19 Climate Change and Ozone Depletion

CORE CASE STUDY Studying a Volcano to Understand Climate Change

In June of 1991, after 600 years of slumber, Mount Pinatubo in the Philippines exploded (Figure 19-1). A huge amount of volcanic material blasted out of the mountain, sending a cloud of air pollutants and ash to a height of 35 kilometers (22 miles). Avalanches of hot gases and ash roared down the sides of the mountain, killing hundreds of people and filling valleys with volcanic deposits. It was the second-largest volcanic eruption of the 20th century. (The largest took place in Alaska in 1912.)

Rick Hoblitt/U.S. Geological Service

Figure 19-1 An enormous cloud of air pollutants and ash rises above Mount Pinatubo in the Philippines on June 12, 1991. The volcano exploded in a catastrophic eruption, killing hundreds. Sulfur dioxide and other gases emitted into the atmosphere by the eruption circled the globe, polluted the air, reduced sunlight reaching the earth's surface, and cooled the atmosphere for 15 months.

Besides killing many people, the eruption of Mount Pinatubo destroyed homes and farmland, and caused hundreds of millions of dollars in damage. At the same time, it enabled scientists to test whether they understood the global climate well enough to estimate how the eruption would affect temperatures on the earth.

By the late 1980s, most of the world's climate scientists had become concerned that human actions, especially fossil fuel use, were enhancing the world's natural greenhouse effect and contributing to a rise in the average temperature of the atmosphere, which in turn would begin changing the earth's climate. Some stated publicly that climate change from such global warming was very likely to occur and could have disastrous ecological and economic effects. Their concerns were based in part on results from computer models of the global climate. But were these models reliable?

Although their complex global climate models mimicked past and present climates well, Mount Pinatubo provided them with an opportunity to perform a more rigorous test of such models. Soon after the volcano erupted, James Hansen, a leading U.S. National Aeronautics and Space Administration (NASA) scientist, estimated that the Pinatubo explosion would probably cool the average temperature of the earth by 0.5 C° (1 F°) over a 19-month period. The earth would then begin to warm, Hansen said, and by 1995 would return to the temperatures observed before the explosion. His projections turned out to be correct.

To make his forecasts, Hansen added the estimated amount of sulfur dioxide released by the volcano's eruption to a global climate model and then used the model to forecast how the earth's temperature would change. His model passed the test with flying colors. Its success helped to convince most scientists and policy makers that climate model projections—including those relating to the impact of human actions—should be taken seriously.

Hansen's model and 18 other climate models indicate that global temperatures are likely to rise several degrees during this century—mostly because of human actions—and to affect global and regional climates and economies and human ways of life. To many scientists and a growing number of business executives, global climate change represents the biggest challenge that humanity faces during this century. The primary question is, "What should we do about it?"

Key Questions and Concepts

19-1 **How might the earth's temperature and climate change in the future?**

CONCEPT 19-1 The overwhelming scientific consensus is that the earth's atmosphere is warming rapidly, mostly because of human activities, and that this will lead to significant climate change during this century.

19-2 **What are some possible effects of a warmer atmosphere?**

CONCEPT 19-2 The projected rapid change in the atmosphere's temperature during this century is very likely to increase drought and flooding, shift areas where food can be grown, raise sea levels, result in intense heat waves, and cause the premature extinction of many species.

19-3 **What can we do to slow climate change?**

CONCEPT 19-3A To slow the rate of global warming and climate change, we can increase energy efficiency, sharply reduce greenhouse gas emissions, rely more on renewable energy resources, and slow population growth.

CONCEPT 19-3B Governments can subsidize energy efficiency and renewable energy use, tax greenhouse gas emissions, set up cap-and-trade emissions reduction systems, and help to slow population growth.

19-4 **How have we depleted ozone in the stratosphere and what can we do about it?**

CONCEPT 19-4A Widespread use of certain chemicals has reduced ozone levels in the stratosphere, which allows for more harmful ultraviolet radiation to reach the earth's surface.

CONCEPT 19-4B To reverse ozone depletion, we must stop producing ozone-depleting chemicals and adhere to the international treaties that ban such chemicals.

Note: Supplements 2 (p. S4), 3 (p. S10), 4 (p. S20), 6 (p. S39), 8 (p. S47), 10 (p. S59), and 13 (p. S78) can be used with this chapter.

Civilization has evolved during a period of remarkable climate stability, but this era is drawing to a close. We are entering a new era, a period of rapid and often unpredictable climate change. The new climate norm is change.

LESTER R. BROWN

19-1 How Might the Earth's Temperature and Climate Change in the Future?

▶ **CONCEPT 19-1 The overwhelming scientific consensus is that the earth's atmosphere is warming rapidly, mostly because of human activities, and that this will lead to significant climate change during this century.**

Global Warming and Global Cooling Are Not New

Changes in the earth's climate are neither new nor unusual. Over the past 4.5 billion years, the planet's climate has been altered by volcanic emissions (**Core Case Study**), changes in solar input, continents moving slowly atop shifting tectonic plates (Figure 4-6, p. 85, and **Concept 4-3**, p. 84), impacts by large meteors, and other factors.

CORE CASE STUDY

CONCEPT LINK

Over the past 900,000 years, the atmosphere has experienced prolonged periods of *global cooling* and *global warming* (Figure 19-2, top left, p. 498). These alternating cycles of freezing and thawing are known as *glacial and interglacial* (between ice ages) *periods.*

For roughly 10,000 years, we have had the good fortune to live in an interglacial period characterized by a fairly stable climate and a fairly steady average global surface temperature (Figure 19-2, bottom left). These conditions allowed agriculture, and then cities to flourish, as the human population grew.

For the past 1,000 years, the average temperature of the atmosphere has remained fairly stable but began rising during the last century (Figure 19-2, bottom right) when people began clearing more forests and burning more fossil fuels. Figure 19-2, top right, shows that most of the recent increase in temperature has taken place since 1975.

Past temperature changes such as those depicted in Figure 19-2 are estimated by analysis of radioisotopes in

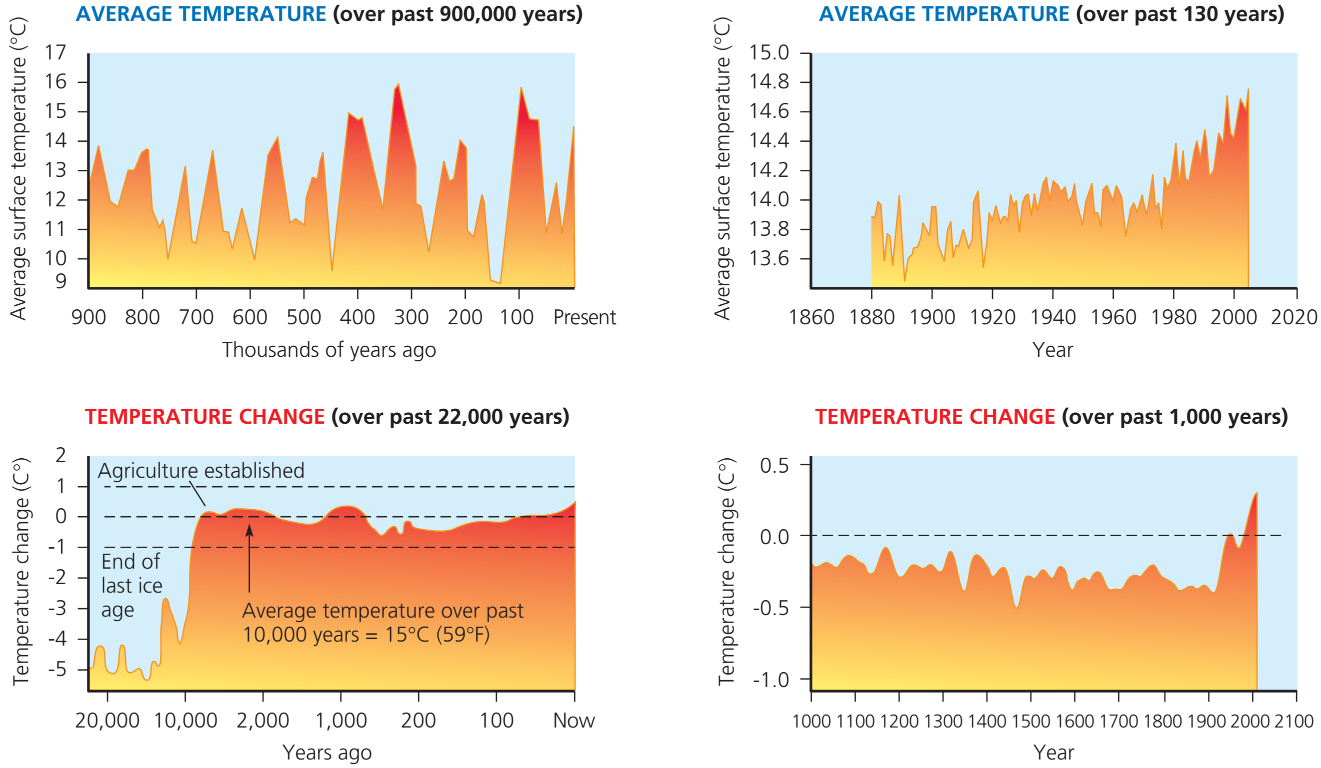


Figure 19-2 **Science:** estimated changes in the average global temperature of the atmosphere near the earth's surface over different periods of time. The graphs in this figure are rough estimates of global average temperatures and temperature changes based on limited evidence, but they do indicate general trends. **Question:** Assuming these estimates are correct, what are two conclusions you can draw from these diagrams? (Data from Goddard Institute for Space Studies, Intergovernmental Panel on Climate Change, National Academy of Sciences, National Aeronautics and Space Agency, National Center for Atmospheric Research, and National Oceanic and Atmospheric Administration)

U.S. Geological Survey

Figure 19-3 **Science:** *Ice cores* are extracted by drilling deep holes in ancient glaciers at various sites such as this one in Antarctica (the South Pole). Scientists analyze tiny air bubbles, layers of soot, and other materials trapped in different segments of such ice cores to uncover information about past composition of the lower atmosphere, temperature trends such as those shown in Figure 19-2, greenhouse gas concentrations, solar activity, snowfall, and forest fire frequency.

rocks and fossils; plankton and radioisotopes in ocean sediments; tiny bubbles of ancient air found in ice cores from glaciers (Figure 19-3); temperature measurements taken at different depths from boreholes drilled deep into the earth's surface; pollen from the bottoms of lakes and bogs; tree rings; historical records; insects, pollen, and minerals in different layers of bat dung deposited in caves over thousands of years; and temperature measurements taken regularly since 1861. Such measurements have limitations, but they show general changes in temperature, which in turn can affect the earth's climate. See *The Habitable Planet,* Video 12, at **www.learner.org/resources/series209.html** for a discussion of how scientists are analyzing ice cores from mountain glaciers to understand past climate change.

Our Climate, Lives, and Economies Depend on the Natural Greenhouse Effect

Along with solar energy, a natural process called the *greenhouse effect* warms the earth's lower atmosphere and surface (Figure 3-8, p. 56). It occurs when some of the solar energy absorbed by the earth radiates into the atmosphere as infrared radiation (heat). About 1% of the earth's lower atmosphere is composed of greenhouse gases, primarily water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Heat radiated into the atmosphere by the earth causes molecules of these greenhouse gases to vibrate and release infrared radiation with an even longer wavelength into the lower atmosphere. As this radiation interacts with molecules in the air, it increases their kinetic energy and warms the lower atmosphere and the earth's surface, which in turn affects the earth's climate.

Swedish chemist Svante Arrhenius first recognized the natural greenhouse effect in 1896. Since then, numerous laboratory experiments and measurements of temperatures at different altitudes have confirmed this effect—now one of the most widely accepted theories in the atmospheric sciences.

Life on the earth and the world's economies are totally dependent on the natural greenhouse effect—one of the planet's most important forms of natural capital. Without this natural greenhouse effect, the world would be a cold, uninhabitable place.

CENGAGE**NOW**™ See how greenhouse gases trap heat in the lower atmosphere and raise the earth's temperature at CengageNOW™.

Human Activities Emit Large Quantities of Greenhouse Gases

Since the beginning of the Industrial Revolution about 275 years ago, human actions have led to significant increases in the concentration of earth-warming, and thus climate-changing, CO_2, CH_4, and N_2O in the lower atmosphere. These increases came mainly from agriculture, deforestation, and burning of fossil fuels. Measurements of CO_2 and CH_4 in bubbles at various depths in ancient glacial ice (Figure 19-3) indicate that changes in the levels of CO_2 and CH_4 in the lower atmosphere correlate fairly closely with changes in the average global temperature near the earth's surface during the past 400,000 years, and with changes in the global sea level (Figure 19-4, p. 500).

Carbon dioxide levels are increasing exponentially at a rapid rate. For example, the atmospheric concentration of carbon dioxide emitted largely by burning fossil fuels has risen from a level of 280 parts per million at the start of the Industrial Revolution about 275 years ago to 384 parts per million in 2007 (see Figure 20, p. S71, in Supplement 10) and is increasing by about 2 parts per million each year.

According to a 2007 study by scientists Christopher Field and Gregg Marland, if CO_2 emissions continue to increase at the current exponential rate of about 3.3% a year, levels in the atmosphere will rise to 560 ppm by 2050 and soar to 1,390 ppm by 2100, bringing about significant changes in the earth's climate and causing major ecological and economic disruption in the latter half of this century. Scientific studies and models indicate that we should try to prevent CO_2 levels from exceeding 450 ppm—an estimated threshold, or irreversible *tipping point,* that could set into motion large-scale climate changes for hundreds to thousands of years. And according to climate expert James Hansen (**Core Case Study**), ideally we need to reduce the atmospheric concentration of CO_2 to 350 parts per million—which is below current levels—to help stabilize the earth's climate.

CORE CASE STUDY

In 2007, the largest CO_2 emitting countries were, in order, the United States, China, the European Union (with 27 countries), Indonesia, Russia, Japan, and India. The United States has been responsible for 25% of the world's cumulative CO_2 emissions, compared to China's 5% contribution. A 2007 study by Tao Wang and Jim Watson estimated that about one-fourth of China's rapidly rising CO_2 emissions are a result of its export trade to Europe and the United States. Without this demand for goods from industrialized nations, China's economy would not have developed so rapidly and its CO_2 emissions would not have risen so sharply.

In 2008, U.S. economists Maximillian Auffhammer and Richard Carson found that China's growth in emissions of CO_2 and other air pollutants was much greater than previously estimated. They found that some of China's more affluent provinces were building cleaner and more efficient coal-burning power plants. However, other provinces with fewer financial resources have been building polluting and less efficient coal-burning power plants by replicating inefficient 1950s Soviet technology. The problem is that once they are built, China and the rest of the world are stuck with these polluting plants throughout their 40- to 75-year lifetimes.

It is also important to compare the per capita emissions of CO_2 emitted by various countries, as shown in Figure 21, p. S71, in Supplement 10. Although China's total CO_2 emissions are high and growing rapidly, its per capita emissions are low. The United States emits about five times more CO_2 per person than China.

Ice core analysis also reveals that about 60% of methane emissions during the last 275 years are the result of human activities such as extracting fossil fuels, creating landfills, raising cattle and sheep (which belch methane), and constructing reservoirs behind large dams in tropical countries. Some good news is that methane emissions have leveled off since 1990, but they are expected to rise in the future as the atmosphere warms and melts some of the permafrost in the arctic tundra, which will release more methane into the atmosphere.

Nitrous oxide levels have risen about 20% during the last 275 years, mostly as a result of increased use of nitrogen fertilizers. A given volume of N_2O traps 3–10 times more heat than the same amount of CO_2 traps and accounts for about 9% of greenhouse gas emissions from human activities. Fertilizers and other sources of nitrogen have greatly increased nitrogen inputs into the environment (Figure 3-20, p. 70).

