vapor in one tile affect conditions in that tile and in each of the adjacent tiles. The computer continually performs calculations, taking into account the fundamental laws involving conservation of mass, momentum, and energy. These calculations can stretch out to centuries, specifying, as appropriate, any changes in the concentrations of greenhouse gases, solar radiation, or some other parameter.

mechanism). As additional case studies are carried out and as new understanding about these and other uncertainties becomes available, the predictions of the models are viewed with greater confidence.

Most climate models are used to project what the climate will be like a few decades or a century from now. One model, developed at Princeton University, has been used to examine the implications of climate warming five centuries from now. The model simulation assumed that limitations on emissions will be implemented in time to stabilize the CO_2 concentration in 2050 at double the **preindustrial CO_2 level**. It presents a dramatic scenario of a warmer climate that future generations will have to live with. Among other changes, the model projects that the rising sea level would inundate the southern end of Florida from Key Largo to Fort Lauderdale. Average summer temperatures in the southeastern and mideastern states (north to Pennsylvania) would increase from the current 27°C (80°F) to 31°C (87°F), but because this warm air would hold more moisture, the average temperature would feel more like 36°C (97°F).

Climate models present humans with a potential ethical dilemma. How do we balance scientific uncertainty about the rate and extent of climate change with the similar uncertainty about the economic impacts of reducing greenhouse gas emissions? The IPCC has established a "business as usual" scenario, which estimates the amount of carbon dioxide that will be released over the next century if economies develop as expected with no intentional attempts to reduce emissions on a large scale. This scenario projects a doubling of atmospheric carbon by around 2050. Knowing this baseline allows us to think about what combination of strategies will most effectively and efficiently avoid this doubling.

Models also take into account variability in the sun's power output. The sun is a dynamic system, and the energy reaching Earth varies over time. Climate modelers calculate possible effects of this variability but conclude that it cannot explain much, if any, of the climate change observed over the past several hundred years.

UNPREDICTABLE AND EXTREME CLIMATE CHANGE

Our current knowledge of global climate is so incomplete that unanticipated effects from a globally warmed world will undoubtedly occur. Some of these effects are simply unpredictable—that is, there will be complete surprises. Others are conceptually predictable, but there are thresholds (as in the case of dying coral reefs, discussed later in the chapter) and tipping points, and we don't know when they might occur.

As an example of a tipping point, there could be a disruption of the ocean conveyor belt, which transports heat around the globe (see Figure 4.16). The ocean conveyor belt delivers heat from the tropics into the northern part of the North Atlantic Ocean. Some of this heat is transferred to the atmosphere, thereby helping to warm Europe and adjacent lands as much as 10°C (18°F). As the warm North Atlantic water transfers heat to the atmosphere, it cools, sinks, and flows southward. The cooler, sinking water carries some of the CO_2 from the atmosphere deep into the ocean, where, through incompletely understood mechanisms, much of the carbon is sequestered (stored).

Models based on the behavior of the ocean conveyor belt during past episodes of climate warming—immediately following the ice ages, for example—suggest that an abrupt climate change could occur. Climate warming, with its associated freshwater melting off the Greenland ice sheet, could weaken or even shut down the ocean conveyor belt in as short a period as a decade. Changes in the ocean conveyor belt could cause major cooling in Europe even as greater global warming occurs elsewhere. In addition, a weakened ocean conveyor belt would not sequester as much carbon in the ocean, leading to a positive feedback loop: Less CO_2 stored in the ocean would mean more CO_2 in the atmosphere, which would cause additional atmospheric warming, which, in turn, would cause the ocean conveyor belt to weaken even further.

In 2014, researchers at NASA concluded that a large portion of the West Antarctic ice sheet is undergoing a breakup that appears to be irreversible, at least over the next several decades. Water warming the edge of the ice sheet doesn't just melt that ice, but in doing so destabilizes the entire ice sheet. Because the ice sheet sits on land, any ice that melts will cause sea levels to rise worldwide.

Parts of North America experienced an unusually cold winter in 2013–2014, which many climatologists interpret as an effect of our changing climate. During the winter, cold air from the poles can move towards the equator in irregular patterns, a phenomenon called a **polar vortex**. The difference in temperature between the poles and the equator determines how far cold air can travel. Over the past few decades, the poles have warmed more quickly than has the equator, reducing the temperature differential. This allows the polar vortex to significantly reduce temperatures at middle latitudes, such as what much of the northern United States experienced in January and February 2014.

In this case overall warming of Earth's climate led to unusually cold weather in the short term across a large region. These same areas experienced higher than normal summertime temperatures both before and after the extreme polar vortex cold spells. Shortly after the polar vortex in the northern United States, the west coast of the United States experienced record springtime high temperatures.

Climate models project expected or most likely outcomes and ranges of possible outcomes. The outcomes usually reported represent a range that modelers feel is reasonably likely to include the actual outcome. Sometimes these ranges include best cases that might be somewhat troubling and worst cases that might cause serious disruptions. For example, a 0.5°C (0.9°F) increase in average summer temperature at some location might not make much difference, whereas a 4°C (7.2°F) increase certainly would.

In addition, climate model outputs often include possible extreme cases, such as a 6°C (11°F) increase in global annual average temperatures or a 6-m (19-ft) sea-level rise. As you read the next section on the effects of climate change, keep in mind that there may be effects beyond what is described here and that there are likely to be surprises we cannot currently predict.

REVIEW

1. What is the enhanced greenhouse effect, and what are the five main greenhouse gases that contribute to it?
2. How do climate models project future climate conditions?
3. Why are unpredictable and extreme climate changes important?

The Effects of Global Climate Change

LEARNING OBJECTIVES

- Differentiate between sea-level rise due to melting ice and that due to the thermal expansion of water.
- Describe how climate change impacts the physical environment.
- Give examples of effects of climate change on organisms, including humans.

Global climate change directly or indirectly affects many physical and biological systems. Many effects have already been observed—temperature increases, shifts in plant and animal habitats, and sea-level rise. Climate researchers expect that these changes will continue in the future, and they anticipate some new changes. In addition, researchers expect surprises—that is, they know changes will occur that we cannot predict.

In this section, we consider some observed and potential effects of global climate change, including changes in sea level, precipitation patterns (including the frequency and intensity of storms), ecosystems, human health, agriculture, and wildfires (**Figure 20.5**). A more complete, but still not exhaustive, list of impacts of climate change would also include changes in forests (and thus the timber industry), tourism and recreation, and coastal infrastructure.

MELTING ICE AND RISING SEA LEVELS

The IPCC projects a sea-level rise of 18 to 59 cm (0.6 to 1.9 ft) by 2100, while noting that it could be much more. Two factors cause sea-level rise. Water, like other substances, expands as it warms. The IPCC reports that during the 20th century, sea level rose about 0.2 m (8 in.), much of it due to **thermal expansion**. Thermal expansion contributes more than half of sea-level rise. The current rate of thermal expansion leads to about 3 mm of sea-level rise per year, and that rate is increasing. In addition, sea level rises due to the retreat of glaciers and thawing of ice at the South Pole. Water absorbs more heat than does ice, which is highly reflective. As a consequence, melting ice has a positive feedback effect on heating: Water absorbs more heat, which causes more ice to melt.