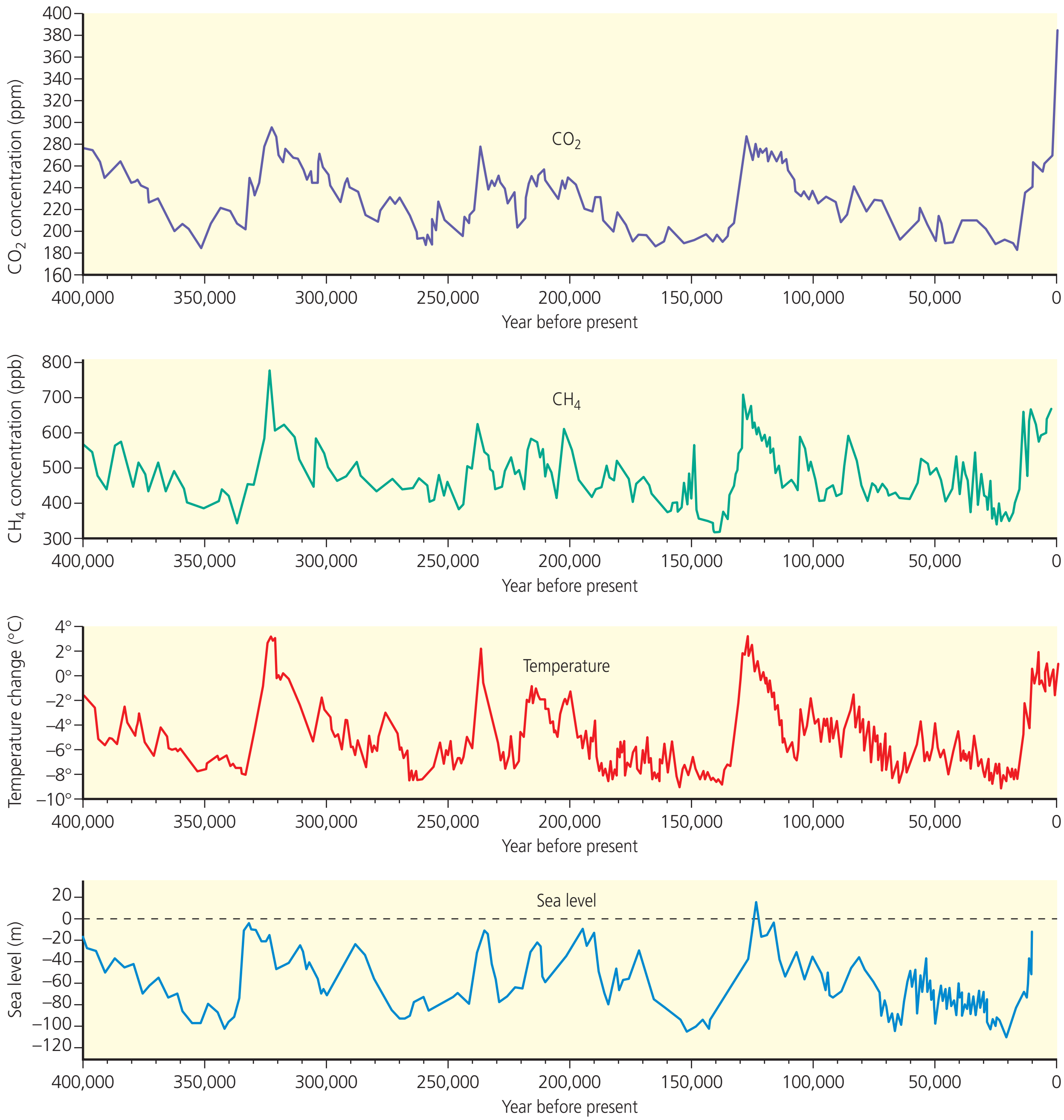


Figure 19-4 **Science:** atmospheric levels of carbon dioxide (CO_2) and methane (CH_4), changes in average global temperature of the atmosphere near the earth's surface, and changes in average sea level over the past 400,000 years. These data were obtained by analysis of ice cores removed at Russia's Vostok Research Station in Antarctica. More recent ice core analyses from Antarctica in 2007 indicate that current levels of CO_2 in the atmosphere are higher than at any time during the past 800,000 years. Carbon dioxide remains in the atmosphere for about 120 years compared to 15 years for methane. However, each molecule of methane can warm the atmosphere 23 times more than a molecule of carbon dioxide. **Question:** What are two conclusions that you can draw from these data? (Data from Intergovernmental Panel on Climate Change, National Center for Atmospheric Research, and F. Vimeux, et al. 2002. *Earth and Planetary Science Letters,* vol. 203: 829–843)

Scientific Consensus: The Atmosphere Is Warming Mostly Because of Human Activities

In 1988, the United Nations and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC) to document past climate changes and project future changes. The IPCC network includes more than 2,500 climate experts from more than 130 countries. Its 2007 report was based on more than 29,000 sets of data, much of it collected since 2002. In this report, the IPCC listed a number of findings indicating that it is *very likely* (a 90–99% probability) that the lower atmosphere is getting warmer (Science Focus, p. 502) (**Concept 19-1**) and that human activities are responsible for most of the recent temperature increase and will be responsible for most of the larger increase projected for this century.

In 2007, former U.S. Vice President Al Gore shared the Nobel Peace Prize with the IPCC for alerting the world to the reality and dangers of global warming and its effects on the world's climate. In his acceptance speech he said, " . . . the Earth has a fever. And the fever is rising. . . . We are what is wrong, and we must make it right."

RESEARCH FRONTIER

Computer modeling of climate change. See **academic .cengage.com/biology/miller**.

Here is some of the evidence that supports the major conclusions of the 2007 IPCC report:

- Between 1906 and 2005, the average global surface temperature has risen by about 0.74 C° (1.3 F°). Most of this increase has taken place since 1980 (Figure 19-2, top right).
- Annual greenhouse gas emissions from human activities rose 70% between 1970 and 2005 and average CO_2 concentrations are higher than they have been in 650,000 years (and 800,000 years, according to a 2007 study).
- Over the past 50 years, arctic temperatures have risen almost twice as fast as average temperatures in the rest of the world have risen.
- In some parts of the world, glaciers (Figure 19-5) and floating sea ice (Figure 19-6) are melting and shrinking at increasing rates, rainfall patterns are changing, and extreme and prolonged drought is increasing.
- During the last century, the world's average sea level rose by 10–20 centimeters (4–8 inches), mostly because of runoff from melting land-based ice and the expansion of ocean water as its temperature increased.

National Snow and Ice Data Center at Boulder, CO (USA)

National Snow and Ice Data Center at Boulder, CO (USA)

Figure 19-5 Melting of Alaska's Muir Glacier in the popular Glacier Bay National Park and Preserve between 1948 and 2004. Mountain glaciers are now melting almost everywhere in the world. **Question:** How might melting glaciers in Alaska and other parts of the world affect your lifestyle?

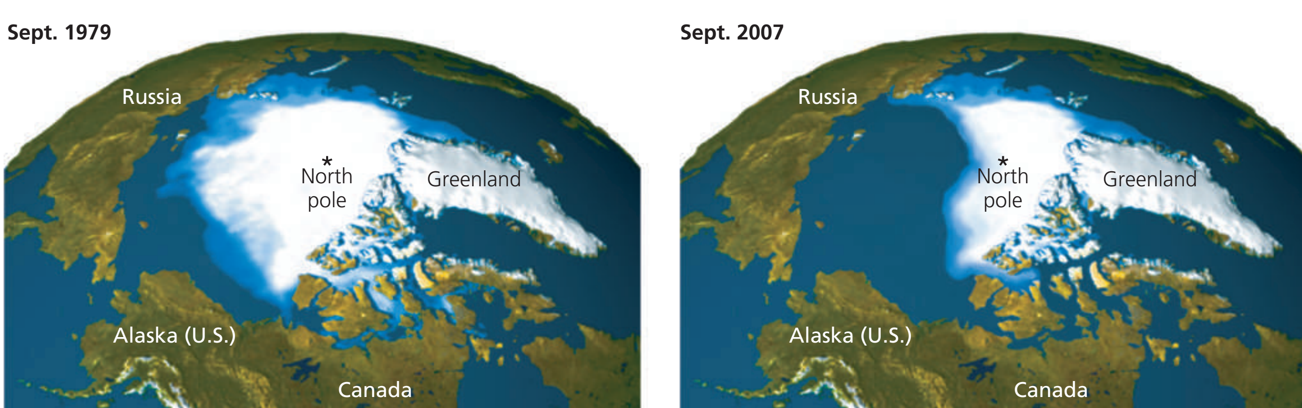


Figure 19-6 *The big melt.* Each summer, some of the floating sea ice in the Arctic Sea melts. But in recent years, rising atmospheric and ocean temperatures have caused more and more ice to melt. Satellite data show a large drop in the average cover of summer arctic sea ice between 1979 and 2007. In 2007 alone, the sea ice shrank by an area equal to that of six Californias or two Alaskas, much more than in any year since 1979 when scientists began taking satellite measurements. Such summer ice may be gone by 2030, and perhaps by as early as 2013, according to an estimate made by NASA climate scientist Jay Zwally in 2007. **Question:** Do you think that the increased melting of floating arctic sea ice is part of a positive or negative feedback loop (p. 45)? Explain? (Data U.S. Goddard Space Flight Center, NASA, National Snow and Ice Data Center)

SCIENCE FOCUS

What Is the Scientific Consensus about Future Temperature Change?

To project the effects of increasing levels of greenhouse gases on average global temperatures, scientists develop complex *mathematical models,* which simulate interactions among the earth's sunlight, clouds, landmasses, oceans, ocean currents, concentrations of greenhouse gases and pollutants, and positive and negative feedback loops (Figures 2-11 and 2-12, p. 45) within the climate system. Then they run these continually improving models on supercomputers and compare the results to known past climate changes, from which they project future changes in the atmosphere's average temperature. Figure 19-A gives a greatly simplified summary of some of the interactions in the global climate system.

Such models provide scenarios or projections of what is *very likely* (90–99% level of confidence) or *likely* (66–89% level of confidence) to happen to the average temperature of the lower atmosphere. How well the results correspond to the real world depends on the validity of the assumptions and

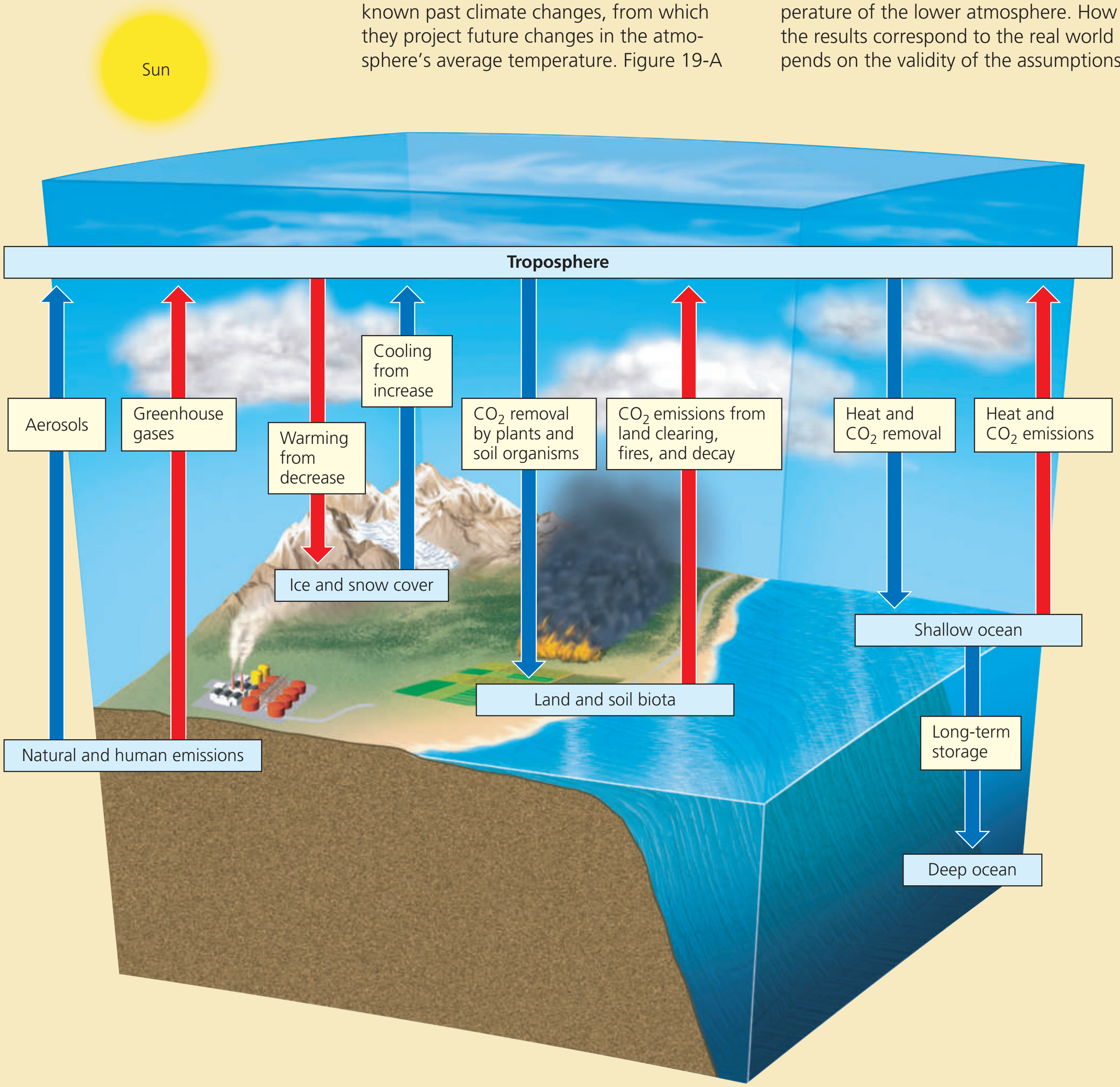


Figure 19-A **Science:** simplified model of some major processes that interact to determine the average temperature and greenhouse gas content of the lower atmosphere and thus the earth's climate. Red arrows show processes that warm the atmosphere and blue arrows show those that cool the atmosphere. **Question:** Why do you think a decrease in snow and ice cover would increase global warming?

variables built into the models and on the accuracy of the data used.

In 1990, 1995, 2001, and 2007, the IPCC published reports on how global temperatures have changed in the past (Figure 19-2) and made forecasts of how they are likely to change during this century and how such changes can affect the earth's climate. According to the 2007 report, based on analysis of past climate data and use of 19 climate models, it is very likely (a 90–99% probability) that human activities, especially the burning of fossil fuels, have been the main cause of the observed atmospheric warming during the past 50 years.

The 2007 report and recent runs of 19 different climate models suggest that it is *very likely* that the earth's mean surface temperature will increase by 2–4.5 C° (3.6–8.1 F°) between 2005 and 2100 (Figure 19-B), with about 3 C° (5.4 F°) the most likely rise, unless the world halts deforestation and makes drastic cuts in greenhouse gas emissions from fossil fuel burning power plants, factories, and cars. The lower temperature in this range is likely only if global greenhouse gas emissions fall 50–85% by 2050.

There is an overwhelming consensus among the world's climate scientists that global warming is occurring at a rapid rate, that human activities are the major factor in this temperature increase since 1950, and that human activities will play an even greater role in the warming projected to take place during this century and thus in the resulting changes to the earth's climate (**Concept 19-1**).

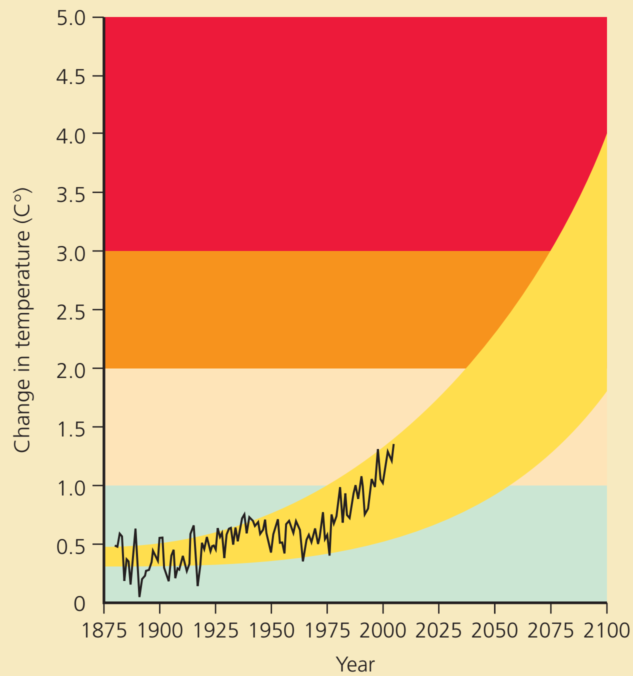


Figure 19-B **Science:** comparison of measured changes in the average temperature of the atmosphere at the earth's surface between 1860 and 2007 and the projected range of temperature increase during the rest of this century (**Concept 19-1**). (Data from U.S. National Academy of Sciences, National Center for Atmospheric Research, Intergovernmental Panel on Climate Change, and Hadley Center for Climate Prediction and Research)

Critical Thinking

If projected temperature increases shown in Figure 19-B take place, what are some major ways in which this will affect your lifestyle and that of any children or grandchildren you might have?

Data reveal that the melting of ice in the Arctic (Figure 19-6) has accelerated since the 2007 IPCC report. According to climate scientist Allan Robock, "the climate is changing even faster than the current models said. In fact, arctic sea ice is melting much faster than any models predicted, and sea level is rising faster than the IPCC previously predicted."

HOW WOULD YOU VOTE? ✓

Do you think that we will experience significant global warming and climate change during this century? Cast your vote online at **academic.cengage.com/biology/miller**.

Scientists have identified several natural and human-influenced factors that might *amplify* (give positive feedback to) or *dampen* (give negative feedback to) the projected changes in the average temperature of the atmosphere shown in Figure 19-B.

Recall that a positive feedback loop occurs when a small change leads to an even larger change of the same type and the spiral of change keeps growing (Figure 2-11, p. 45). The earth's complex climate system has both positive (harmful or amplifying) and negative (corrective) feedback loops (Figure 19-A), but positive feedback loops are more common than negative feedback loops. Let us look more closely at a few factors that could affect the atmospheric temperature projected in Figure 19-B.

Is a Hotter Sun the Culprit?

The energy output of the sun affects the earth's temperature, and this output has varied over millions of years. However, in 2007, Swiss, British, and American climate researchers (Claus Froelich, Mike Lockwood, and Ben Santer, respectively) concluded that the rapid rise in global mean temperatures since 1980 (Figure 19-2, top right, and Figure 19-B) could not be the result of increased solar output.

According to satellite and weather balloon measurements, since 1975, the lower atmosphere, or troposphere, has warmed while the stratosphere has cooled. This is not what a warmer sun would do. According to researcher Ben Santer, "If you increase output from the sun, you increase the amount of energy that arrives at the top of the Earth's atmosphere and get heating throughout the atmosphere." Instead, the atmosphere is now heating from the bottom up, which indicates that inputs at the earth's surface (from human activities) are the main cause.

Can the Oceans Save Us?

The world's oceans have absorbed about half of all the carbon dioxide released to the atmosphere since the beginning of the Industrial Revolution. Today, the oceans help to moderate the earth's average surface temperature and thus its climate by removing about 25–30% of the CO_2 pumped into the lower atmosphere by human activities. Some of this carbon is converted to insoluble carbonate salts that are buried in bottom sediments for several hundred million years, as part of the carbon cycle (Figure 3-18, p. 68).

The solubility of CO_2 in ocean water decreases with increasing temperature. Thus, as the oceans heat up, some of their dissolved CO_2 could be released into the lower atmosphere—like CO_2 bubbling out of a warm carbonated soft drink. This could amplify global warming and speed up climate change through a positive feedback loop. Scientific measurements show that the upper portion of the ocean warmed by 0.32–0.67 C° (0.6–1.2 F°) during the last century—an astounding increase considering the huge volume of water involved.

According to a 2007 report of a study carried out for 10 years by a team of researchers, led by Corinne Le Quere, and a 2008 report by European Union scientists, some of the world's oceans now appear to be absorbing less CO_2 from the atmosphere as they have started to warm. The 2007 study found that the rate of CO_2 absorption in the Southern Ocean around Antarctica—the world's largest sink for removing CO_2—has been dropping in every decade since 1981 and had dropped by half between the mid-1990s and 2005. This could help to accelerate the rise of CO_2 levels in the atmosphere, causing it to warm more rapidly in another positive feedback loop.

The 2008 study confirmed the findings about a decrease in CO_2 uptake by Antarctica's Southern Ocean. It also found a decrease in CO_2 uptake in the North Atlantic Ocean. But it will take at least another 20 years of data to establish the drop in CO_2 uptake as a trend.

In 2008, oceanographer Jeffrey Polovin and his colleagues reported that between 1998 and 2007, the net primary productivity (NPP) of the least productive open ocean areas (Figure 3-16, p. 64) in the Atlantic and Pacific oceans increased by about 15%. This represented an increase in phytoplankton, and the researchers hypothesized that it was the result of warmer ocean water temperatures. It could increase the absorption of CO_2 from the atmosphere. But the authors cautioned that the study covered just nine years, too short a time to determine any relationship between the NPP increase and long-term climate change caused by human activities. And it is possible that the change may be due to a shorter, natural cycle.

In 2005, the U.K. Royal Society reported that higher levels of CO_2 in the ocean have increased the acidity of the ocean surface by 30% since preindustrial times and could reach dangerous levels before 2050. This happens because much of the CO_2 absorbed by the ocean reacts with water to produce carbonic acid (H_2CO_3)—the same weak acid found in carbonated drinks. The increased acidity could decrease the ability of corals and other organisms to make calcium carbonate shells and bodies, and it could dissolve these shells. You can see this effect by dropping a piece of chalk (made of calcium carbonate) in a glass of vinegar (a weak acid) and watching it rapidly dissolve.

Increasing acidity also reduces the ability of the oceans to help regulate atmospheric warming and climate change by removing CO_2 from the lower atmosphere and storing it in bottom sediments. It thus can accelerate global warming and climate change in another positive feedback loop.

In 2007, a report by Ken Calderia and 16 other scientists warned that warmer and more acidic oceans threaten to destroy much of the world's ecologically important coral reef ecosystems before the end of this century. This would expose more people to coastal flooding, increase coastal erosion, reduce yields and revenues for reef-based fisheries and tourism, and greatly decrease aquatic biodiversity.

In 2006, satellite tracking by NASA found that as ocean water temperatures increased between 1999 and 2004, there was a sharp drop in populations of phytoplankton, which serve as the base of ocean food webs and, through photosynthesis, remove CO_2 from the atmosphere. In addition to disrupting food webs, reduced phytoplankton populations would remove less CO_2 from the atmosphere, leading to amplified global warming and more rapid climate change in yet another positive feedback loop. However, a preliminary study in 2008 by a team of British scientists led by M. Debora Iglesias-Rodríguez found that the populations of coccolithophore algae increased as the acidity of ocean water increased. More research is needed to understand the effects of acidity on populations of various phytoplankton species.

Bottom line: Temperature, acidity, the ability to absorb CO_2 from the atmosphere, and other properties of the oceans are changing as a result of human activities, and if these trends continue, they are likely to intensify and accelerate global warming and climate change.

There Is Uncertainty about the Effects of Cloud Cover on Global Warming

A major unknown in global climate models is the effect that changes in the global distribution of clouds might have on the temperature of the atmosphere. Warmer temperatures increase evaporation of surface water and create more clouds. Depending on their content and reflectivity, these additional clouds could have two effects. An increase in thick and continuous light-colored clouds at low altitudes could *decrease* surface warming by reflecting more sunlight back into space. But an increase in thin and discontinuous cirrus clouds at high altitudes could warm the lower atmosphere.

In addition, infrared satellite images indicate that the wispy condensation trails (contrails) left behind by jet planes might have a greater impact on atmospheric temperatures than scientists once thought. Although air travel is responsible for less than 2% of global greenhouse gas emissions, NASA scientists found that jet contrails expand and turn into large cirrus clouds that tend to release heat into the upper troposphere. If these preliminary results are confirmed, emissions from jet planes could be responsible for as much as half of the warming of the lower atmosphere in the northern hemisphere. Air travel is increasing rapidly and there is no technological fix for this problem unless hydrogen is phased in as a fuel for planes. Much more research is needed to evaluate the effects of clouds on global warming and climate change.

Outdoor Air Pollution Can Temporarily Slow Global Warming

Aerosols (suspended microscopic droplets and solid particles) of various air pollutants are released or formed in the troposphere by volcanic eruptions (**Core Case Study**) and human activities (Figure 18-8, p. 476). They can either warm or cool the air and hinder or enhance cloud formation depending on factors such as their size and reflectivity.

CORE CASE STUDY

Most aerosols, such as light-colored sulfate particles produced by fossil fuel combustion, tend to reflect incoming sunlight and cool the lower atmosphere. Sulfate particles also cool the lower atmosphere by serving as condensation nuclei that form cooling clouds. Scientists estimate that sulfate particles played a roll in slowing global warming between 1880 and 1970. However, a 2008 study by atmospheric scientist V. Ramanathan and his colleagues found that the black carbon particulate matter emitted into the air by diesel exhaust, burning forests (Figure 10-16, p. 226) and grasslands, and cooking with solid fuels (such as coal, wood, charcoal, and cow dung) has a warming effect on the atmosphere four times greater than was estimated earlier.

Climate scientists do not expect aerosol and soot pollutants to counteract or enhance projected global warming and the resulting climate change very much in the next 50 years for two reasons. *First,* aerosols and soot fall back to the earth or are washed out of the lower atmosphere within weeks or months, whereas CO_2 remains in the lower atmosphere for about 120 years. *Second,* aerosol and soot inputs into the lower atmosphere are being reduced because of their harmful impacts on plants and human health—especially in developed countries.

According to the IPCC, the fall in sulfate concentrations in most developed countries since 1970 has played a role in the warming of the atmosphere, especially since 1990. This trend will allow further increased global warming as sulphate concentrations continue to drop because of improved air pollution regulations.

19-2 What Are Some Possible Effects of a Warmer Atmosphere?

CONCEPT 19-2 The projected rapid change in the atmosphere's temperature during this century is very likely to increase drought and flooding, shift areas where food can be grown, raise sea levels, result in intense heat waves, and cause the premature extinction of many species.

Enhanced Global Warming Could Have Severe Consequences: Some Worst-Case Scenarios

So what is the big deal? Why should we worry about the projected rise of only a few degrees in the earth's average surface temperature? We often have that much change between May and July, or between yesterday and today. The key distinction is that we are not considering normal swings in *local weather* (see pp. S47–S48 in Supplement 8), but a projected, very rapid, *global change in climate*—weather measurements averaged over decades, centuries, and millennia (**Concept 19-2**).

Climate scientists are concerned not only about how much the temperature changes, but also about how rapidly it occurs. Most past changes in the temperature of the lower atmosphere took place over thousands to hundreds of thousands of years (Figure 19-2, top left). *The key problem we face is a projected rapid increase in the average temperature of the lower atmosphere during this century* (Figure 19-B).

Climate models indicate that we must deal with a rapidly changing climate that will determine where food can be grown and how much food can be grown; which areas will suffer from increased drought and which will experience increased flooding; and where people and many forms of wildlife will live. And we must deal with this within this century—warp speed, in terms of the earth's overall climate history (Figure 19-2).

A 2003 U.S. National Academy of Sciences report laid out a nightmarish *worst-case scenario* in which human activities, alone or in combination with natural factors, trigger new and abrupt climate and ecological changes. At that point, the global climate system would reach an irreversible *tipping point* after which it would be too late to reverse catastrophic changes for tens of thousands of years. The report describes ecosystems suddenly collapsing, low-lying cities being flooded, forests being consumed in vast wildfires, and grasslands drying out from prolonged drought and turning into dust bowls. It speculates on rivers that now supply drinking and irrigation water drying up as mountain glaciers that feed them melt. And it describes premature extinction of up to half of the world's species, prolonged heat waves and droughts, increased flooding, more destructive storms, and tropical infectious diseases spreading rapidly beyond their current ranges.

Climate change already threatens peace and economic and military security, as changing patterns of rainfall are increasing competition for water and food resources, especially in Africa. The much greater changes in climate projected for this century could cause migrations of tens of millions of people, and lead to extensive economic and social disruption.

These possibilities were supported by a 2003 analysis carried out by Peter Schwartz and Doug Randall for the U.S. Department of Defense. They concluded that global warming and the resulting climate change "must be viewed as a serious threat to global stability and should be elevated to a U.S. national security concern." In 2004, the United Kingdom's chief science adviser, David A. King, wrote, "In my view, climate change is the most severe problem we are facing today—more serious even than the threat of terrorism."

In 2007, the International Institute for Strategic Studies, a military security think-tank, warned that if the emission of greenhouse gases is allowed to continue, "the effects will be catastrophic—on the level of nuclear war." In 2007, International Alert, a London-based conflict resolution group, identified 102 countries with a high risk of becoming failed states during this century. (See Figure 17, p. S19, Supplement 3 for a list of current failed states.) These failures would stem partly from violent conflict and political instability resulting from shrinking supplies of key resources such as food, water, and land, due largely to climate change.

Figure 19-7 summarizes some of the projected effects of global warming and the resulting changes in global climate. These projected changes will affect parts of the world differently, as summarized in the maps in Figures 22 and 23 on pp. S72–S73 in Supplement 10.

According to the IPCC, a 2 C° (3.6 F°) warming appears to be inevitable because we have waited too long to prevent it, ignoring warnings from a number of prestigious committees of climate scientists for more than 25 years. Such a temperature increase is probably manageable. But as temperatures increase beyond this level, the projected harmful effects and costs of the resulting irreversible climate change will escalate rapidly (Figure 19-7, middle and right). Climate scientists warn that a 4 C° (7.2 F°) warming will threaten human civilization as we know it and much of the earth's biodiversity. If we do little or nothing, the projected warming could be 5 C° (9 F°) by the end of this century. Scientists warn that the resulting irreversible changes in global climate could lead to a 33–50% decrease in global food production, a significant drop in the human population, and widespread loss of biodiversity.

It is very important to distinguish between short-term daily and annual changes in the *weather* in an area and long-term changes in an area's *climate,* based mostly on temperature and precipitation. Climate is described by an area's weather factors averaged over several decades to thousands of years. It is clear that the average temperature of the lower atmosphere has increased during the last 35 years (Figure 19-B). But this does not necessarily mean that the area where you live is getting hotter each year. Some years the weather will be warmer, and some years it will be cooler.

Thus, a warmer-than-average year cannot necessarily be attributed to climate change from global warming, and a cooler-than-average year is not necessarily a sign of global cooling or a sign that global warming is not taking place. The latter is a common misconception that people get when they do not distinguish between weather and climate. Nevertheless, average atmospheric temperatures are clearly on the rise.

The good news is that we can avoid or sharply reduce the projected harmful effects of global warming and the resulting climate change if the world takes strong global emergency action, beginning now, to sharply decrease greenhouse gas emissions and to stabilize greenhouse gas concentrations in the 450–550 ppm range, and thus to slow the rate of climate change. Climate scientists urge immediate emergency action, because if we exceed certain tipping points, we will set into motion *irreversible* climate change that will last for hundreds to thousands of years.

In 2007, economist and climate change expert Nicholas Stern prepared a report for the British government that formed the basis for much of the information in Figure 19-7. In 2008, Stern said that he had underestimated the threat from global warming. According to Stern,

> *Emissions are growing much faster than we'd thought, the absorptive capacity of the planet is less than we thought,*

2°C (3.6°F) Warming with 450 ppm CO_2 (now unavoidable effects)

- Forest fires worsen
- Prolonged droughts intensify
- Deserts spread
- Major heat waves more common
- Fewer winter deaths in higher latitudes
- Conflicts over water supplies increase
- Modest increases in crop production in temperate regions
- Crop yields fall by 5–10% in tropical Africa
- Coral reefs affected by bleaching
- Many glaciers melt faster and threaten water supplies for up to 100 million people
- Sea levels rise enough to flood low-lying coastal areas such as Bangladesh
- More people exposed to malaria
- High risk of extinction for Arctic species such as the polar bear

3°C (5.4°F) Warming with 550 ppm CO_2 (potentially avoidable effects)

- Forest fires get much worse
- Prolonged droughts get much worse
- Deserts spread more
- Major heat waves and deaths from heat increase
- Irrigation and hydropower decline
- 1.4 billion people suffer water shortages
- Water wars, environmental refugees, and terrorism increase
- Malaria and several other tropical diseases spread faster and further
- Crop pests multiply and spread
- Crop yields fall sharply in many areas, especially Africa
- Coral reefs severely threatened
- Amazon rainforest may begin collapsing
- Up to half of Arctic tundra melts
- Sea levels continue to rise
- 20–30% of plant and animal species face premature extinction

4°C (7.2°F) Warming with 650 ppm CO_2 (potentially avoidable effects)

- Forest fires and drought increase sharply
- Water shortages affect almost all people
- Crop yields fall sharply in all regions and cease in some regions
- Tropical diseases spread even faster and further
- Water wars, environmental refugees, terrorism, and economic collapse increase sharply
- Methane emissions from melting permafrost accelerate
- Ecosystems such as coral reefs, tropical forests, alpine and Arctic tundra, polar seas, coastal wetlands, and high-elevation mountaintops begin collapsing
- Glaciers and ice sheets melt faster
- Sea levels rise faster and flood many low-lying cities and agricultural areas
- At least half of plant and animal species face premature extinction

Figure 19-7 Some projected effects of global warming and the resulting changes in global climate, based on the extent of warming and the total atmospheric concentrations of greenhouse gases in parts per million. According to the IPCC, a warming of 2 C° (3.6 F°) over 2005 levels is unavoidable, and an increase of at least 3 C° (5.4 F°) is likely sometime during this century (Figure 19-B). (Data from 2007 Intergovernmental Panel on Climate Change Report and Nicolas Stern, *The Economics of Climate Change: The Stern Report,* Cambridge University Press, 2006)

the risks of greenhouse gases are potentially bigger than more cautious estimates, and the speed of climate change seems to be faster.

Let us look more closely at some of the current signs of, and projected effects, of global warming on the earth's climate.

> **THINKING ABOUT**
> **Weather and Climate**
>
> In 2008, some radio talk show hosts said that a colder winter in parts of the United States was evidence that all the talk about global warming and climate change was wrong. How would you respond to such reasoning?

Severe Drought Is Increasing: The Browning of the Earth

Recall that *drought* occurs when evaporation from increased temperatures greatly exceeds precipitation for a prolonged period. According to a 2005 study by Aiguo Dai and his colleagues, between 1979 and 2002, the area of the earth's land (excluding Antarctica) experiencing severe drought increased from about 15% to 30%—a total area about the size of Asia.

Prolonged drought over several decades is caused by a combination of natural changes and cycles in the earth's climate system and human activities such as widespread deforestation and increased greenhouse gas emissions. According to the 2007 IPCC report, these human influences are very likely to increase throughout this century.