ALVIN JORNADA/EPA / Newscom

Figure 20.5 Wildfire in California, September 2014. While California has always experienced wildfires, major fires, like the one shown here, have been rare. Beginning in the mid-1980s, wildfires in the western United States have become more frequent, have lasted longer, and have occurred over a longer fire season. Changes in land use may have some effect, but the main driver appears to be climate warming, due to both temperature increases and snowmelt earlier in the spring.

The area of ice-covered ocean in the Arctic has decreased significantly over the past several decades. The average latitude of the southern edge of arctic ice (between 71°N and 72°N latitude during the 1970s) has retreated northward, to 75°N. Sonar measurements from naval submarines operating under the ice indicate that the remaining arctic ice pack has thinned rapidly, losing 40% of its volume in less than three decades.

Mountain glaciers around the world are also melting at accelerating rates, contributing to sea-level rise. Qori Kalis Glacier, the largest glacier in the Peruvian Andes, has almost completely melted, having retreated about 60 m (200 ft) a year for the past 25 years. The Gangotri Glacier in India is retreating at a similar rate. According to the National Park Service, in 1850 Glacier National Park had 150 glaciers; today, only 25 are big enough to be considered functional (larger than 25 acres in area; **Figure 20.6**). Glacier regression models predict that they will probably be gone by 2030.

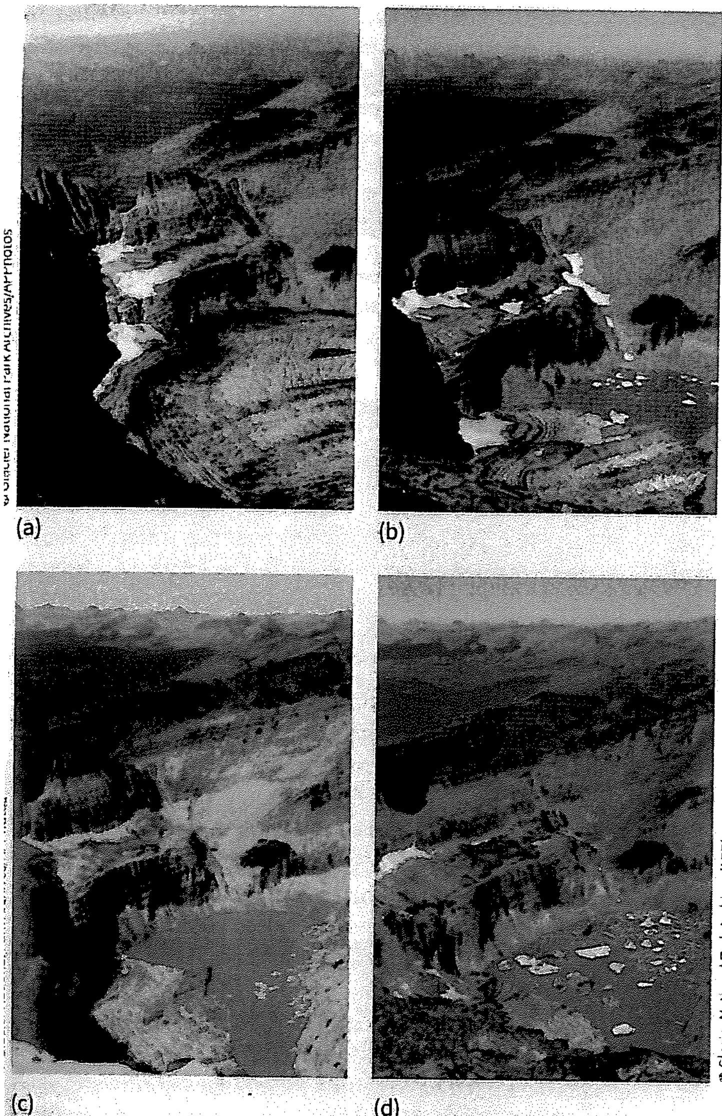
The Greenland ice sheet (the world's second-largest expanse of landbound ice) is losing over 250 km^3 (57 mi^3) of ice each year, up from estimates of 44 km^3 (11 mi^3) in 2002 and 8.3 km^3 (2 mi^3) in the period 1993–1998. In 2014, a report in *Nature Climate Change* indicated that this melt is contributing at least 0.5 mm (0.02 in.), and possibly as much as 3.2 mm (0.13 in.), to sea-level rise each year. If half of the Greenland ice sheet were to melt, sea level would rise several meters.

CASE IN POINT

IMPACTS IN FRAGILE AREAS

The Eskimo Inuit, the indigenous people of Alaska's and Canada's far north, pursue a way of life dictated by the frigid climate. Effects of global climate change are altering the traditional Inuit way of life. Many populations of wildlife, which the Inuit harvest for food, are smaller or displaced. Other changes that threaten subsistence livelihoods include reduced snow cover, shorter river ice seasons, and thawing of permafrost. Warmer temperatures increase the risk of water supplies being contaminated, as bacteria move more freely through thawed soil. Larger thawed areas could lead to the collapse of bridges, buildings, roads, and oil pipelines.

Glimpses of these observed and potential changes are gained from the region's natives, who report changes linked to warmer temperatures: drying tundra; thinner and retreating sea ice; warmer winters; and changes in the numbers, distribution, and migration of some wildlife species. Climate change data support the Inuits' observations. Scientists analyzing lake-sediment cores to explore climate changes for the past 400 years note that the greatest warming trend occurred from 1840 to the late 20th century. With temperatures projected to rise even faster in the 21st century, scientists caution that the relatively undisturbed Arctic may be particularly susceptible to the effects of climate change.



© Glacier National Park Archives/APPhotos

Figure 20.6 Grinnell Glacier, a monitor of climate change. As with many other glaciers worldwide, Grinnell Glacier, in Glacier National Park, is decreasing rapidly due to increasing temperature. Here, the glacier is shown photographed in 1938 (a), 1981 (b), 1998 (c), and 2005 (d).

Melting ice that drains into the ocean raises the sea level, but what about landbound melting ice? Evidence indicates that **permafrost**, the permanently frozen subsoil characteristic of the tundra and boreal forests of Alaska, Canada, Russia, China, and Mongolia, is thawing. Permafrost provides the foundation on which tundra plants and forest trees are anchored and on which houses and roads are built. As the permafrost thaws, this foundation collapses. Near Fairbanks, Alaska, hundreds of homes and telephone poles are sinking at odd angles into the ground (**Figure 20.7**). Thawing permafrost also releases methane and other greenhouse gases—another positive feedback.

While melting ice and thawing permafrost are important in the extreme north, sea-level rise has begun to impact small island nations. In 1999, two uninhabited islands (Tebua Tarawa and Abanuea) in the South Pacific were submerged under rising water.

© Gary Cook / Alamy

Figure 20.7 Thawing permafrost. These buildings are sinking as the permafrost on which they were built thaws. Thawing permafrost causes ground subsidence, erosion, and landslides.

In 2001, the 11,000 residents of nearby Tuvalu announced that they had to evacuate because the rise in sea level had caused lowland flooding, harming their water supply and food production. New Zealand has offered to allow some Tuvaluans to emigrate there each year. Small island nations such as the Maldives, a chain of 1200 islands in the Indian Ocean, are considered highly vulnerable to a rise in sea level. About 80% of the Maldives is less than 1 m (39 in.) above sea level, and the country's highest point is only 2 m above sea level. As sea levels rise, storm surges could easily sweep over entire islands. ■

CHANGES IN PRECIPITATION PATTERNS

Computer models indicate that, as global climate change occurs, precipitation patterns will change, causing some areas to have more frequent droughts (**Figure 20.8**). At the same time, heavier snow and rainstorms are projected to cause more frequent flooding in other areas. Some recent flooding, including heavy floods in England, has most likely been caused by changing climate.