As this browning of the land increases, in the affected areas, there will be less moisture in the soil; stream flows and available surface water will decline; net primary productivity will fall; growth of trees and other plants will slow, which will reduce CO_2 removal from the atmosphere and intensify global warming; forest and grassland fires will increase, which will add CO_2 to the atmosphere; water tables will fall with more evaporation and irrigation; some lakes and seas will shrink or disappear; more rivers will fail to reach the sea; 1–3 billion people will face a severe shortage of water; biodiversity will decrease; and the area of dry climate biomes, such as savannas, chaparral, and

SCIENCE FOCUS

Melting Ice in Greenland

Greenland, the world's largest island, has a population of about 60,000 people. Glaciers as deep as 3.2 kilometers (2 miles) cover about 80% of this mountainous island, which is roughly one-fourth the size of the continental United States.

Greenland's ice is a result of the last ice age and survives only because of its huge mass. Its glaciers contain about 10% of the world's freshwater—enough water to raise the global sea level by as much as 7 meters (23 feet) if the glaciers all melt. This would flood many coastal cities and much of the earth's farmland. The large moving ice mass in a glacier scrapes along very slowly, but it can pick up speed when meltwater flowing downward through its crevices lubricates its bottom, which sits on bedrock. As the thickness of the glacier decreases, its grip on the land weakens, further accelerating its movement toward the sea.

Recent satellite measurements show that Greenland's net loss of ice more than doubled between 1996 and 2007 and is not being replaced by increased snowfall (Figure 19-C). According to glacial ice expert Konrad Steffen, the record amount of ice melted from Greenland's ice sheet during the summer of 2007 was equivalent to two times all of the ice in the Alps of south-central Europe. If this trend continues throughout much of this century, more of Greenland's land-based ice will melt, helping to raise the world's average sea level.

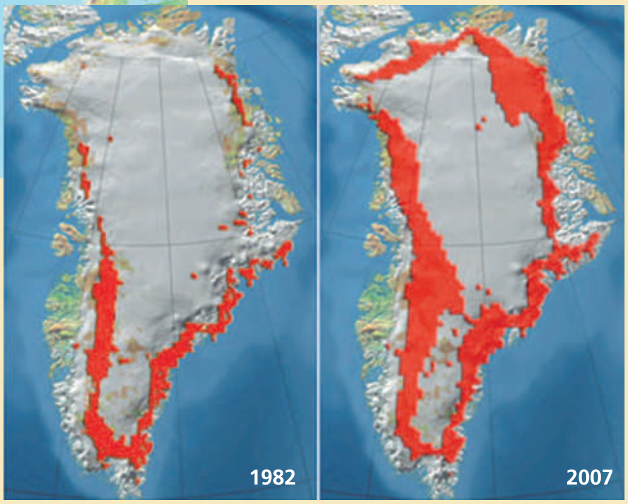


Figure 19-C Areas of glacial ice melting in Greenland during summer increased dramatically between 1982 and 2007. If this net melting of Greenland's land-based ice continues over a number of decades, the world's average sea level will rise sharply. (Data from Konrad Steffen and Russell Huff, University of Colorado, Boulder)

Critical Thinking

List three ways in which the rapid melting of ice in Greenland over the next few decades could affect your lifestyle or that of any children or grandchildren you might have.

deserts, will increase. In other words, some of the effects of prolonged drought over several decades create conditions that, through positive feedback, accelerate global warming and climate change and lead to even more drought.

Ice and Snow Are Melting

Climate models predict that global warming will be the most severe in the world's polar regions, the Arctic and Antarctica. Light colored ice and snow in the polar regions help to cool the earth by reflecting incoming solar energy. The melting of such ice and snow exposes much darker land and sea, which absorb more solar energy. This will likely cause polar regions to warm faster than lower latitudes, which will further accelerate global warming and the resulting climate change, which in turn will melt more sea ice, which will raise atmospheric temperatures more, and faster, in a runaway positive feedback loop.

The world is losing ice in mountain glaciers and in the vast polar ice sheets much faster than scientists thought possible only a few years ago. Over the past 30 years, snow cover in the Arctic has declined by about 10%, and mountain glaciers are melting and retreating (Figure 19-5) in many parts of the world. In 2006, the U.S. National Oceanic and Atmospheric Administration issued a *State of the Arctic* report in which researchers predicted arctic summers without floating sea ice (Figure 19-6) by 2040, and perhaps as early as 2013 according to some recent studies.

So why should we care if arctic sea ice is melting? The answer is that this sea ice plays an important role in the earth's climate by affecting the average amount of precipitation that falls in certain areas to the south over several decades or centuries. For example, a loss of arctic sea ice could reduce long-term average rainfall and snowfall in the already arid American West (Figure 13-5, p. 318), thereby affecting food production by reducing the availability of irrigation water. A loss of arctic sea ice could also increase long-term average precipitation and flooding in western and southern Europe.

Some good news is that because sea ice floats, it does not contribute to a rising sea level when it melts. The Arctic's contribution to a rising sea level will come from land-based ice that melts and runs into the sea faster than new ice forms. This is especially true of Greenland (Science Focus, at left).

Mountain glaciers are affected by two climatic factors: average snowfall, which adds to their mass during the winter, and average warm temperatures, which spur their melting during the summer. These high-elevation reservoirs play a vital role in the water cycle (Figure 3-17, p. 66) by storing water as ice during cold wet seasons and releasing it slowly as meltwater during warmer dry seasons. Such glaciers are a major source of water for large rivers such as the Ganges, which provides water for 407 million people in India and Bangladesh, and the Yangtze and Yellow Rivers in China. In 2004, Yao Tandong, a leading Chinese glaciologist, predicted that by 2060, two-thirds of China's glaciers will be gone, a development that "will eventually lead to an ecological catastrophe."

During the last 25 years, many of the world's mountain glaciers have been melting and shrinking at accelerating rates. For example, climate models predict that by 2070, Glacier National Park in the United States will have no glaciers for the first time in at least 7,000 years.

In 2007, scientists projected that at their current rate of melting, most glaciers will disappear from Europe's Alps somewhere between 2037 and 2059. Other scientists estimate that 80% of the mountain glaciers in South America will be gone by 2025. As these mountain glaciers disappear, millions of people in countries such as Bolivia, Peru, and Ecuador, who rely on meltwater from the glaciers for irrigation and hydropower, could face severe water, power, and food shortages.

Since 2006, veteran glaciologists and ice watchers have been amazed and alarmed at how fast ice in the polar regions and on the world's mountaintops is melting. According to a 2008 survey of more than 100 leading climate scientists, the two irreversible climate tipping points most likely to be exceeded during this century are the disappearance of floating ice in the Arctic Ocean during the Arctic summers and the accelerating loss of ice from the Greenland ice sheet (Science Focus, at left) and from many of the world's mountaintop glaciers.

Sea Levels Are Rising

According to the 2007 IPCC report, the world's average sea level is *very likely* (with 90–99% certainty) to rise 18–59 centimeters (0.6–1.9 feet) during this century, and to keep rising for centuries. About two-thirds of the increase will result from expansion of water as it warms, and the other third from the melting of land-based ice, especially from the melting of thousands of small mountaintop glaciers.

Newer models developed in 2008 suggest that sea levels could rise as much as 1–2 meters (3.3–6.6 feet) sometime between 2050 and 2100, if glaciers in Greenland (Figure 19-C) reach an irreversible tipping point and continue melting at their current or higher rates as the atmosphere warms. The total area of land threatened by rising sea levels increases significantly when we factor in storm surges of 6 meters (20-feet) or higher, which can accompany tropical cyclones and tsunamis. Figure 19-8 shows areas of the U.S. state of Florida that would be flooded with an average sea level rise of 1 meter (3.2 feet).

Figure 19-8 Areas of the U.S. state of Florida that will be flooded (red) if the average sea level rises by 1 meter (3.2 feet). (Data from Jonathan Overpeck and Jeremy Weiss based on U.S. Geological Service Data)

According to the IPCC, the projected rise in sea levels during this century (excluding the additional effects of storm surges) could cause the following essentially irreversible effects:

- Degradation or destruction of at least one third of the world's coastal estuaries, wetlands, and coral reefs.
- Disruption of many of the world's coastal fisheries.
- Flooding of low-lying barrier islands and erosion and retreat of gently sloping coastlines (especially on the U.S. Eastern and Gulf Coasts). U.S. states that would loose the most land to flooding are Louisiana (Figure 8-19, p. 178), Florida (Figure 19-8), North Carolina, Texas, and South Carolina.
- Flooding of agricultural lowlands and deltas in coastal areas where much of the world's rice is grown.
- Contamination of freshwater coastal aquifers with saltwater and brackish water and decreased supplies of groundwater currently used for irrigation, drinking, and cooling power plants in such areas.
- Submergence of low-lying islands in the Pacific Ocean, the Caribbean Sea, and the Indian Ocean (Figure 19-9, p. 510), which are home to 1 of every 20 of the world's people.

Figure 19-9 For a low-lying island nation like the Maldives in the Indian Ocean, even a small rise in sea level could spell disaster for most of its 295,000 people. About 80% of the 1,192 small islands that make up this country lie less than 1 meter (3.2 feet) above sea level. Rising sea levels and higher storm surges during this century could flood most of these islands and their coral reefs.

- Flooding of coastal areas, including some of the world's largest cities, and displacement of at least 100 million people, especially in China, India, Bangladesh, Vietnam, Indonesia, Japan, Egypt, the United States, Thailand, and the Philippines. A 2007 study by the Organization for Economic Cooperation and Development (OECD) estimated that, by 2070, coastal flooding from a sea level rise of 0.5 meter (1.6 feet) would affect 150 million people and cause property and other damages of $35 trillion (roughly equal to the current global world product). The United States would suffer the highest estimated monetary loss—over $3.5 trillion. The study projected that the following cities, in order, as most likely to suffer serious damages from such flooding: Calcutta (India), Mumbai (India), Dhaka (Bangladesh), Guangzhou (China), Ho Chi Minh City (Vietnam), Shanghai (China), Bangkok (Thailand), Rangoon (Myanmar), Miami (USA), and Hai Phong (Vietnam). See *The Habitable Planet,* Video 5, at **www.learner.org/resources/series209.html** for a discussion of the effects of projected rising sea levels on densely populated, low-elevation coastal areas in Vietnam, and on New York City in the United States.

Figure 19-10 Projected decline in arctic tundra (Figure 7-12, bottom, p. 151) in portions of eastern Russia between 2004 and 2100 as a result of global warming. The melting of permafrost in such tundra soils could release the greenhouse gases CH_4 and CO_2 and accelerate global warming, which would melt more tundra. This loss of arctic tundra could reduce grazing lands for caribou and breeding areas for a number of tundra-dwelling bird species. Shrubs and small trees and eventually boreal, or northern coniferous, forests (Figure 7-15, bottom, p. 154) would gradually replace the lost tundra. (Data from Intergovernmental Panel on Climate Change and 2004 Arctic Climate Impact Assessment)

Such changes are unlikely to take place soon. But climate scientists warn that they are very likely to occur during your lifetime, unless the world takes immediate emergency action to slow or prevent such irreversible changes. Many scientists argue that our most urgent priority is *to do all we can to avoid any and all irreversible climate or ecological tipping points.* Once we reach such a point, there is no going back. It is like going over a cliff.

Permafrost Is Likely to Melt: Another Dangerous Scenario

The amount of carbon locked up as methane in permafrost soils is 50–60 times the amount emitted as carbon dioxide from burning fossil fuels each year. If the permafrost in soil and lake bottoms in parts of the rapidly warming Arctic melts, significant amounts of methane (CH_4) and carbon dioxide (CO_2) will be released into the atmosphere, and this will accelerate global warming and the resulting climate change.

According to the 2004 Arctic Climate Impact Assessment, 10–20% of the Arctic's current permafrost might thaw during this century, decreasing the total area of arctic tundra (Figure 19-10). The resulting increase in emissions of CH_4 and CO_2 would cause more warming, which would in turn melt more permafrost and cause still more warming and climate change in yet another positive feedback loop.

Ocean Currents Are Changing but the Threat Is Unknown

Shallow and deep ocean currents are connected and move like a gigantic conveyor belt, transferring CO_2 and warm and cool water between the surface and the depths and between the tropics and the poles (Figure 7-5, p. 143).

Scientists are concerned that melting of land-based glaciers (especially in Greenland) and increased rain in the North Atlantic, both due to global warming, could add enough freshwater to the ocean in the arctic area to slow or disrupt this conveyor belt. Reaching this irreversible tipping point would drastically alter the climates of northern Europe, northeastern North

America, and probably Japan (**Concept 19-2**). Most climate scientists do not see this as a threat in the near future, based on projected temperature increases (Figure 19-B). But we still have much to learn about this pattern of ocean circulation, and ice in land-based glaciers is melting faster than most scientists expected.

Extreme Weather Will Increase in Some Areas

According to the IPCC, global warming will increase the incidence of extreme weather such as heat waves and droughts in some areas, which could kill large numbers of people, reduce crop production, and expand deserts. At the same time, because a warmer atmosphere can hold more moisture, other areas will experience increased flooding (especially flash floods) from heavy and prolonged precipitation. (See Figures 22 and 23, pp. S72 and S73, in Supplement 10 for maps of how different parts of the world may be affected by projected global warming.)

There is controversy over the question of whether global warming will increase the frequency and intensity of tropical storms and hurricanes (Figure 9, p. S51, Supplement 8). In 2008, climatologists Mark Saunders and Adam Lea analyzed data collected since 1950 and found that for every increase of about 0.8 C° (1 F°) in the water temperature of the Atlantic Ocean, the overall number of hurricanes and tropical storms increased by about a third. The number of intense hurricanes, with winds over 177 kilometers per hour (110 miles per hour), increased by 45%.

An example of such increasing hurricane intensity was Hurricane Katrina, which occurred in 2005, a year when Atlantic water temperatures were especially warm. With an 8.5-meter-(28-foot-) high storm surge, Katrina caused massive damage and flooding in New Orleans, Louisiana (USA) (Figure 8-18, p. 177) and the surrounding area and killed more than 1,500 people. The 2005 hurricane season was the most active on record.

Satellite imaging revealed that wind and long-term exposure to water from hurricanes Katrina and Rita in 2005 killed or severely damaged more trees in Mississippi and Louisiana than any recorded forestry disaster in U.S. history. This contributed to global warming, according to a 2007 study by Jeffrey Q. Chambers and his colleagues. They found that the estimated loss of over 320 million big trees sharply reduced the amount of CO_2 removed from the atmosphere. In addition, the researchers estimated that as the dead and damaged trees decayed, they emitted CO_2 equal to the total amount that all forest trees in the United States absorb in a year.

A 2005 statistical analysis by MIT climatologist Kerry Emmanuel and six other peer-reviewed studies published in 2006 also indicated that global warming, on average, could increase the size and strength of Atlantic storms and their storm surges by warming the ocean's surface water. However, some researchers blame the ups and downs in ferocity of tropical Atlantic hurricanes on natural climate cycles that can change ocean circulation patterns. And in 2007, NASA climate researchers hypothesized that warmer water in the Atlantic could increase vertical wind shear—the difference in wind direction or speed at different altitudes—which can help to inhibit hurricane formation. More research is needed to resolve the scientific controversy over the effects of global warming on hurricane frequency and intensity.

Global Warming Is a Major Threat to Biodiversity

According to the 2007 IPCC report, changes in climate resulting from global warming are now affecting physical and biological systems on every continent and are altering ecosystem services (Figure 1-3, p. 8) in some areas. A warmer climate could expand ranges and populations of some plant and animal species that can adapt to warmer climates, including certain weeds; insect pests, such as cockroaches, fire ants, and ticks; and some disease-carrying organisms.

According to the 2007 IPCC study, approximately 30% of the land-based plant and animal species assessed so far could disappear if the average global temperature change exceeds 1.5–2.5 C° (2.7–4.5 F°). This percentage could grow to 70% if the temperature change exceeds 3.5 C° (6.3 F°) (**Concept 19-2**). The hardest hit will be plant and animal species in colder climates, such as the polar bear in the Arctic and penguins in Antarctica; species at higher elevations; plant and animal species with limited ranges, such as some amphibians (Figure 4-9, p. 87); and those with limited tolerance for temperature change.

A 2007 study by the Convention on Migratory Species warned that global warming could also disrupt the biological clocks of birds, whales, and other migratory species. This could put many of them in the wrong places at the wrong times and make them more vulnerable to food shortages, heat waves, droughts, or cold snaps that would accompany climate change in various parts of the world.