Changes in precipitation patterns are likely to affect the availability and quality of fresh water in many locations. Arid or semiarid areas, such as the Sahel region just south of the Sahara Desert (see Figure 4.22), may have the most troublesome water shortages as the climate changes. Closer to home, experts predict water shortages in the American West because warmer winter temperatures will cause more precipitation to fall as rain rather than snow; melting snow currently provides 70% of stream flows in the West during summer months. The UN Security Council began meetings in 2007 to consider the security implications of climate change–related drought.

The frequency and intensity of storms over warm surface waters appear likely to increase. In 1998, NOAA developed a computer model examining how global climate change might affect hurricanes, and since Hurricane Katrina devastated New Orleans in 2005, there has been increased interest in the relationship between climate change and the intensity and frequency of hurricanes. Severe flooding in Australia in late 2010, caused by Cyclone Tasha, reminds us that this is a global phenomenon.

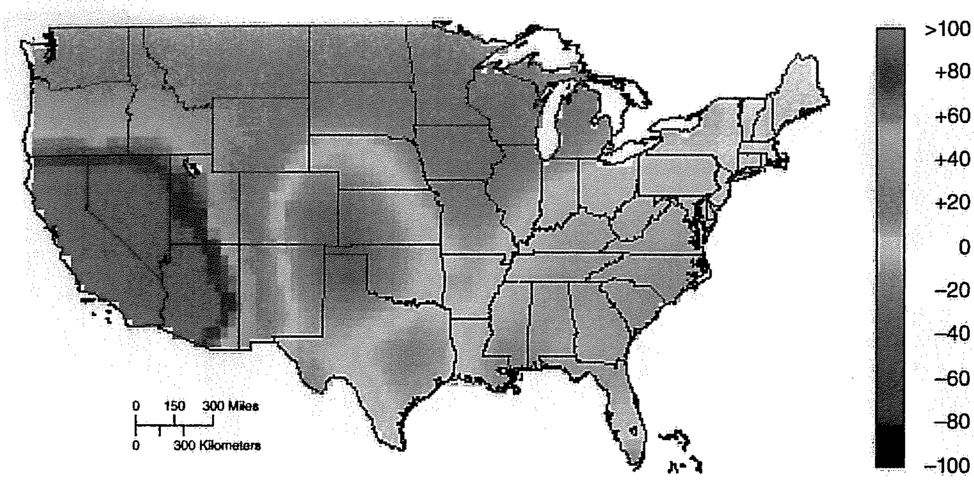


Figure 20.8 Effect of climate warming on precipitation. This model shows one scenario (the Canadian Model Scenario) of how warmer global temperatures might alter precipitation in the United States over the next 100 years. Colors indicate the percent change in annual precipitation per century. Locate the state you live in. Will it be wetter, drier, or about the same? (U. S. Climate Change Research Program)

Recent research suggests that a sea-surface temperature 2.2°C (4.0°F) warmer than today's will result in hurricanes with higher maximum wind speeds and increased total precipitation. Changes in storm intensity are expected because as Earth warms, more water evaporates, which in turn releases more energy into the atmosphere (recall the discussion of water's heat of vaporization in Chapter 13). This energy can generate more powerful storms. While the number of hurricanes each year does not appear to have changed over the past several decades in response to climate change, the mean and peak intensities have increased in correlation to increased surface-water temperature.

As discussed in Chapter 4, the El Niño–Southern Oscillation (ENSO), the periodic warming (El Niño) and cooling (La Niña) of the tropical Pacific Ocean, affects precipitation and other aspects of the entire global climate system. Until recently, climate scientists could not predict whether human-induced global climate change would affect ENSO. The IPCC's most recent analysis predicts greater extremes of drying and heavy rainfall during El Niño events. Scientists are uncertain whether El Niño events will occur more frequently with global climate change.

EFFECTS ON ORGANISMS

An increasing number of studies report measurable changes in the biology of plant and animal species as a result of climate warming. Such effects range from earlier flowering times for plant species to changes in migration patterns of aquatic species. Changes are also evident in many populations, communities, and ecosystems. Other human-induced factors, such as pollution and changes in land use, exacerbate threats posed by climate change. Here we report on the results of several of the thousands of studies conducted to date.

Researchers determined that populations of zooplankton in parts of the California Current, which flows from Oregon southward along the California coast, had declined 80% since 1951, apparently because the current has warmed slightly. The decline in zooplankton in the California Current has affected the entire food web there, and populations of plankton-eating fishes and seabirds have declined.

As temperatures have risen in the waters around Antarctica during the past two decades, a similar decline in shrimp-like krill has contributed to a reduction in Adélie penguin populations (see Case in Point: How Humans Have Affected the Antarctic Food Web, in Chapter 3). Because there are fewer krill, the birds do not get enough food. Warmer temperatures in Antarctica—during the past 50 years the average annual temperature on the Antarctic Peninsula has increased 2.6°C (4.5°F)—have contributed to reproductive failure in Adélie penguins. The birds normally lay their eggs in snow-free rocky outcrops. However, open water is now closer to the nesting ground, resulting in increased air moisture and increased snowfall. When the penguins incubate the eggs, this snow melts into cold pools of slush that kill the developing chick embryos.

Some species have shifted their geographic ranges in response to global climate change. One type of western butterfly (the Edith's checkerspot butterfly) has disappeared in the southern parts of its range, while its northern range has expanded about 160 km (about 100 mi) northward, establishing new colonies there. Similar studies conducted in Europe have found that 22 butterfly species out of the 35 species examined have shifted their ranges northward, anywhere from 32 to 240 km (20 to 150 mi). Scientists studying birds in Great Britain also report that the ranges of several dozen species have moved northward an average of 19 km (12 mi).

The ranges of some species are also shifting up in altitude. For over 100 years, researchers at the University of California at Berkeley have been collecting small mammal specimens from Yosemite National Park. This collection clearly shows that small mammals previously found only at relatively low elevations are now found at higher elevations; a steady upward shift has been documented during this time.

Biologists in the Netherlands have determined that in the past (as recently as 1980), trees leafed out, then winter moth caterpillars hatched, and then great tit eggs hatched, and the parents fed and successfully raised their chicks. Species react to warming differently: Some changes are triggered by temperature, others by seasonal changes in the length of the day. The interdependent "leaves/caterpillars/birds" system has become uncoupled because the peak number of caterpillars now occurs when the trees leaf out, which is before the chicks are hatched (egg-laying time for this species has not changed), to the detriment of the bird populations.

As warming accelerates in the 21st century, many species will undoubtedly become extinct, particularly those with narrow

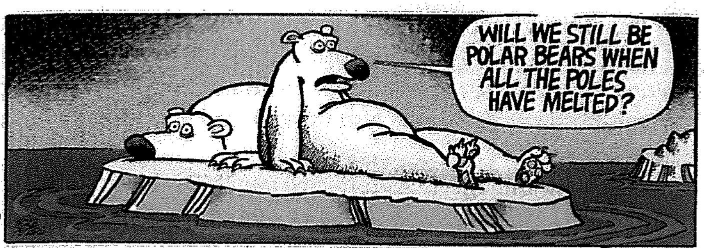
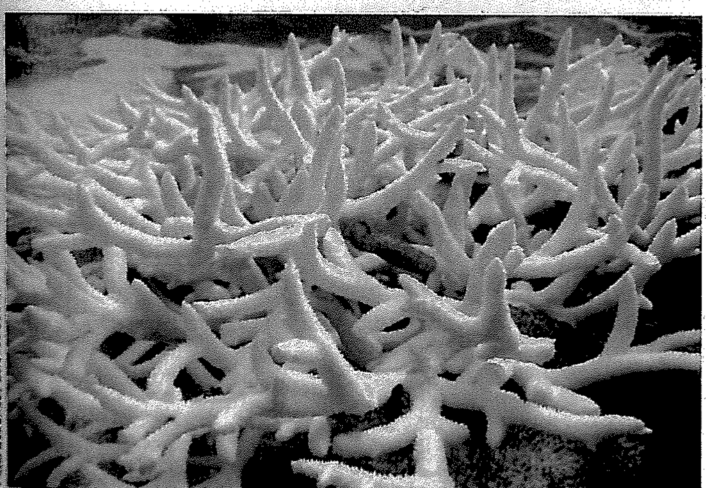


Figure 20.9 Polar bears are encountering difficulties surviving in a world with less contiguous (unbroken) polar ice. What does this cartoon imply about human obligations to other animals?

(a) The corals in this image are normal and healthy.



(b) Bleached corals. Coral researchers expect that many of Earth's corals will die from the combined effects of ocean warming and acidification.

Figure 20.10 Effects of climate change on coral reefs.

temperature requirements; those confined to small, specialized habitats; and those living in fragile ecosystems. Other species may survive in greatly reduced numbers and ranges. Ecosystems considered at greatest risk of species loss in the short term are coral reefs, mountain ecosystems, coastal wetlands, tundra, and polar areas (**Figure 20.9**).

Coral reefs are systems that include the corals, symbiotic organisms living within the reefs, and other organisms, including fish, that live, eat, and reproduce around the reefs (**Figure 20.10a**). Corals are impacted by climate change in two ways: acidification and temperature increases. The ocean absorbs about half of the CO_2 released into the atmosphere by human activities. This moderates the CO_2 in the atmosphere; if the ocean were not acting as a sink for CO_2, warming would be much more severe now than it is. However, CO_2 reacts with water to form carbonic acid, H_2CO_3. As more and more CO_2 is absorbed, it has made the ocean more acidic. Many organisms, such as corals, shellfish, and plankton, incorporate $CaCO_3$ into their protective shells, a chemical process that is sensitive to acidity.

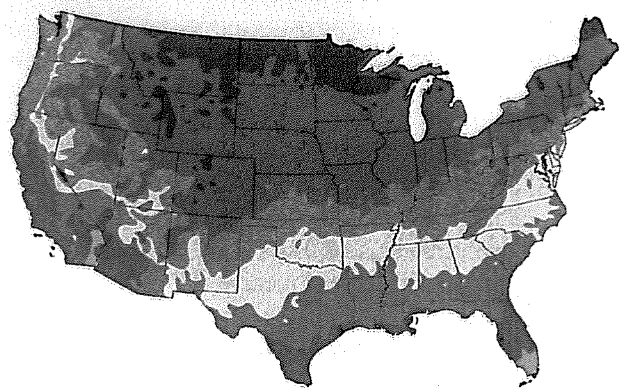
Temperature-related coral bleaching occurs when water temperature exceeds a threshold, affecting the coral symbiotes and making them and the corals more susceptible to disease-causing organisms that healthy corals are normally resistant to (**Figure 20.10b**). Increased acidity exacerbates this effect—two parts of the delicately balanced ocean system change at once. The IPCC predicts that with a 2°C (3.6°F) increase in global mean annual temperature, most corals worldwide will experience bleaching, with widespread coral mortality occurring above an increase of 3°C (5.4°F). In 1998, scientists documented the most geographically extensive and severe epidemic of coral bleaching ever observed. About 10% of the world's corals died that year, in many cases from viral, bacterial, or fungal infections. (Coral bleaching is also discussed in Chapter 6.)

Biologists generally agree that global climate change will have an especially severe impact on plants because they cannot move about when environmental conditions change. Although wind and animals disperse seeds, sometimes over long distances, limits in seed dispersal rates can limit the speed of migration. During past climate warmings, such as during the glacial retreat that took place some 12,000 years ago, analysis of tree pollens indicates that species were able to migrate at rates of only 4 to 200 km (2.5 to 124 mi) per century.

If Earth warms the projected 1.8 to 4.0°C (3.2 to 7.2°F) during the 21st century, the ideal ranges for some temperate tree species (i.e., the environment where they grow the best) may shift northward as much as about 500 km (about 300 mi). The U.S. Department of Agriculture reports hardiness zones, based on the average low temperature in an area, to determine which plants will do well around the country. By 2006, these zones had shifted enough that they had to be updated—the first time that an update had been necessary (**Figure 20.11**). Moreover, soil characteristics, water availability, competition with other plant species, and habitat fragmentation will affect the rate at which plants can move into a new area.

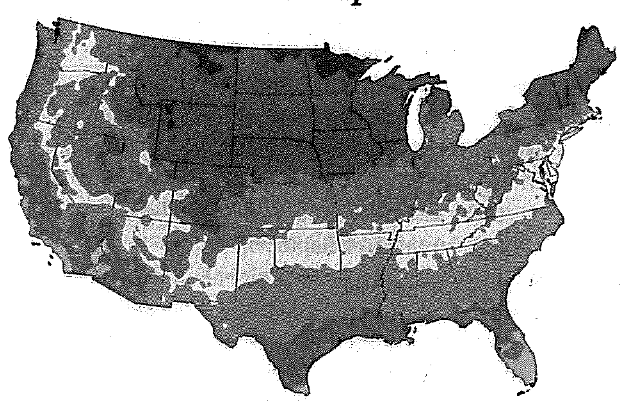
Some species will come out of global climate change as winners, with greatly expanded numbers and range. Those organisms considered most likely to prosper include certain weeds, insect pests, and disease-carrying organisms common in a wide range of environments. A 3°C (5.4°F) increase in average surface temperature, for example, could allow the Mediterranean fruit fly, an economically important insect pest, to expand its range into northern Europe.

1990 Map



After USDA Plant Hardiness Zone Map, USDA Miscellaneous Publication No. 1475, Issued January 1990.

2006 Map



National Arbor Day Foundation Plant Hardiness Zone Map published in 2006.

Zone

2 3 4 5 6 7 8 9 10

Figure 20.11 U.S. Department of Agriculture/National Arbor Day Foundation hardiness zones, 1990 and 2006. In 1990, the U.S. Department of Agriculture published a "Plant Hardiness Zone Map" for farmers and gardeners to identify which plants were best suited to their locations. Climate change necessitated an updated map in 2006. A few places have become colder, but shifts to more heat-tolerant plants have been necessary in many others. Has the hardiness zone changed where you live? (Courtesy USDA and National Arbor Day Foundation).