The ecosystems most likely to suffer disruption and species loss from climate change are coral reefs (Figure 19-11, p. 512), polar seas, coastal wetlands, high-elevation mountaintops, and alpine and arctic tundra (Figure 19-10). Some types of forests unable to migrate fast enough to keep up with climate shifts will decline, and others, such as oak–pine and oak–hickory forests in the United States, may expand northward. Mostly because of drier conditions, forest fires may increase in some areas such as the southeastern and western United States. This would severely degrade some forest ecosystems, add more CO_2 to the atmosphere, reduce total CO_2 uptake by plants, and accelerate global

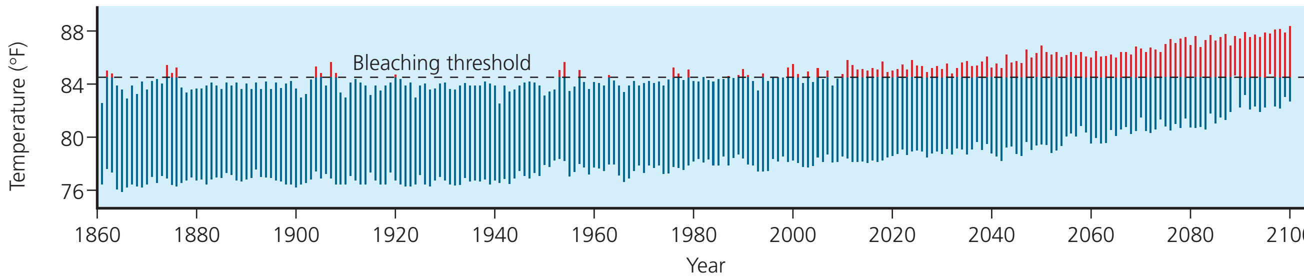


Figure 19-11 Changes in average temperatures of ocean water, relative to the coral bleaching threshold, past and projected, 1860–2100. As temperatures consistently remain above the bleaching threshold, global losses of coral reefs due to coral bleaching (Figure 8-1, right, p. 162) are projected to increase dramatically. Other threats to reefs are increasing ocean acidity and the spread of infectious diseases as ocean temperatures rise due to projected global warming. However, a 2007 study by researchers at the Australian Institute of Marine Science suggested that some reefs store several types of algae, including heat-resistant types that can cope with warmer water. Nevertheless, this would not help to prevent disintegration of some coral reefs caused by the increasing acidity of ocean water. (Data from Intergovernmental Panel on Climate Change)

warming and climate change through still another positive feedback loop.

A warmer climate can also greatly increase populations of insects and fungi that damage trees. In the Canadian province of British Columbia, for example, warmer winters have led to surges in mountain pine beetle populations that have infected huge areas of lodgepole pine forests, which are now dying (Figure 19-12). Pine beetles have also damaged about 60% of the lodgepole pines in the U.S. state of Colorado, which has been experiencing warmer winters. In Yellowstone Park in the United States, global warming has increased beetle infestations of white bark pine trees that grow at high altitudes. This threatens the park's grizzly bears, which feed on white bark pine seeds.

Natural Resources Canada, Canadian Forest Service

Figure 19-12 With warmer winters, exploding populations of mountain pine beetles have munched their way through large areas of lodgepole pine forest (orange colored trees) in the Canadian province of British Columbia. Foresters are trying to reduce the threat by planting a mix of trees less susceptible to the pest—an example of applying the biodiversity **principle of sustainability**.

Shifts in regional climate would also threaten many existing parks, wildlife reserves, wilderness areas, and wetlands—wiping out more biodiversity. In other words, slowing global warming and the resulting climate change would help to sustain the earth's biodiversity, which in turn supports us and our economies (Science Focus, p. 218).

Climate Change Will Shift Areas Where Crops Can Be Grown

Farming, probably more than any other human activity, depends on a stable climate. Thus, farmers will face dramatic changes due to shifting climates and a faster hydrologic cycle, if global warming continues as projected (Figure 19-B).

Agricultural productivity may increase in some areas and decrease in others. According to the 2007 IPCC report, crop productivity is projected to increase slightly at middle to high latitudes if global temperatures rise by 1–3 C° (1.8–5.4 F°), but productivity would likely decrease at higher temperatures (Figure 22, p. S72, in Supplement 10). Models project that moderately warmer temperatures and increased precipitation at northern latitudes may lead to a northward shift of some agricultural production to parts of midwestern Canada, Russia, and Ukraine. But overall food production could decrease because of unsuitable soils in these northern regions. There could be a 10–15% drop in rainfall in the United States and several other parts of the world. But as long as the temperature does not rise by more than 3 C° (5.4 F°), scientists hope that new genetically modified varieties of key food crops could tolerate this drier climate.

Climate change models predict a decline in agricultural productivity in tropical and subtropical regions, especially in Southeast Asia and Central America, where many of the world's poorest people live. In addition, flooding of river deltas due to rising sea levels could reduce crop and fish production in these productive agricultural lands and nearby coastal aquaculture ponds. Food production could also decrease in farm regions dependent on rivers fed by snowmelt and glacier melt; arid and semiarid areas where prolonged drought will increase; and humid areas in southeastern Asia that are vulnerable to changes in monsoon patterns, which could bring more devastating storms and heavier flooding.

According to the IPCC, for a time, food will be plentiful because of the longer growing season in northern regions. But by 2050, the IPCC warns that some 200–600 million of the world's poorest and most vulnerable people could face starvation and malnutrition from the effects of climate change.

Climate Change Will Threaten the Health of Many People

According to the IPCC and a 2006 study by U.S National Center for Atmospheric Research, heat waves in some areas will be hotter, more frequent and longer. This will increase the number of deaths and illnesses, especially among older people, those with poor health, and the urban poor who cannot afford air conditioning. During the summer of 2003, a major heat wave killed about 52,000 people in Europe (an estimate based on a detailed analysis in 2006 by the Earth Policy Institute)—almost two-thirds of them in Italy and France.

On the other hand, in a warmer world, fewer people will die from cold weather. However, a 2007 study by Mercedes Medin-Ramon and his colleagues suggests that increased numbers of heat-related deaths will be greater than the projected drop in cold-related deaths in a warmer world.

A warmer, CO_2-rich world will be a great place for rapidly multiplying insects, microbes, toxic molds, and fungi that make us sick, and for plants that produce allergenic pollens. Longer and more intense pollen seasons will mean more itchy eyes, runny noses, and asthma attacks. Insect pests and weeds will likely multiply, spread, and reduce crop yields.

In a warmer world, microbes that cause tropical infectious diseases such as dengue fever, yellow fever, and malaria (Figure 17-7, p. 445) are likely to expand their ranges and their prevalence, if mosquitoes that carry them spread to temperate and higher elevation areas that are getting warmer. And while more frequent prolonged droughts would sharply reduce populations of mosquitoes, populations of their predators, such as dragonflies and damselflies would also decline. In addition, hunger and malnutrition will increase in areas where agricultural production drops.

Higher atmospheric temperatures will also increase some forms of air pollution. The greatest effect will be to speed up the rate of the chemical reactions that produce ozone and other harmful chemicals in photochemical smog in urban areas (Figure 18-10, p. 477).

Increasing illness, hunger, flooding, and drought will likely lead to forced migrations of tens of millions of people. Environmental scientist Norman Myers says that climate change during this century could produce at least 150 million, and perhaps 250 million, environmental refugees. The higher estimate would be equal to about four-fifths of the current U.S. population. (See Myers's Guest Essay on this topic on the website for this chapter.)

A 2005 WHO study estimates that each year, climate change already contributes to the premature deaths of more than 150,000 people—an average of 410 people a day—and that this number could double by 2030. Most of these deaths are the result of increases in malaria, diarrhea, malnutrition, and floods that can be traced to climate change. In addition, the WHO estimates that climate change causes 5 million sicknesses each year. By the end of this century, the annual death toll from climate change could be in the millions.

19-3 What Can We Do to Slow Climate Change?

CONCEPT 19-3A To slow the rate of global warming and climate change, we can increase energy efficiency, sharply reduce greenhouse gas emissions, rely more on renewable energy resources, and slow population growth.

CONCEPT 19-3B Governments can subsidize energy efficiency and renewable energy use, tax greenhouse gas emissions, set up cap-and-trade emissions reduction systems, and help to slow population growth.

Dealing with Climate Change Is Difficult

It is becoming increasingly clear that addressing climate change could be one of the most urgent scientific, political, economic, and ethical issues that humanity faces. But the following characteristics of this complex problem make it difficult to tackle:

- *The problem is global.* Dealing with this threat will require unprecedented and prolonged international cooperation.

- *The effects will last a long time.* Carbon dioxide molecules emitted by burning coal for the past 120 years are still in the atmosphere and those we emit today will also be around for about 120 years. Once set into motion, irreversible climate change due to excessive emissions of greenhouse gases will last hundreds to thousands of years.

- *The problem is a long-term political issue.* Voters and elected officials generally respond well to short-term problems but have difficulty acknowledging and coping with long-term threats. Most of the people who will suffer the most serious harm from projected climate change during the latter half of this century, caused by our failure to act, have yet to be born.

- *The harmful and beneficial impacts of climate change are not spread evenly.* There will be winners and losers in the event of moderate climate change. Higher latitude nations such as Canada, Russia, Scandinavia, Greenland, and New Zealand, could have higher crop yields [with temperature increases no greater than 3 C° (5.4 F°)], fewer deaths in winter, lower heating bills, and more tourism. The catch: We will not know who will benefit and who will suffer until it is too late to avoid harmful effects. And at some temperature threshold (Figure 19-7), essentially everyone will be harmed directly or indirectly.

- *Many proposed actions that might reduce the threat of climate change, such as phasing out use of fossil fuels, are controversial because they would disrupt economies and lifestyles.* But waiting too long to slow climate change would also disrupt economies and lifestyles, probably to an even greater extent, according to a 2008 study by the OECD.

RESEARCH FRONTIER

Predicting the effects of climate change caused mostly by global warming in different parts of the world. See **academic .cengage.com/biology/miller**.

What Are Our Options?

There are two basic approaches to dealing with the projected harmful effects of global climate change. One is to drastically reduce greenhouse gas emissions to slow down the rate of warming in time to prevent major climate changes. The other is to recognize that some warming is unavoidable and to devise strategies to reduce its harmful effects. Most analysts believe we need a mix of both approaches.

In 2006, NASA climate scientist, James Hansen (**Core Case Study**), warned that we probably have no longer than a decade to mount a massive global effort to prevent an irreversible change in the earth's climate that will fundamentally alter the planet, cause ecological and economic havoc, and threaten civilization as we know it. He and other prominent climate scientists urge policymakers and business leaders to mount an unprecedented crash program to cut global carbon dioxide emissions by 50–85% by 2050 in an effort to slow down or avoid major climate change and its harmful effects (Figure 19-7).

The question is, will enough individuals exert sufficient bottom up political pressure and consumer pressure (through their purchases) to reach a *political tipping point?* At that point, such pressure could force elected officials and business leaders to implement well-known solutions on an urgent basis to avoid reaching various irreversible *climate change tipping points.*

HOW WOULD YOU VOTE?

Should we take serious action now to help slow climate change resulting from human activities? Cast your vote online at **academic.cengage.com/biology/miller**.

Avoiding Catastrophe: We Can Reduce the Threat of Climate Change

The good news is that we know a number of ways to slow the rate and degree of global warming and the resulting climate change caused by our activities, as summarized in Figure 19-13.

These solutions come down to three major *input* or *prevention* strategies: *improve energy efficiency to reduce fossil fuel use; shift from nonrenewable carbon-based fossil fuels to a mix of carbon-free renewable energy resources;* and *stop cutting down tropical forests* (**Concept 19-3A**). A fourth strategy—which is an *output strategy*—is to keep burning fossils fuels but to *capture and store as much CO_2 as possible in soil, in vegetation, underground, and in the deep ocean and to hope that it will never leak out.* If a substantial amount of stored CO_2 somehow leaked into the environment, it would rapidly increase global warming and accelerate global climate change.

The effectiveness of these strategies would be enhanced by *reducing population,* which would decrease the number of fossil fuel consumers and CO_2 emitters. It would also help to *reduce poverty,* which would decrease the need of the poor to clear more land for crops and fuelwood. The three input strategies and the population control strategy follow the four **scientific principles of sustainability** (see back cover).

U.S. scientists Robert Socolow and Stephen Pacala at Princeton University have outlined a plan for holding 2057 CO_2 levels to those in 2007 in order to help us avoid harmful effects such as those shown in the middle section of Figure 19-7. They have identified 15 different strategies, which they call *climate stabilization*

SOLUTIONS

Global Warming

Prevention

Cut fossil fuel use (especially coal)

Shift from coal to natural gas

Improve energy efficiency

Shift to renewable energy resources

Transfer energy efficiency and renewable energy technologies to developing countries

Reduce deforestation

Use more sustainable agriculture and forestry

Limit urban sprawl

Reduce poverty

Slow population growth

Cleanup

Remove CO_2 from smokestack and vehicle emissions

Store (sequester) CO_2 by planting trees

Sequester CO_2 deep underground (with no leaks allowed)

Sequester CO_2 in soil by using no-till cultivation and taking cropland out of production

Sequester CO_2 in the deep ocean (with no leaks allowed)

Repair leaky natural gas pipelines and facilities

Use animal feeds that reduce CH_4 emissions from cows (belching)

Figure 19-13 Methods for slowing atmospheric warming and the resulting climate change during this century (**Concept 19-3A**). **Question:** Which five of these solutions do you think are the most important? Why?

wedges (Figure 19-14). Phasing in each wedge would reduce CO_2 emissions by roughly the same amount during the coming 50-year period. They estimate that getting CO_2 emissions to 2007 levels by 2057, and holding them there would require implementing any 8 of the 15 wedges during the next 5 decades or phasing in amounts of all 15 wedges sufficient to be the equivalent of implementing 8 wedges.

Socolow and Pacala have turned their proposals into a role-playing wedges game that is being adapted and used in some schools. A 2007 study by the American Solar Energy Association showed how implementing just the energy efficiency and renewable energy wedge strategies alone could lead to a 60–80% reduction in greenhouse gas emissions by 2050.

HOW WOULD YOU VOTE?

Should we drastically reduce the use of fossil fuels over the next 50 years? Cast your vote online at **academic.cengage .com/biology/miller**.

Environmental expert Lester R. Brown, believes that the CO_2 reductions proposed by Socolow and Pacala are not enough. In his 2008 book, *Plan B 3.0: Mobilizing to Save Civilization* (Norton), he outlines a global emergency plan to cut CO_2 emissions by 80% by 2020. Brown argues that such a course is necessary in order to keep climate change from spiraling out of control and threatening human civilization as we know it.

We have looked at several ways to reduce the release of greenhouse gases to the atmosphere in order to slow climate change, involving energy efficiency, renewable energy, nuclear power, synfuels from coal, stopping or sharply reducing tropical deforestation,

Energy Efficiency and Conservation

- Increase the average fuel economy of the 2 billion cars projected to exist by 2057 to 26 kpl (60 mpg).
- Cut the average distance traveled by all cars in 2057 to no more than 8,000 kilometers (5,000 miles) per year.
- Cut electricity use in homes, offices, and stores by 25%.
- Increase efficiency of 1,600 large coal-fired power plants from 40% to 60%.

Renewable Energy

- Increase solar power 700-fold to displace coal-fired plants.
- Increase wind power 25-fold to displace coal-fired plants.
- Increase wind power 50-fold to make hydrogen for fuel-cell cars.

Lower Carbon Emitting Fuels

- Increase ethanol biofuel production 50-fold by growing crops on one-sixth of the world's cropland.
- Replace 1,400 coal-fired plants with natural-gas-fired plants.
- Displace coal-fired plants by tripling electricity production from nuclear power plants.

Forestry and Agriculture

- Stop all deforestation.
- Use conservation tillage on all cropland.

Carbon Capture and Storage (CCS)

- Install Carbon Capture and Storage (CCS) at 800 large coal-fired plants
- Install CCS at enough large coal-fired plants to produce hydrogen for 1 million fuel-cell cars.
- Install CSS at enough coal-to-syngas plants to produce 30 million barrels of synfuels per day.