EFFECTS ON HUMAN HEALTH

Although the precise extent to which climate change contributes to adverse health effects is uncertain, it is clear that climate change can significantly impact human health and will have an increasing effect in the future. The relationships between human health and climate work at the systemic level and are both complex and inseparable. Some immediate health impacts are clear—for example, the 2010 heat wave in Russia resulted in around 15,000 deaths and cost the country as much as $15 billion in lost GDP. Most of the health effects associated with climate change are indirect and have multiple, interrelated causes; people in Russia are less prepared for multiple days of extreme heat than are residents of Nevada or Saudi Arabia.

Climate warming has also affected human (and animal) health indirectly. The ranges of mosquitoes and other disease carriers have expanded to the newly warm areas and could, in the absence of other limiting factors, spread malaria, dengue fever, schistosomiasis, and yellow fever, as well as livestock diseases such as bovine brucellosis. Changes in temperature and precipitation could increase certain food and waterborne diseases (see Chapter 7). Warmer winters could actually reduce the rates of some respiratory diseases (like the flu), but shifting of human populations into cities could counteract this effect. Also, local changes in soil ecology, humidity, and other physical factors could affect the range and prevalence of fungi, molds, and mildew. **Table 20.2** summarizes some observed and possible impacts of climate change on diseases in North America.

EFFECTS ON AGRICULTURE

Agriculture, as demonstrated in Chapter 18, is a carefully manipulated ecological system. Consequently, the impacts of global climate change on agriculture are difficult to anticipate. Agricultural productivity could increase because higher levels of CO_2 in the atmosphere could allow a higher rate of photosynthesis. However, many interacting factors are at work. How will growing seasons change? Will certain pests become more or less of a problem? How many of the types of crops traditionally grown in a given area have to change?

The rise in sea level may cause water to inundate river deltas, which are some of the world's best agricultural lands. Certain agricultural pests and disease-causing organisms will probably proliferate and reduce yields. Scientists think global climate change will increase the frequency and duration of droughts, a problem that will be particularly serious for countries with limited water resources. It is likely that warmer temperatures will result in decreases in soil moisture in many agricultural soils (warmer temperatures cause increased evaporation).

Another effect of climate warming on agriculture involves nighttime temperatures, which have generally increased more than daytime temperatures since 1950, when measurements began. Changing nighttime temperatures will have positive effects on some crops, but others—like tomatoes, which set their fruit only if nighttime temperatures go below a certain level—will become more difficult to grow. Other crops that require cool summers and/or winter freezes include blueberries, sugar maples, apples, and broccoli.

In 1999, a study at the National Science Foundation's Long-Term Ecological Research Site in Colorado linked warmer nighttime temperatures to changes in the types and distribution of grasses on the prairie. Most notably, weeds and nonnative grasses have largely replaced buffalo grass, an important food for cattle and other livestock. Range scientists point out that buffalo grass can withstand continuous grazing, but the invading plants replacing buffalo grass may be more sensitive to grazing pressures.

Table 20.2 Some Known and Expected Effects of Climate Change on Human Diseases

Type of Disease	*Known Effects*	*Predicted Effects*
Vector-borne* disease (e.g., Lyme disease, malaria)	Warming-related expansion or shift of geographic range of disease vector. Precipitation-related expansion or shift of geographic range. Travel-related risk of disease. Changes in temperature, precipitation could lead to major ecosystem shifts, impacting disease burden and incidence.	Increased transmission of some diseases transmitted from animals to humans. Establishment of novel imported infectious diseases. Regional variability in changes; some areas will be impacted more than others.
Water- and food-borne disease (e.g., *E. coli*, *Salmonella*)	Temperature-related increase in survival of disease organisms. Precipitation-related shifts in geographic range of disease organisms. Increased temperature expected to shift northernmost tolerance of many diseases.	Increased intensity and frequency of water- and food-borne diseases, particularly in the northernmost parts of the United States and Canada.
Respiratory disease (e.g., influenza, *Streptococcus bacillus*)	Shorter/warmer winter could reduce disease incidence and burden. Migration of nonimmune populations to areas with endemic disease increases incidence. Air pollution changes could cause/exacerbate disease.	Reduced number of respiratory diseases with cold weather.** Increased respiratory diseases associated with dense populations.** Increased respiratory diseases associated with diminished air quality.**
Fungal diseases (e.g., *Blastomyces dermaditis*, *Cryptococcus gatti*)	Soil ecology changes could shift range of fungus populations. Warm, dry summers followed by warm, wet winters could increase fungus counts. Changes in temperature, precipitation, and humidity could expand geographic range of some fungi	Growing conditions that favor infectious fungal spores. Regional variability in changes of numbers and types of fungi.

*Vectors are the animals that carry a disease organism or a stage of a disease organism. Mosquitoes are a common vector, but many diseases require a mammalian vector (e.g., fox, deer, rat).
**It is not clear which of these effects will dominate.
Source: Greer, Ny, and Fisman, "Climate Change and Infectious Diseases in North America: The road ahead, *Canadian Medical Association Journal* (2008).

Ecologists suggest that such changes in the structure and dynamics of rangeland ecosystems worldwide could have a profound effect on livestock production.

On a regional scale, current models forecast that with modest warming, agricultural productivity will increase in some areas and decline in others. Canada and Russia may be able to increase their agricultural productivity in a warmer climate, whereas tropical and subtropical regions, where many of the world's poorest people live, will be hardest hit by declining agricultural productivity. Central America and Southeast Asia may experience some of the greatest declines in agricultural productivity.

In addition to these expected impacts of climate warming on agriculture, modern, energy-intensive agricultural methods may have to be altered so that they are less reliant on CO_2–producing fossil fuels (see Chapter 18). The manufacture of fertilizers, pesticides, and other agricultural chemicals requires a huge input of energy from fossil fuels, as does the production and use of modern farm equipment.

Climate-induced changes to agriculture will require cultural, economic, and infrastructure adaptation. Some farmers will do much better, while others will no longer be able to compete. The agriculture-related fraction of GDP will go up in some countries and down in others. The types of crops that do well—and therefore the diets of many people—will change. The extent to which such adaptation can keep pace with climate change is uncertain.

INTERNATIONAL IMPLICATIONS OF GLOBAL CLIMATE CHANGE

Dealing with global climate change is complicated by social, economic, and political factors that vary from one country to another. How will the global community deal with the environmental refugees of global climate change, such as those who might be affected by extreme weather events that lead to agricultural failures? Where will they go? Who will help them resettle? It will be difficult for all countries to develop a consensus on dealing with global climate change, partly because it will clearly have greater impacts on some nations than on others. All major nations must cooperate if we are to effectively address global climate change and its impacts.

Although highly developed countries are the primary producers of greenhouse gases, the rate of production by certain developing countries is rapidly increasing (even though their per capita emissions remain well below those for highly developed countries). In 2007, China surpassed the United States as the largest single contributor of CO_2, although the per capita rate in the United States remains about three times that of China. Furthermore, although highly developed countries have huge amounts of coastal infrastructure at risk, many developing countries may experience the greatest impacts of global climate change: Because developing countries have less technical expertise and fewer economic resources, they are least likely to be able to respond to the challenges of global climate change.