Figure 19-14 Fifteen ways to cut CO_2 emissions. Each strategy, called a *climate stabilization wedge,* cuts CO_2 emissions by roughly the same amount. Princeton University scientists, Robert Socolow and Stephen Pacala, who developed this strategy, estimate that to keep global CO_2 emissions from doubling as projected between 2007 and 2057, the world would have to phase in eight of these wedges or the equivalent of that by 2057. Wedges based on other technologies or strategies could also be used. **Questions:** Which of these wedges are input strategies that prevent or reduce CO_2 emissions and which are output strategies that try to deal with CO_2 after it is produced? Which eight of these wedges would you choose to implement over the next 50 years? Explain. (Data from Robert H. Socolow and Stephen W. Pacala, 2006, 2007)

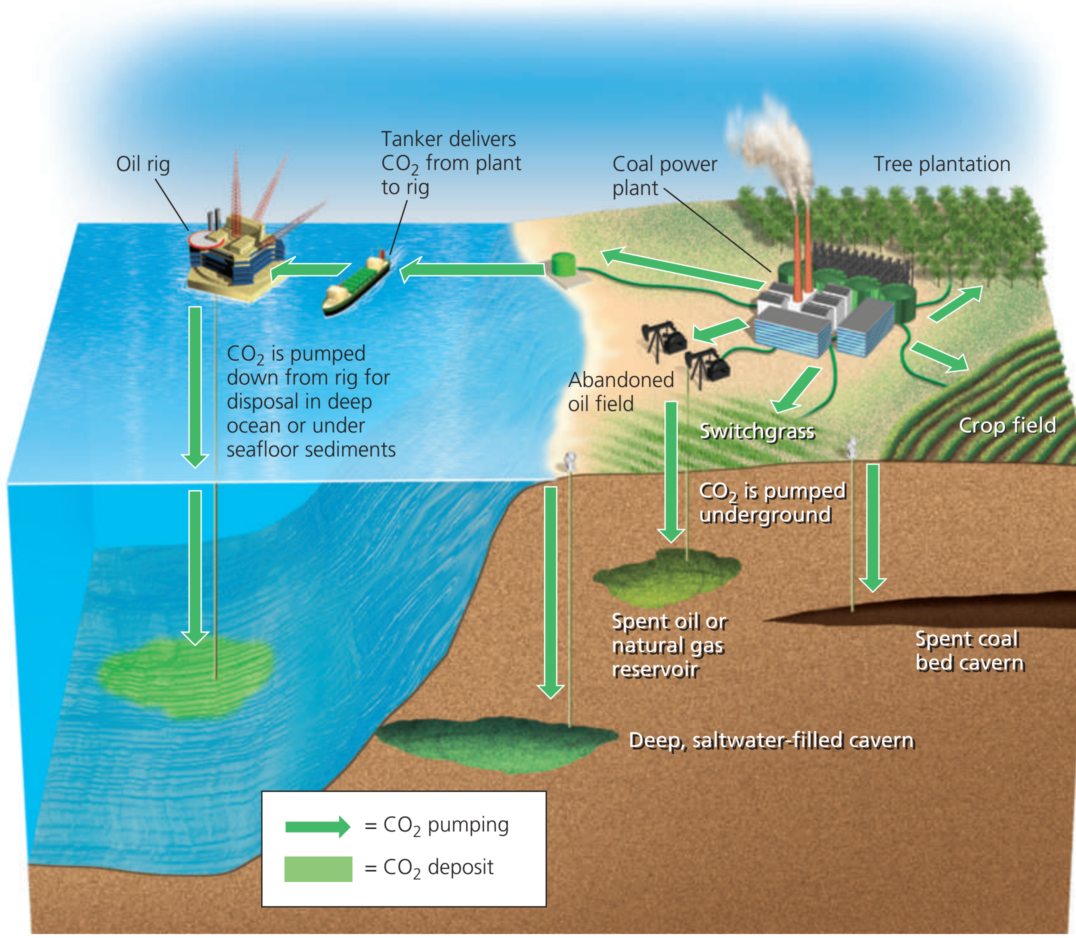


Figure 19-15 **Solutions:** some output methods for removing carbon dioxide from the atmosphere or from smokestacks and storing it in plants, soil, deep underground reservoirs, or the deep ocean. **Question:** Which two of these solutions do you think are the most important? Why?

and using no-till soil cultivation. Let us now look more closely at some of the output solutions shown in Figure 19-15—strategies for removing some of the CO_2 from the atmosphere or from smokestacks and storing (sequestering) it in other parts of the environment.

One way to increase the uptake of CO_2 is by implementing a massive global tree-planting program, especially on degraded land in the tropics, on an emergency basis. The 2007 global campaign to plant a billion trees, inspired by Nobel laureate Wangari Maathai (Individuals Matter, p. 230), is a start. China and Africa each have a program to plant a Great Green Wall of Trees to stop the spread of desertification.

However, according to estimates by Lester R. Brown and the Swedish energy firm Vattenfall, to effectively slow global warming and the resulting climate change, the world must plant at least 4 billion trees, assuming that half of them will survive. This will cost about $200 billion or $20 billion a year for a decade. Tree planting would have to continue to a lesser degree, indefinitely, because trees decrease their CO_2 uptake as they mature and release their stored CO_2 back into the atmosphere when they die and decompose or are burned.

A second output approach is to plant large areas of degraded land with fast-growing perennial plants such as switchgrass (Figure 16-26, p. 425), which remove CO_2 from the air and store it in the soil and can be harvested to produce biofuels such as ethanol. This approach would not involve clearing forests. (See *The Habitable Planet,* Video 10, at **www.learner.org/resources/series209.html** for a discussion of how scientists are using an outdoor grassland as a laboratory to measure the carbon uptake of plants.)

In 2007, biologist Renton Righelato and climate scientist Dominick Spracklen analyzed a number of strategies for reducing or avoiding CO_2 emissions. They concluded that the amount of carbon that could be sequestered by restoring forests is greater than the amount of carbon in CO_2 emissions that would be avoided by the use of biofuels, such as ethanol and biodiesel (pp. 423–426). The Case Study that follows explores another output approach.

■ CASE STUDY
Is Capturing and Storing CO_2 the Answer?

A third output approach is **carbon capture and storage (CCS).** It involves *removing CO_2 from the smokestacks of coal-burning power and industrial plants and then storing it somewhere.* CO_2 gas could be pumped deep underground into coal beds and abandoned oil and gas fields. (See *The Habitable Planet,* Video 10, at **www.learner.org/resources/series209.html** for a discussion of how scientists are evaluating this form of CCS.) Or the gas could be liquefied and injected into thick sediments under the sea floor (Figure 19-15).

Analysts point to several problems with this approach. One is that power plants using CCS are much more expensive to build and operate than conventional coal-burning plants and thus would sharply raise the price of electricity for consumers. Without strict government regulation of CO_2 emissions, carbon taxes to bring coal prices in line with environmental costs, or generous subsidies and tax breaks, coal-burning utilities and industries have no incentive to build such plants. According to the U.S. Department of Energy, the current costs of CCS systems will have to be reduced by a factor of ten before these systems will be widely used.

A second problem is that CCS is an unproven technology that would remove only part (perhaps 25–35%) of the CO_2 from smokestack emissions. No plants using CCS exist, and building and testing them could take 20–30 years and huge amounts of money with no guaranteed successes. A third problem is that this process requires large inputs of energy, which could increase CO_2 emissions and cancel out some of the gains made from collecting and storing some of the CO_2.

A fourth problem is that CCS promotes the continued use of coal, which should probably be phased out. Coal companies talk about a future based on greatly increased use of *clean coal technologies,* such as coal-to-synfuels. But even with successful CCS and cleaner coal technologies, *coal is by far the world's dirtiest fuel* to dig up and burn (Figures 15-15, right, p. 385, and 15-16, right, p. 386). And if coal's harmful environmental costs were included in its price, burning coal would be a very costly way to produce electricity compared to most other alternatives (Table 16-1, p. 416).

It is not surprising that coal companies are pushing for a shift to CCS coal-fired plants to be funded with the help of generous taxpayer subsidies and tax breaks. Indeed, without CCS, the conventional coal industry probably will not survive in the long term. And because converting coal to synfuels produces twice as much CO_2 per volume of fuel as burning gasoline, CCS also helps to make the coal-to-synfuels industry more feasible. This helps to assure a future for the coal industry, which will ensure continued increasing CO_2 emissions.

A fifth problem is that providing huge government subsidies and taxbreaks for developing and testing CCS technology would divert or reduce the huge subsidies and taxbreaks needed for the rapid development of solar, wind, geothermal, and other forms of renewable energy that reduce rather than attempt to deal with CO_2 emissions.

A sixth very serious potential problem with CCS is that essentially *no leaks are allowed.* In effect, the stored CO_2 would have to remain sealed from the atmosphere forever. Any large-scale leaks due to earthquakes, other geological events, or wars, as well as any number of smaller continuous leaks from storage sites around the world, could dramatically increase global warming and the resulting climate change in a very short time.

According to a 2007 estimate by environmental scientist Peter Montague, if 25% of the carbon in the world's estimated remaining fossil fuels were sequestered, any leakage greater than 0.16% of the total amount stored per year could eventually result in runaway global warming and climate change. And if 75% of the world's estimated remaining carbon in fossil fuels were sequestered, it would take a leakage of only 0.05% of the amount stored per year to lead to the same result. Montague contends that we cannot bury several trillion tons of CO_2 in the ground or under the sea with complete confidence that leaks totaling 0.05% of the total amount stored per year will not occur at any time in the future.

According to the precautionary principle (**Concept 9-4C**, p. 206), we should not rely on a technology that commits us to an essentially irreversible threat. Reliance on nuclear power commits human societies to fail-safe storage of dangerous radioactive wastes for up to 240,000 years. But Montague points out that relying on CCS to store much of the CO_2 we produce commits human societies to fail-safe storage of the CO_2 *forever.*

CONCEPT LINK

To coal companies, CCS is the wave of the future that will help to keep them in business. To scientists like Peter Montague, CCS is an extremely risky output solution to a serious problem that can be dealt with by using a variety of cheaper, quicker, and safer input approaches (Figure 19-13, left). To these scientists, when we face a problem such as CO_2 coming out of a smokestack or exhaust pipe, the most important question to ask is not what do we do with it, but how do we avoid producing the CO_2 in the first place?

THINKING ABOUT
Carbon Capture and Storage

Are you in favor of relying on carbon capture and storage to deal with some of the carbon dioxide that we produce by burning coal? Explain.

Should We Use Geo-Engineering Schemes to Help Slow Climate Change?

Carbon capture and storage (CCS) is one proposed *geo-engineering* scheme for helping us to slow global warming and the resulting climate change. Most scientists oppose using such large-scale solutions, because the long-term effects of such projects on the earth's energy flow, chemical cycling processes, and vital biodiversity are unknown.

However, in recent years, some scientists have become discouraged by the glacially slow response of governments to what they see as the global emergency of climate change with its projected serious harmful effects. Some of these scientists are suggesting that we at least look at the possible implications and costs of using large-scale geo-engineering schemes as a last resort, if humanity fails to deal with the world's climate change emergency soon enough.

For example, some scientists have suggested using balloons, large jet planes, or giant cannons to inject sulfate particles into the stratosphere where they might reflect some of the incoming sunlight into space and thus cool the troposphere. It is thought that the effect would be similar to the cooling effect that lasted about 15 months after the 1991 volcanic eruption of Mt. Pinatubo (**Core Case Study,** Figure 19-1). Huge amounts of SO_2 would have to be injected into the stratosphere about every 2 years.

CORE CASE STUDY

Other scientists reject this idea as being too risky because of our limited knowledge about possible unknown effects. In addition, such a scheme could accelerate ozone depletion by boosting levels of ozone-destroying chlorine in the stratosphere; it could also increase acid rain in the troposphere (Figure 18-12, p. 479). This short-term technological fix would also allow CO_2 levels in the lower atmosphere to continue rising, which would increase the acidity of the oceans, thereby decreasing their ability to absorb CO_2 and disrupting ocean life (p. 504). This could then accelerate global warming and climate change.

Some scientists would deal with this problem by building a global network of thousands of chemical plants that would remove hydrochloric acid from seawater to reduce ocean acidity. But this also could have unpredictable and possibly harmful ecological effects.

THINKING ABOUT
Tinkering with the Stratosphere

Would you support the proposal to inject large quantities of sulfate particles into the stratosphere every 2 years to help cool the troposphere? Explain.

Scientist James Lovelock has suggested that we anchor huge vertical pipes in the sea as part of a system that would allow wave motion to pump nutrient-rich water up from the deep ocean to fertilize algae on the ocean surface. He contends that the resulting algal blooms would remove CO_2 from the atmosphere and emit dimethyl sulfide (Figure 3-22, p. 72), which would contribute to the formation of low clouds that would reflect sunlight.

Another scheme is to tow 8,000 ice-making barges to the Arctic each year to re-ice the Arctic Sea. And another is to wrap large areas of glaciers with insulating blankets to slow down their melting and to help preserve ski resort businesses.

The major problem with these techno fixes is that if they ever fail while we continue adding CO_2 to the atmosphere, the rebound effects could be calamitous. Geo-engineering schemes all depend on complex machinery running constantly and flawlessly, and essentially forever, mostly to pump something from one place to another in the environment. Once the machines break down, natural processes would overwhelm such a system, and atmospheric temperatures would soar at a rapid rate and accelerate climate change.

Critics of large-scale geo-engineering schemes argue for slowing climate change by using prevention approaches, such as improving energy efficiency, replacing fossil fuels with already available renewable energy resources, and drastically reducing tropical deforestation. They say this makes more sense than gambling on large-scale, costly changes to the global environment that could have unknown and potentially long-lasting harmful effects.

How Much Will It Cost to Slow Climate Change?

Estimates of the financial costs of damages from projected global warming and the resulting climate change vary widely, based on different economic assumptions and on differing rates and degrees of temperature change. In 2007, the IPCC estimated that by the year 2030, the global economic cost of stabilizing greenhouse gas emissions to keep the global temperature from rising more than 2 C° (3.6 F°) (Figure 19-7, left) would cost only about 0.12% of the projected 2030 gross world product.

Other economists dispute these estimates and project that preventing average atmospheric temperatures from increasing more than 2 C° (3.6 F°) would reduce the gross world product by as much as 3% in 2030. However, there is considerable agreement that the short-term costs of slowing climate change will be much lower than the long-term costs of climate change caused largely by human activities. A number of economic studies indicate that implementing the strategies listed in Figures 19-13 and 19-14 would boost global and national economies, provide millions of much-needed jobs, and cost much less than struggling with the harmful effects that these problems would ultimately cost.

Governments Can Help Reduce the Threat of Climate Change

Governments can use four major methods to promote the solutions listed in Figures 19-13 and 19-14 (**Concept 19-3B**).

One is to *strictly regulate carbon dioxide and methane as pollutants.* Second, governments could phase in *carbon taxes* on each unit of CO_2 or CH_4 emitted by fossil fuel use, or they could levy *energy taxes* on each unit of fossil fuel that is burned. Decreasing taxes on income, wages, and profits to offset such taxes could help make such a strategy more politically acceptable. In other words, *tax pollution, not payrolls and profits*. Some European countries are phasing in such a tax shift.

A related approach is to place a cap on total human-generated CO_2 and CH_4 emissions in a country or region, issue permits to emit these pollutants, and then let polluters trade their permits in the marketplace. This *cap-and-trade approach* has a political advantage over taxes, but it would be difficult to manage because there are so many emitters of greenhouse gases, including industries, power plants, motor vehicles, buildings, and homes. And according to a 2008 study by Goldman Sachs, one of the world's largest investment banks, a cap-and-trade strategy is an important way to cut CO_2 emissions, but by itself would not be enough to achieve the desired drop in such emissions.

Environmental economists argue that, regardless of whether governments use taxes or a cap-and-trade system, the most important goal is to get all emitters to pay the full environmental and social costs of their carbon emissions. The resulting higher costs for fossil fuels would spur innovation in finding ways to reduce carbon emissions, improve energy efficiency, and phase in noncarbon renewable energy alternatives.

A third strategy is to *level the economic playing field* by greatly increasing government subsidies to businesses and individuals to encourage their use of energy-efficiency technologies, carbon-free renewable energy sources, and more sustainable agriculture. This would also include phasing out or sharply reducing subsidies and tax breaks that encourage use of fossil fuels and nuclear power, unsustainable agriculture, and clearing of forests. In other words, we could shift from environmentally-degrading to environmentally-sustaining subsidies and tax breaks.

A fourth strategy would focus on *technology transfer*. Governments of developed countries could help to fund the transfer of the latest green technologies to developing countries so that they could bypass older, energy-wasting and polluting technologies. Helping poorer countries to deal with the harmful effects of climate change would make sense, because these are the countries that will suffer the most from these effects, which have been caused mostly by developed countries. Increasing the current tax on each international currency transaction by a quarter of a penny could finance this technology transfer, which would then generate wealth for developing countries and help to stimulate a more environmentally sustainable global economy.

Governments Can Enter into International Climate Negotiations: The Kyoto Protocol

In December 1997, more than 2,200 delegates from 161 nations met in Kyoto, Japan, to negotiate a treaty to slow climate change. The first phase of the resulting *Kyoto Protocol* went into effect in February 2005 with 174 of the world's 194 countries (but not the United States) ratifying the agreement by mid-2008. It requires 36 participating developed countries to cut their emissions of CO_2, CH_4, and N_2O to an average of at least 5.2% below their 1990 levels by 2012. Developing countries were excluded from having to reduce greenhouse gas emissions in this first phase, because such reductions would curb their economic growth. In 2005, countries began negotiating a second phase that is supposed to go into effect after 2012.

The protocol also allows trading of greenhouse gas emissions among participating countries. For example, a country or business that reduces its CO_2 emissions or plants trees receives a certain number of credits. It can use these credits to avoid having to reduce its emissions in other areas, or it can bank them for future use or sell them to other countries or businesses.

In 2005, the European Union instituted such a cap-and-trade system for carbon emissions. However, in 2007, critics pointed out that the system was not working well because the caps were set too high and thus have been encouraging greenhouse gas emissions. Environmental economists warn that the success of any cap-and-trade emissions system depends on setting caps low enough to increase the value of the tradable allowances and periodically reducing the caps to encourage further innovation in reducing emissions. They also advise that such a system by itself will not achieve the desired reductions in greenhouse gas emissions.