As the economies of developing countries progress, they are likely to follow the path of industrialized countries and consume more fossil fuels—and emit more greenhouse gases. Most of the increase in emissions would be a direct result of providing basic human needs for increasing populations. Because of their rapid population growth, developing countries are predicted to release higher levels of greenhouse gases than industrialized nations by 2020. This scenario may not unfold exactly as projected because some developing countries—such as China, India, Mexico, Saudi Arabia, South Africa, and Brazil—are making progress toward controlling greenhouse gas emissions.

Efforts to reduce carbon emissions include increasing energy efficiency, limiting fossil-fuel use, and developing alternative energy programs. Increased control of greenhouse gas emissions in developing countries may not be the result of specific climate change policies; instead, this may be a secondary benefit of these nations' efforts to meet their own social, economic, and health needs. Air pollution arising from the use of fossil fuels creates serious public health problems in developing countries, so curbing fossil-fuel consumption creates healthier living conditions locally while improving global air quality.

Highly developed and developing countries have different interests, needs, and perspectives. Most developing countries see increased use of fossil fuels as their route to industrial development and resist pressure from highly developed countries to decrease fossil-fuel consumption. Developing countries often ask why they should have to take actions to curb CO_2 emissions when the rich industrialized nations historically have been the main cause of the problem. Since 1950, the 20% of the world's population living in highly developed countries have produced 74% of the CO_2 emissions. Currently, highly developed countries produce about 10 times more CO_2 emissions per person than developing countries (**Figure 20.12**). Highly developed countries counter that the booming economic growth and much greater number of people living in developing countries will dominate global carbon production in the near future.

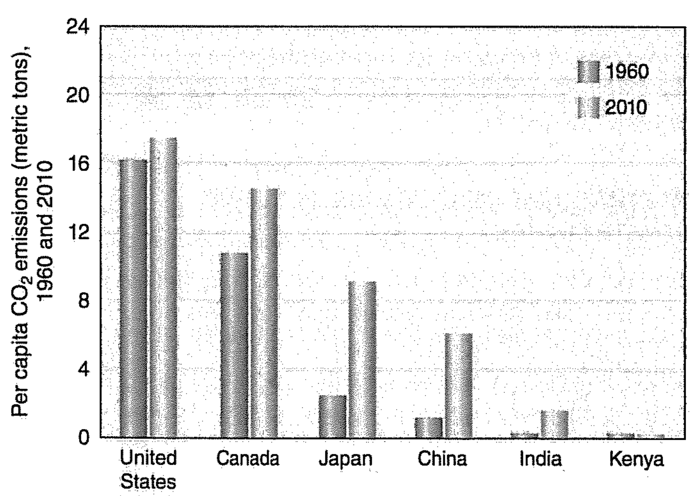


Figure 20.12 Per capita carbon dioxide (CO_2) emission estimates for selected countries, 1960 and 2010. For each country, the column on the left is the 1960 value and the column on the right is the 2010 value. In all cases except Kenya, per capita CO_2 emissions have grown. Currently, industrialized nations produce a disproportionate share of CO_2 emissions. As developing countries such as China and India industrialize, however, their per capita CO_2 emissions increase. China's per capita use has more than quadrupled in the past five decades. (World Bank)

LINKS AMONG GLOBAL CLIMATE CHANGE, OZONE DEPLETION, AND ACID DEPOSITION

Environmental studies often examine a single issue, such as global climate change, acid deposition, or ozone depletion (see Chapter 19). Canadian researchers at the Experimental Lakes Area in Ontario, Canada, decided to take a different approach and explore the interactions of all three environmental problems simultaneously. They reported that organisms in North American lakes may be more susceptible to damage from ultraviolet (UV) radiation than the thinning of the ozone layer would indicate. The combined effects of acid deposition and climate warming may increase how far UV radiation penetrates lake water. Some of the possible effects of increased UV penetration are to disrupt photosynthesis in algae and aquatic plants and to cause sunburn damage (skin lesions) in fishes.

How far UV radiation penetrates lake water is related to the presence of dissolved organic compounds. This organic material, which is present even in the clearest, least polluted lakes, comes from the decomposition of dead organisms. Dissolved organic material acts like a sunscreen, absorbing UV radiation so that it penetrates only a few inches into the water.

A warmer climate increases evaporation, which reduces the amount of water flowing into a lake from the surrounding watershed. Because most of a lake's dissolved organic compounds wash into the lake in the stream flow, even a slightly drier climate reduces how much organic material is present in the lake. Therefore, UV radiation penetrates deeper into the lake as a result of climate warming.

Acid deposition also affects the amount of dissolved organic compounds in a lake. The presence of acid causes organic matter to clump and settle on the lake floor. The removal of organic material from the water allows UV radiation to penetrate farther.

REVIEW

1. How do melting ice and thermal expansion of water contribute to sea-level rise?
2. How has climate change impacted precipitation? What other future precipitation changes do we expect?
3. What are some effects of climate change already experienced by organisms, including humans?

Dealing with Global Climate Change

LEARNING OBJECTIVES

- Define *mitigation* and *adaptation* and provide some examples of each.
- Explain why reducing greenhouse gas emissions requires international efforts.

Our understanding of the changing global climate and its potential impact on human society and other species gives us many legitimate reasons to develop strategies to deal with this problem. Even if we immediately stopped greenhouse gas emissions (which we cannot do, given the importance to society of the energy associated with them), global temperature would continue increasing for several decades. Sea levels would continue to rise for centuries as the Earth's climate system adjusts to the influences of the greenhouse gases that have accumulated during the past two centuries. For the same reasons that the global climate system is slow to respond to increases in greenhouse gas concentrations, it will be slow to respond even if emissions are stopped quickly.

Although stopping climate change will require that we deal with all greenhouse gases, our focus will be on CO_2 because it is produced in the greatest quantities and has the largest influence (about 60%) of all the greenhouse gases. The increase in the CO_2 level caused by human activities will persist for centuries, so the emissions we are producing today will still be around in the 22nd century and beyond. The amount and severity of global climate change that will be left to future generations are thus directly related to the amount of additional greenhouse gases we add to the atmosphere during our lifetimes.

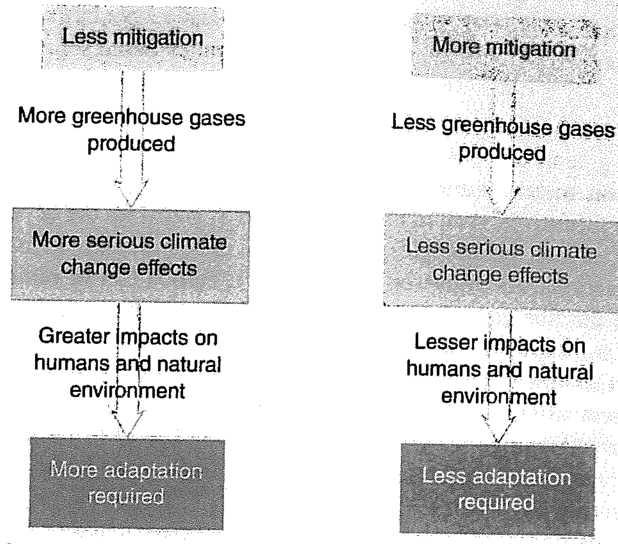
To avoid the most dangerous consequences of climate change, many studies indicate that the atmospheric CO_2 concentration needs to be stabilized at 550 ppm. This is roughly twice the concentration of atmospheric CO_2 that scientists estimate existed in the preindustrial world and only about 40% higher than the current CO_2 concentration.

There are two basic ways to manage global climate change: mitigation and adaptation (**Figure 20.13**). **Mitigation** focuses on limiting greenhouse gas emissions to moderate or postpone global climate change, thus buying time to pursue solutions that stop or reverse the change. **Adaptation** focuses on learning to live with the environmental changes and societal consequences brought about by global climate change.

tigation An action tions that diminish e causes of climate ıge, thereby reduc-ıg the rate at which climate changes.

ıptation Prepara-y actions that help ımans tolerate the fects of a changing climate.

Although some people have objected to the development of strategies to adapt to climate change because they feel this implies an acceptance that global climate change is certain, the widespread observations that the climate is changing make it clear that adaptation will be unavoidable. What is unclear is which changes we can and will prepare for, and which we will need to react to. How we deal with climate change is a decision with multigenerational consequences.



(a) If we make fewer efforts to mitigate climate change, we will have to adapt to more serious problems that impact food and water resources, biological diversity, and human health.

(b) If we take aggressive mitigation measures, the long-range changes in climate will be less and have less serious impacts on humans and the natural environment.

Figure 20.13 Relationship between mitigation and adaptation.

MITIGATION OF GLOBAL CLIMATE CHANGE

Because global warming is essentially a consequence of the choices that are made in the generation and use of energy, alternatives to fossil fuels have the potential to eventually halt the warming caused by CO_2 emissions. Alternatives to petroleum and natural gas (but not coal) are also likely to become necessary over coming decades because these fuels are present in limited amounts. Energy efficiency and conservation, discussed in Chapter 10, could help address a significant part of the climate change problem. Many alternatives to fossil fuels, including solar, nuclear, and wind energy, were discussed in Chapter 12.

Many studies indicate that energy use and greenhouse gas emissions can be significantly reduced with little cost to society by adopting the best currently available technologies and implementing certain policies to encourage their use. For example, increasing the efficiency of automobiles and appliances would reduce the use of fossil fuels and the output of CO_2. In California, regulatory programs that increase minimum energy-efficiency standards for appliances and buildings have cut per capita electricity use to half the U.S. average. The higher price of gasoline has led consumers to want cars with increased gas mileage, which carmakers have proven they can make profitably, as shown by the rising sales of hybrid vehicles.

Energy-pricing strategies, such as carbon taxes and the elimination of energy subsidies, are other policies that could help lead to reductions in emissions. A carbon tax could be levied on fossil fuels, based on the proportion of CO_2 emissions produced per unit of heat released when the fuel is burned (see Chapter 2). Because coal is carbon-intensive, it would have the highest carbon taxes of all fossil fuels. Alternatively, a *cap and trade* system, which limits the total amount of carbon worldwide but lets people buy and sell carbon emission rights, would be an economics-based solution.

Carbon Capture and Storage In addition to taking steps to curb greenhouse gas emissions, many countries are investigating **carbon management**, ways to capture and store CO_2. Government incentives, such as providing research grants for the development of such technologies, most likely will be necessary to inspire innovations. As discussed in Chapter 11, carbon can be removed from the flue gases of coal-fired power plants, although this is a new and expensive technology.

Carbon capture and storage (CCS), also called **carbon sequestration**, would require a dramatic shift in where fossil fuels are used. Trying to remove the CO_2 from the engine in a gasoline-powered car or diesel train would be a huge logistical challenge: Capturing CO_2 is difficult, and transporting CO_2 as a gas or as calcium carbonate ($CaCO_3$) to some separate location would require additional energy. Most proposals for CCS involve generating electricity or hydrogen at a fixed location where the CO_2 can most easily be captured.

Sequestering Carbon in Trees One way to mitigate global climate change involves removing atmospheric carbon dioxide from the air by planting and maintaining forests (recall the chapter introduction). Like other green plants, trees incorporate the carbon into organic matter in leaves, stems, and roots through the process of photosynthesis. Because trees typically live for 100 or more years, the carbon in their roots and stems remains sequestered away from the atmosphere for a relatively long time. Although estimates vary widely, planting trees could probably remove 10% to 15% of the excess CO_2 in the atmosphere; to do so would require enormous plantings. Scientists who have studied sequestering carbon in trees think this proposal might provide short-term benefits for the climate, although it is no substitute for cutting emissions of greenhouse gases.

Geoengineering Considerable controversy surrounds the idea of using **geoengineering** to mitigate climate change. Geoengineering refers to projects that take place on a global scale. Some possibilities include seeding the ocean with iron to allow more carbon to be taken up by algae, building devices that extract massive amounts of carbon from the atmosphere, and ejecting sulfur particles into the atmosphere to reflect sunlight. One of the biggest concerns is that it is difficult to predict the efficacy of such large-scale projects, and they might either not succeed or cause unintended consequences. Proponents of geoengineering argue that the rapid rise in greenhouse gases was caused by humans and is thus an example of geoengineering and that a human intervention of an equivalent scale is appropriate.

ADAPTATION TO GLOBAL CLIMATE CHANGE

Because the overwhelming majority of climate experts think that significant human-induced global climate change is inevitable (the only question being how significant), government planners and social scientists are developing strategies to help various regions and sectors of society adapt to climate warming. One of the most pressing issues is rising sea level. People living in coastal areas could be moved inland, away from the dangers of storm surges. These people would become **climate change refugees**, people forced by climatic change to abandon their homes. This solution would have high societal and economic costs, especially given the increasing fraction of the population living near the ocean. Another alternative is the construction of dikes and levees to protect coastal land—an expensive option, but perhaps less so than relocating the people protected by such constructions. Rivers and canals that spill into the ocean would have to be channeled to prevent saltwater intrusion into fresh water and agricultural land.

We will also need to adapt to shifting agricultural zones. Many countries with temperate climates are evaluating semitropical crops to determine the best substitutes for traditional crops as the climate warms. Large lumber companies are currently developing drought-resistant strains of trees. Trees planted today will be harvested in the last half of the 21st century, when global climate change may be well advanced.

Adaptation to global climate change is currently under study at locations around the United States. Study groups typically consist of scientists and various representatives of municipal governments, state and federal agencies, local businesses, and community organizations. One of the potential problems identified in the New York City study group involves its sewer system. The waterways for storm runoff normally close during high tides to prevent salt water from the Atlantic Ocean from backing into the system. As the sea level rises in response to global climate change, the waterways will have to be shut during many low tides, which will greatly increase the risk of flooding during storms. (When the waterways are closed, excess water does not drain away.) City planners will have to rebuild the storm runoff system, which is an expensive proposition, or find some other way to prevent flooding. Evaluating such problems and finding and implementing solutions now will ease the future stresses of climate change.

INTERNATIONAL EFFORTS TO REDUCE GREENHOUSE GAS EMISSIONS

Despite all the posturing, the international community recognizes that it must stabilize CO_2 emissions. At least 192 nations, including the United States, have now signed the UN Framework Convention on Climate Change (UNFCCC) developed at the 1992 Earth Summit. Its ultimate goal was to stabilize greenhouse gas concentrations in the atmosphere at levels low enough to prevent dangerous human influences on the climate. The details of how that goal was to be accomplished were left to future conferences.