Some analysts praise the Kyoto agreement as a small but important step in attempting to slow projected global warming. They hope that rapidly developing nations such as China, Brazil, India, and Indonesia will agree to reduce their greenhouse gases in the second phase of the protocol. Others see the agreement as a weak and slow response to an urgent global problem.

In 2001, President George W. Bush withdrew the United States from participation in the Kyoto Protocol, arguing that it would harm the U.S. economy. He also objected to the agreement because it did not require emissions reductions by rapidly developing countries such as China, India, Brazil, and Indonesia, which were producing large and increasing emissions of greenhouse gases. Most analysts, and 59% of Americans responding to a 2007 poll, believe that the United States, which has the world's highest overall and per capita CO_2 emissions, should use its influence to improve the treaty rather than to weaken and abandon it.

HOW WOULD YOU VOTE?

Should the United States participate in the Kyoto Protocol and try to strengthen it? Cast your vote online at **academic .cengage.com/biology/miller**.

We Can Move Beyond the Kyoto Protocol

In 2004, environmental law experts Richard B. Stewart and Jonathan B. Wiener proposed that countries work together to develop a new strategy for slowing climate change. They concluded that the Kyoto Protocol would have little effect on future global warming without support and action by the United States and by China, India, Brazil, and other developing countries, which will soon be emitting more than half of the world's greenhouse gases.

Stewart and Wiener urge the development of a new climate treaty among the United States, China, India, Russia, Australia, Japan, South Korea, Brazil, Indonesia, the European Union, and other major greenhouse gas emitters. The treaty would create a cap-and-trade emissions program that includes developing countries omitted from the trading plan under the first phase of the Kyoto Protocol. In addition, it would set achievable 10-year goals for reducing emissions over the next 40 years. It would include evaluation of global and national strategies for adapting to the harmful ecological and economic effects of climate change caused by a warmer atmosphere. Stewart and Wiener call for the United States to lead in developing such a treaty and to take strong steps to drastically cut its own greenhouse gas emissions.

Some Governments Are Leading the Way

Some nations are leading the way. Costa Rica aims to be the first country to become *carbon neutral* by cutting its net carbon emissions to zero by 2030. The country generates 78% of its electricity with renewable hydroelectric power and another 18% from renewable wind and geothermal energy. In 2007, Norway announced that it aims to become carbon neutral by 2050.

Some analysts are urging rapidly developing countries such as China and India to shift toward more sustainable, low-carbon economic development by leapfrogging over the traditional forms of economic development that have led to the global warming problem. If China and India continue their massive coal burning and other high-carbon activities, the world will not be able to avoid the projected harmful effects of climate change set in motion by global warming (Figure 19-7, middle and right). And such effects will be especially severe for China and India. Both countries can benefit economically by becoming leaders in designing, manufacturing, and selling cleaner power systems, appliances, cars, and homes. Such green technologies will make up much of the world's global industry during this century.

Growing weary of waiting for the federal government to get serious about slowing projected climate change, some U.S. states have taken action. By 2007, 21 states and the District of Columbia had required utilities to increase their reliance on renewable energy resources, especially solar and wind power. California has led the way (Case Study, below).

Since 1990, local governments in more than 650 cities around the world (including 453 U.S. cities) have established programs to reduce their greenhouse gas emissions. The first major U.S. city to do this was Portland, Oregon. Between 1993 and 2005, the city cut its greenhouse gas emissions back to 1990 levels, while national levels rose by 16%. The city promotes energy-efficient buildings and the use of electricity from wind and solar sources. It has also built bicycle trails and has greatly expanded its mass transit system. Far from hurting Portland's economy, these strategies have produced an economic boom and have saved the city $2 million a year on its energy bills.

Other U.S. cities striving to be more sustainable and to reduce their greenhouse gas emissions are Seattle, Washington; San Francisco, California; New York City; Chattanooga, Tennessee (Case Study, p. 21); Boulder, Colorado; Chicago, Illinois; Minneapolis, Minnesota; and Salt Lake City, Utah.

■ CASE STUDY
Reducing Greenhouse Gas Emissions in California

The U.S. state of California, where one of every eight Americans lives, is the world's sixth largest economy and twelfth largest producer of greenhouse gases. Many of the most important advances in reducing air pollution and improving energy efficiency started in California, spread across the United States, and eventually were enacted into federal legislation and regulations. Until these federal regulations went into effect, many businesses lost money trying to comply with a patchwork of different standards imposed by various states.

California has set increasingly higher standards for the energy efficiency of appliances and buildings and has created incentives for utilities to encourage consumers to use less power (Case Study, p. 433). This has helped to slow CO_2 emissions and saved California from having to build 24 large power plants.

In 2006, California passed a law to cut its greenhouse gas emissions to 25% below its 1990 levels by 2020 and to 80% below its 1990 levels by 2050. Its approach is to set fuel efficiency and carbon emission standards and let the free market find the best ways to meet the standards. However, in 2008, the EPA refused California's request to lead the way in setting tougher CO_2 emission standards than those enacted by other states, even though it had approved such requests in the past for setting tougher standards for other air pollutants. California and 17 other states are suing the federal government to overturn this decision and lobbying

Congress to amend the Clean Air Act so that it allows California and other states to set tougher CO_2 emission standards.

> **THINKING ABOUT**
> **What States and Localities Can Do**
> What are three steps that you think the state or locality where you live should take to help slow climate change from global warming caused mostly by human actions?

Some Companies and Schools Are Reducing Their Carbon Footprints

A growing number of major global companies, including Alcoa, DuPont, IBM, Toyota, General Electric, Johnson & Johnson, Volvo, and British Petroleum (BP), have established targets for reducing their greenhouse gas emissions to 10–65% below 1990 levels by 2010. Between 1990 and 2006, DuPont slashed its energy usage and cut its greenhouse emissions by 72%. In the process, it saved \$3 billion while increasing its business by 30%.

Wal-Mart has become the world's largest seller of energy-saving, more climate-friendly, compact fluorescent lightbulbs. It saves \$12 million a year using energy-efficient LED bulbs in its refrigeration units. The company, which has the country's second largest corporate truck fleet, saved \$22 million in 2006 by installing auxiliary power units that allow drivers to operate their trucks' electrical systems without idling their motors. In 2007, the company ordered its truck manufacturers to double the gas mileage of its entire truck fleet by 2015. In 2007, Wal-Mart also announced a partnership with the Carbon Disclosure Project to measure the energy used to create and transport the products it sells (many of them from China) and the resulting CO_2 emissions. It plans to use the data to find suppliers that are more energy efficient and that produce lower CO_2 emissions.

These and many other major companies see an enormous profit opportunity in developing or using energy-efficient and cleaner-energy technologies, such as fuel-efficient cars, wind turbines, and solar cells. They understand that there is gold in going green. A 2006 study found that companies lagging behind in these efforts are putting their stockholders at risk of losses and lawsuits for failure to take advantage of the rapidly growing international marketplace for green technologies.

Some colleges and universities are also taking action. Students and faculty at Oberlin College in Ohio (USA) have asked their board of trustees to reduce the college's CO_2 emissions to zero by 2020 by buying or producing renewable energy. In the U.S. state of Pennsylvania, 25 colleges have joined to purchase wind power and other forms of mostly carbon-free, renewable energy. In 2005, the president of Yale University committed the school to cutting its considerable greenhouse gas emissions by 44% by 2020.

In February 2008, the United States had the largest teach-in in its history, with more than 1,500 colleges focusing on educating their students and local citizens about climate change and sustainability. If you are interested in finding out more about how to help your school cut its CO_2 emissions, see the 2008 National Wildlife Federation report on this topic, which can be found at **www.nwf.org/campusecology/BusinessCase/index.cfm**.

To calculate your *carbon footprint*, the amount of carbon dioxide generated by your lifestyle, you can go to sites like the following:

nature.org/climatecalculator

epa.gov/climatechange/emissions/ind_calculator.html

carbonfootprint.com

climatecrisis.net/takeaction/carboncalculator

gocarbonzero.org

Most of these websites and others suggest ways for you to reduce, or *offset*, some of your carbon dioxide emissions by helping to fund or participate in projects such as forest restoration and renewable energy development. Other sites are

nativeenergy.com

my-climate.com

conservationfund.org/gozero

climatecare.org

carbon-clear.com

epa.gov/climatechange/wycd/actionsteps.html

But buyers need to do their homework, because some carbon offset programs are not real and do not actually produce emissions cuts. For evaluations of carbon-offset providers, go to **cleanair-coolplanet.org** and **tufts.edu/tie/tci/carbonoffsets**. The nonprofit Consumers Union also has a website (**GreenerChoices.org/calculators.cfm**) to help consumers evaluate conflicting claims of travel agencies over the greenest way to travel.

Critics of such carbon-offset schemes say that most of them primarily offer a way for consumers to ease their guilt. Some critics argue that such programs actually encourage people to continue producing greenhouse gases, instead of making carbon-cutting lifestyle changes, such as driving less, using public transit, and using less electricity.

Figure 19-16 (p. 522) lists some ways in which you can cut your CO_2 emissions. Taking each of these steps

WHAT CAN YOU DO?

Reducing CO_2 Emissions

- Drive a fuel-efficient car, walk, bike, carpool, and use mass transit
- Use energy-efficient windows
- Use energy-efficient appliances and lights
- Heavily insulate your house and seal all air leaks
- Reduce garbage by recycling and reusing more items
- Insulate your hot water heater
- Use compact fluorescent lightbulbs
- Plant trees to shade your house during summer
- Set your water heater no higher than 49°C (120°F)
- Wash laundry in warm or cold water
- Use a low-flow showerhead
- Buy products from, or invest in, companies that are trying to reduce their impact on climate

Figure 19-16 **Individuals matter:** ways to reduce your annual emissions of CO_2. **Question:** Which of these steps, if any, do you take now or plan to take?

makes a small contribution to reducing greenhouse gas emissions. But when millions of people take such steps, the cumulative result is quite large. In addition, political scientists estimate that it would take only 5–10% of the public exerting political pressure to bring about the larger policy changes needed to deal with climate change and other urgent environmental problems.

We Can Prepare for the Harmful Effects of Climate Change

According to the latest global climate models, the world needs to make a 50–85% cut in emissions of greenhouse gases by 2050 to stabilize concentrations of these gases in the atmosphere and prevent the planet from heating up more than 2C° (3.6F°) (Figures 19-B). This will be necessary in order to prevent rapid climate changes and the resulting projected harmful effects (Figure 19-7).

However, because of the difficulty of making such large reductions, many analysts believe that, while we work to slash emissions, we should also begin to prepare for the projected harmful effects of essentially irreversible climate change. Figure 19-17 shows some ways to implement this strategy.

Some analysts and religious leaders call for the world's richer nations to increase technological and monetary aid to poorer regions at risk from climate change in order to help them deal with the changes. Emphasis could be on developing genetically engineered crops that could thrive in a warmer world and constructing flood defenses in low-lying coastal areas of countries such as India, Indonesia, and Bangladesh, which may experience more severe flooding due to global warming.

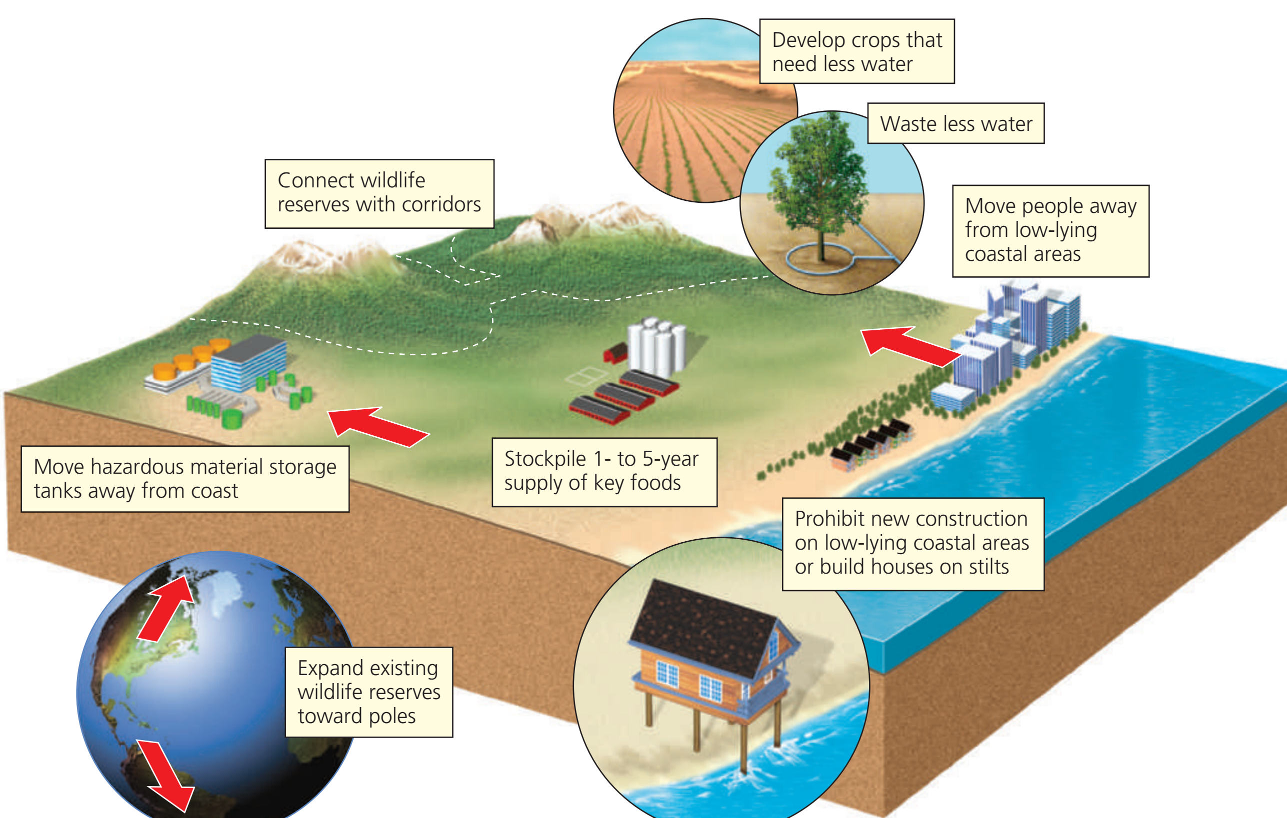


Figure 19-17 **Solutions:** ways to prepare for the possible long-term harmful effects of climate change. **Question:** Which three of these adaptation solutions do you think are the most important? Why?

Relief organizations, including the International Red Cross and Oxfam are turning their attention to projects such as expanding mangrove forests as buffers against storm surges, building shelters on high ground, and planting trees on slopes to help prevent landslides. Sea wall design and construction will be a major growth industry. And low-lying countries such as Bangladesh are trying to figure out what to do with millions of environmental refuges who would be displaced by rising sea levels. Some cities plan to establish cooling centers to shelter residents during increasingly intense heat waves.

Some U.S. cities, including New York City and Seattle, Washington, have developed adaptation plans, as have some states, including California, Alaska, Maryland, Washington, and Oregon. Alaska has plans to relocate coastal villages at risk from rising sea levels and storm surges. California is beefing up its forest firefighting capabilities and is proposing desalination plants to help relieve projected water shortages, which will worsen as mountain glaciers melt. And some coastal communities require that new houses and other new buildings be built high enough off of the ground to survive projected higher storm surges; others are prohibiting new construction in especially vulnerable areas.

Some people fear that emphasizing these adaptation approaches will distract us from the more urgent need to reduce greenhouse gas emissions. However, to some analysts, projected climate change is already such a serious threat that we have no alternative but to implement both prevention and adaptation strategies, and we have no time to lose.

19-4 How Have We Depleted Ozone in the Stratosphere and What Can We Do about It?

CONCEPT 19-4A Widespread use of certain chemicals has reduced ozone levels in the stratosphere, which allows for more harmful ultraviolet radiation to reach the earth's surface.

CONCEPT 19-4B To reverse ozone depletion, we must stop producing ozone-depleting chemicals and adhere to the international treaties that ban such chemicals.

Our Use of Certain Chemicals Threatens the Ozone Layer

A layer of ozone in the lower stratosphere keeps about 95% of the sun's harmful ultraviolet (UV-A and UV-B) radiation from reaching the earth's surface (Figure 18-3, p. 470). But measurements taken by meteorologists using weather balloons, aircraft, and satellites show considerable seasonal depletion (thinning) of ozone concentrations in the stratosphere above Antarctica and the Arctic. Similar measurements reveal a lower overall thinning everywhere except over the tropics. Figure 19-18 shows the average global concentrations of ozone in the stratosphere between 1979 and 2005.

In 1984, researchers analyzing satellite data discovered unexpectedly that each year, 40–50% of the ozone in the upper stratosphere over Antarctica (100% in some places) disappears during October and November. This observed loss of ozone has been called an *ozone hole*. A more accurate term is *ozone thinning* because the ozone depletion varies with altitude and location. Figure 19-19 (p. 524) shows a colorized satellite image of ozone thinning over Antarctica in 2007.