At the 1996 meeting of the parties to the UNFCCC held in Geneva, Switzerland, highly developed countries agreed to establish legally binding timetables to cut emissions of greenhouse gases. These timetables were decided at a meeting of representatives from 160 countries held in Kyoto, Japan, in 1997. By 2014, 192 countries had ratified the resulting **Kyoto Protocol**. This international treaty, which is legally binding, provides operational rules on reducing greenhouse gas emissions.

The U.S. government is involved in ongoing national and international climate policy activities. It supports a continuation of UNFCCC negotiations. Within the United States, policy is being driven by the administration's commitment to reducing greenhouse gases. In 2007, the Supreme Court ruled in *Massachusetts v. EPA* that greenhouse gases are covered under the Clean Air Act as an air pollutant, and in June 2014, the Obama administration established regulations for emissions from all coal-fired power plants.

REVIEW

1. What are some examples of mitigation and adaptation?
2. How do perspectives on climate change of highly developed countries differ from those of less developed countries?

REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Explain radiative forcing, greenhouse gases, and the enhanced greenhouse effect.**

Radiative forcing is the capacity of a gas to affect the balance of energy that enters and leaves the atmosphere. **Greenhouse gases** are the gases in Earth's atmosphere that absorb **infrared radiation.** The **enhanced greenhouse effect** is the additional warming produced by increased levels of gases that absorb infrared radiation (heat). The Intergovernmental Panel on Climate Change concluded in 2007 that human-produced greenhouse gases are the most likely cause of recent climate warming and that the world will almost certainly warm substantially during the 21st century.

- **Explain how climate models project future climate conditions.**

Climate models are computer models that describe the global climate as a system. The models divide the atmosphere and oceans into small, three-dimensional parts and evaluate the effects of changes in one part on adjacent parts. These models incorporate feedbacks that influence such factors as temperature, wind patterns, cloud moisture, and ice cover. Running these models based on different predicted levels of CO_2 leads to projections of possible future climate conditions. Models include **positive feedback**, in which a change in some condition triggers a response that intensifies the changed condition, and **negative feedback**, in which a change in some condition triggers a response that moderates the changed condition.

- **Describe the importance of extreme and unpredictable climate change.**

While we often look at expected results of climate models, the extreme or worst-case scenarios are often of much greater concern. Unpredictable changes are perhaps more problematic. It is almost certain that there will be surprises—things we cannot predict. But not knowing what the surprises will be makes it impossible to prepare for or mitigate them. The only way to avoid such surprises is to eliminate climate change.

- **Differentiate between sea-level rise due to melting ice and that due to the thermal expansion of water.**

More than half of recent and projected sea-level rise is associated with the fact that water expands as it heats up; this is known as **thermal expansion**. How quickly the ocean absorbs increased atmospheric heat will significantly influence the rate of sea-level rise. Melting of glaciers and land-based ice sheets is the other major contributor to sea-level rise, as water previously "stored" on land shifts to the ocean.

- **Describe how climate change impacts the physical environment.**

Globally, average ocean and land surface temperatures are increasing, although effects at individual locations can vary. Precipitation and other weather patterns have begun to shift, with increased flooding in some locations and increased intensity of tropical storms. Ice sheets and glaciers are melting. All of these phenomena are expected to intensify in the future.

- **Give examples of effects of climate change on organisms, including humans.**

Globally, organisms are affected by changes in temperature, precipitation, ocean acidification, sea-level rise, and other climate change–related effects. They are also affected by changes in other populations—for example, some organisms react more to the early arrival of spring than do others, which means that food webs can be disrupted. Humans are affected by heat waves, flooding, and sea-level rise, as well as changes to agriculture.

- **Define *mitigation* and *adaptation* and provide some examples of each.**

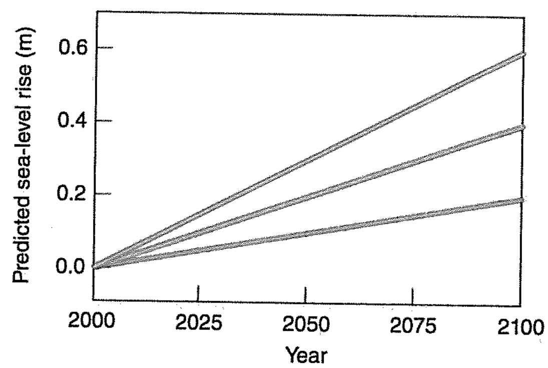
Mitigation is an action or actions that diminish the causes of climate change. Examples include burning less oil, natural gas, and coal; planting trees; and sequestering carbon dioxide. **Adaptation** consists of preparatory actions intended to diminish the effects of a changing climate. Examples include moving people away from shorelines and changing agricultural practices.

- **Explain why reducing greenhouse gas emissions requires international efforts.**

Climate change has global impacts. Reducing carbon emissions and adapting to a changed climate cannot succeed when only a few countries participate. One concern is that, in the short term, a country with strict CO_2 restrictions will be at a competitive disadvantage compared to a country without such restrictions. Thus, having international commitments may be necessary for success in any location.

Critical Thinking and Review Questions

1. One of Socolow and Pacala's wedges (see the introduction) involves reducing the number of miles driven by each car by 50% (they predict 2 billion cars worldwide by 2056). Considering what you know about how people drive now, how could people reduce their driving by 50%? How would this affect their lives?
2. How do greenhouse gases affect global climate conditions?
3. What are climate models? What inputs are used when building them? What can they tell us about future climate?
4. What two factors contribute to sea-level rise?
5. What effect has increased evaporation due to climate change had on regional weather patterns?
6. Austrian biologists who study plants growing high in the Alps found that plants adapted to cold mountain conditions migrated up the peaks as fast as 3.7 m (12 ft) every decade during the 20th century, apparently in response to climate warming. Assuming that warming continues during the 21st century, what will happen to the plants if they reach the tops of the mountains?
7. Suggest some ways in which seasonal changes in plant growth in Canada might affect songbird populations in Mexico.
8. What aspects of adaptation to global climate change would be easier for highly developed countries? For developing countries? Explain.
9. Based on what you've read in this chapter and the information on environmental economics in Chapter 2, explain how a global market for CO_2 permits might function.
10. Insurance companies that provide policies for hurricanes and other natural disasters may shift hundreds of millions of dollars of their investments from fossil fuels to solar energy. On the basis of what you have learned in this chapter, explain why insurance companies would consider such an investment in their best interest.
11. Some environmentalists contend that the wisest way to "use" fossil fuels is to leave them in the ground. How would this affect air pollution? Global climate change? Energy supplies?
12. What do the relationships among acid deposition, stratospheric ozone, and climate change tell us about the importance of thinking about the environment as a system?
13. **John Holdren**, science advisor to President Obama, argues that there are three possible human responses to climate change: mitigation, adaptation, and suffering. Discuss the implications of this for people today and people 50 years from now.
14. Sea level is expected to rise about 0.4 m (1.3 ft) by 2100 (the blue line in the figure below). However, the prediction is uncertain; different models suggest that we can expect anywhere from 0.2 m (green line) to 0.6 m (red line). Which, if any, of these increases should we prepare for? Explain your choice.



Food for Thought

The U.S. Department of Agriculture Hardiness Zones maps are likely to be updated again soon, and further shifts are expected. Consider foods that are currently produced by small farms and home gardeners in your area. How will their choices of what to grow change? What might disappear from your local farmers market? What will replace it? Will this impact your food choices?