When the seasonal thinning ends each year, huge masses of ozone-depleted air above Antarctica flow northward, and these masses linger for a few weeks over parts of Australia, New Zealand, South America, and South Africa. This raises biologically damaging UV-B levels in these areas by 3–10% and in some years as much as 20%.

In 1988, scientists discovered that similar but usually less severe ozone thinning occurs over the Arctic from February to June, resulting in a typical ozone loss of 11–38% (compared to a typical 50% loss above Antarctica). When this mass of air above the Arctic breaks up each spring, large masses of ozone-depleted air flow south to linger over parts of Europe, North America, and Asia.

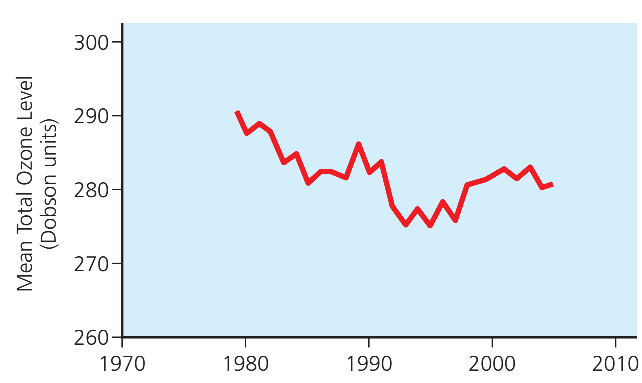


Figure 19-18 Global average total ozone values in the stratosphere at a certain latitude, 1979–2005 (Data from National Oceanic and Atmospheric Administration)

Based on these measurements and mathematical and chemical models, the overwhelming consensus of researchers in this field is that ozone depletion in the stratosphere poses a serious threat to humans, other animals, and some primary producers (mostly plants) that use sunlight to support the earth's food webs (**Concept 19-4A**).

This problem began when Thomas Midgley, Jr., a General Motors chemist, discovered the first chlorofluorocarbon (CFC) in 1930. Chemists soon developed similar compounds to create a family of highly useful CFCs, known by their trade name as Freons. These chemically unreactive, odorless, nonflammable, nontoxic, and noncorrosive compounds seemed to be dream chemicals. Inexpensive to manufacture, they became popular as coolants in air conditioners and refrigerators, propellants in aerosol spray cans, cleaners for electronic parts such as computer chips, fumigants for granaries and ship cargo holds, and gases used to fill tiny bubbles in plastic foam used for insulation and packaging.

It turned out that CFCs were too good to be true. Starting in 1974 with the work of chemists Sherwood Rowland and Mario Molina (Science Focus, at right), scientists demonstrated that CFCs are persistent chemicals that destroy protective ozone in the stratosphere. Measurements and models indicate that 75–85% of the observed ozone losses in the stratosphere since 1976 resulted from people releasing CFCs and other *ozone-depleting chemicals* into the atmosphere, beginning in the 1950s.

CFCs are not the only ozone-depleting chemicals. Others are *halons* and *hydrobromoflurocarbons* (*HBFCs*) (used in fire extinguishers), *methyl bromide* (a widely used fumigant), *hydrogen chloride* (emitted into the stratosphere by space shuttles), and cleaning solvents such as *carbon tetrachloride, methyl chloroform, n-propyl bromide,* and *hexachlorobutadiene.*

Models indicate that the Arctic is unlikely to develop the large-scale ozone thinning found over the Antarctic. They also project that ozone depletion over the Antarctic and Arctic will be at its worst between 2010 and 2019.

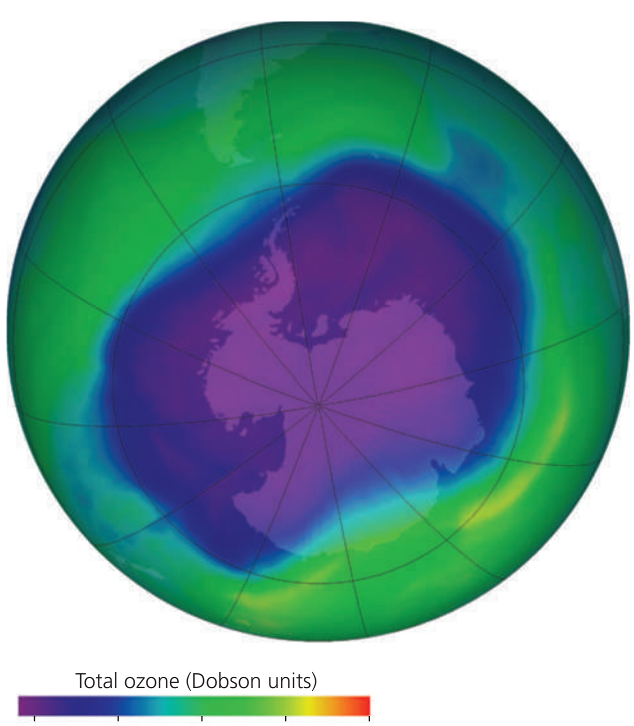


Figure 19-19 **Natural capital degradation:** massive ozone thinning over Antarctica in 2007. The deep blue in this colorized satellite image shows a large area where the concentration of ozone has decreased by 50% or more. (NASA)

NATURAL CAPITAL DEGRADATION

Effects of Ozone Depletion

Human Health

- Worse sunburns
- More eye cataracts
- More skin cancers
- Immune system suppression

Food and Forests

- Reduced yields for some crops
- Reduced seafood supplies from reduced phytoplankton
- Decreased forest productivity for UV-sensitive tree species

Wildlife

- Increased eye cataracts in some species
- Decreased populations of aquatic species sensitive to UV radiation
- Reduced populations of surface phytoplankton
- Disrupted aquatic food webs from reduced phytoplankton

Air Pollution and Materials

- Increased acid deposition
- Increased photochemical smog
- Degradation of outdoor paints and plastics

Global Warming

- While in troposphere, CFCs act as greenhouse gases

Figure 19-20 **Science:** expected effects of decreased levels of ozone in the stratosphere (**Concept 19-4A**). **Question:** Which three of these effects do you think are the most threatening? Why?

Why Should We Worry about Ozone Depletion?

Why should we care about ozone loss? Figure 19-20 lists some of the expected effects of decreased levels of ozone in the stratosphere. One effect is that more bio-

Sherwood Rowland and Mario Molina—A Scientific Story of Courage and

Sherwood Rowland and Mario Molina—A Scientific Story of Courage and Persistence

In 1974, calculations by chemists Sherwood Rowland and Mario Molina at the University of California–Irvine indicated that chlorofluorocarbons (CFCs) were lowering the average concentration of ozone in the stratosphere. They shocked both the scientific community and the $28-billion-per-year CFC industry by calling for an immediate ban of CFCs in spray cans, for which substitutes were available.

The research of these two scientists led them to four major conclusions. *First,* once injected into the atmosphere, these persistent CFCs remain there. *Second,* over 11–20 years, these compounds rise into the stratosphere through convection, random drift, and the turbulent mixing of air in the lower atmosphere.

Third, once they reach the stratosphere, the CFC molecules break down under the influence of high-energy UV radiation. This releases highly reactive chlorine atoms (Cl), as well as atoms of fluorine (F) and bromine (Br), all of which accelerate the breakdown of ozone (O_3) into O_2 and O in a cyclic chain of chemical reactions, one of which is shown in Figure 19-D. As a consequence, ozone is destroyed faster than it forms in some parts of the stratosphere.

Fourth, each CFC molecule can last in the stratosphere for 65–385 years, depending on its type. During that time, each chlorine atom released during the breakdown of CFC can convert hundreds of O_3 molecules to O_2.

The CFC industry (led by DuPont), a powerful, well-funded adversary with a lot of profits and jobs at stake, attacked Rowland's and Molina's calculations and conclusions. The two researchers held their ground, expanded their research, and explained their results to other scientists, elected officials, and the media. After 14 years of delaying tactics, DuPont officials acknowledged in 1988 that CFCs were depleting the ozone layer and they agreed to stop producing them.

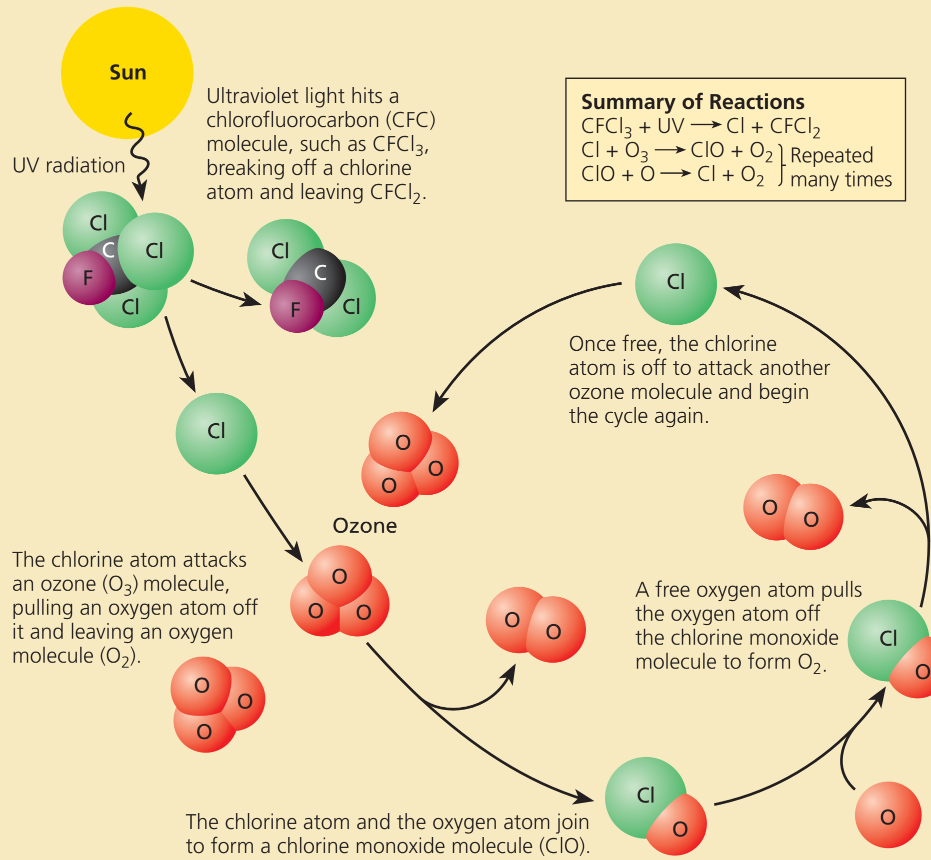


Figure 19-D Simplified summary of how chlorofluorocarbons (CFCs) and other chlorine-containing compounds can destroy ozone in the stratosphere faster than it is formed. Note that chlorine atoms are continuously regenerated as they react with ozone. Thus, they act as *catalysts*—chemicals that speed up chemical reactions without being used up by the reactions. Bromine atoms released from bromine-containing compounds that reach the stratosphere also destroy ozone by a similar mechanism.

In 1995, Rowland and Molina received the Nobel Prize in chemistry for their work on CFCs. In awarding the prize, the Royal Swedish Academy of Sciences said that the two scientists contributed to "our salvation from a global environmental problem that could have catastrophic consequences."

Critical Thinking

How does the problem of ozone depletion in the stratosphere differ from the problem of global warming?

logically damaging UV-A and UV-B radiation will reach the earth's surface (**Concept 19-4A**). This will give people more eye cataracts, worse sunburns, and more skin cancers (Science Focus, p. 526).

The most serious threat from ozone depletion is that the resulting increase in UV radiation could impair or destroy phytoplankton, especially in Antarctic waters (Figure 3-14, p. 63). These tiny marine plants play a key role in removing CO_2 from the atmosphere. They also form the base of ocean food webs. Destroying them would eliminate the vital ecological services they provide. Global warming could make this problem worse by slowing down the upwelling of nutrients that support these populations of phytoplankton. This in turn would accelerate global warming and lead to another runaway positive feedback loop.

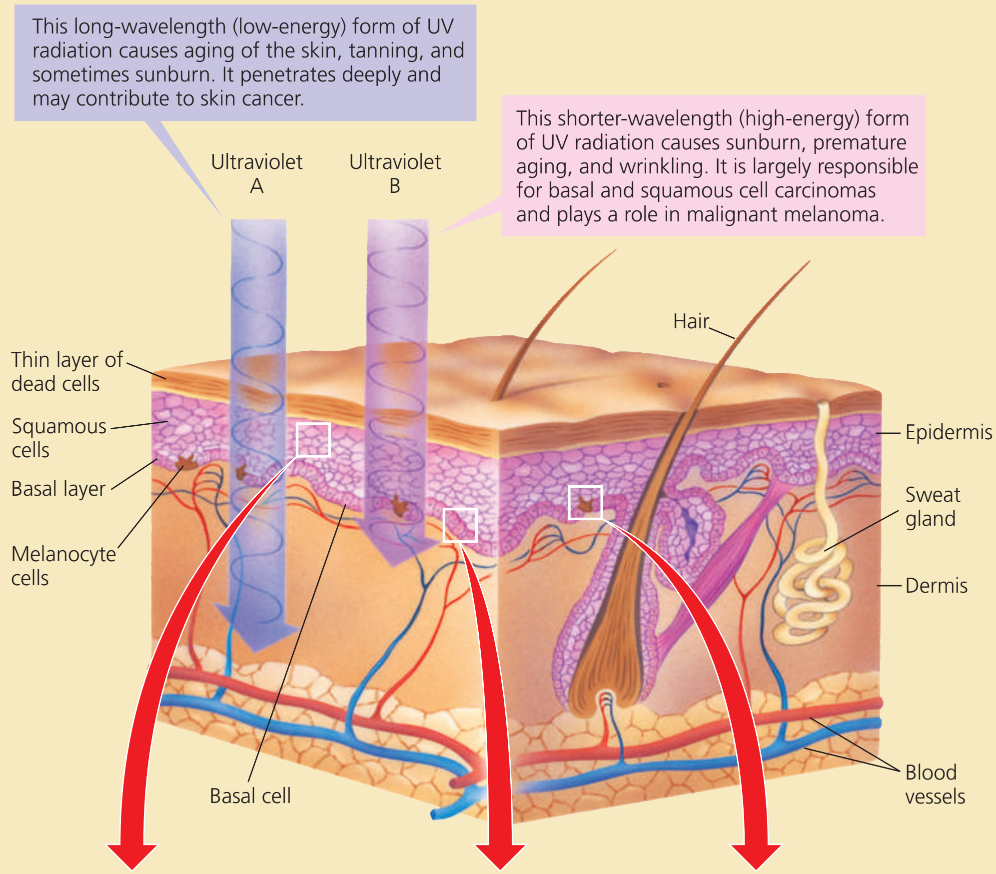
Skin Cancer

Research indicates that exposure to the UV-B ionizing radiation in sunlight is the primary cause of *squamous cell* (Figure 19-E, left) and *basal cell* (Figure 19-E, center) *skin cancers.* Together, these two types account for 95% of all skin cancers. Typically, a 15- to 40-year lag separates excessive exposure to UV-B and the development of these cancers.

Caucasian children and adolescents who experience only a single severe sunburn double their chances of getting these two types of cancers. Some 90–95% of these types of skin cancer can be cured if detected early enough, although their removal may leave disfiguring scars. These cancers kill 1–2% of their victims, which, in the United States, amounts to about 2,300 deaths each year.

A third type of skin cancer, *malignant melanoma* (Figure 19-E, right), occurs in pigmented areas such as moles. Within a few months, this type of cancer can spread to other organs. Melanoma kills about one-fourth of its victims (most of them younger than age 40) within 5 years, despite surgery, chemotherapy, and radiation treatments. Each year, it kills about 100,000 people (including 7,700 Americans), mostly Caucasians, and the number of cases and deaths is rising in many countries.

A 2003 study found that women who visited tanning parlors once a month or



Squamous Cell Carcinoma

Arising from cells in the upper layer of the epidermis, this cancer is also caused by exposure to sunlight or tanning lamps. It is usually curable if treated early. It grows faster than basal cell carcinoma and can spread to other parts of the body (metastasize).

Basal Cell Carcinoma

The most common skin malignancy usually is caused by excessive exposure to sunlight or tanning lamps. It develops slowly, rarely metastasizes and is nearly 100% curable if diagnosed early and treated properly.

Melanoma

This deadliest of skin cancers involves melanocyte cells, which produce pigment. It can develop from a mole or on blemished skin, grows quickly, and can spread to other parts of the body (metastasize).

Figure 19-E Structure of the human skin and the relationships between ultraviolet (UV-A and UV-B) radiation and the three types of skin cancer. (Data and photos from the Skin Cancer Foundation)

more increased their chances of developing malignant melanoma by 55%. The risk was highest for young adults. A 2004 study by Dartmouth College scientists found that people using tanning beds were also more likely to develop basal cell and squamous cell skin cancers.

People (especially Caucasians) who experience three or more blistering sunburns before age 20 are five times more likely to develop malignant melanoma than are those who have never had severe sunburns. About 10% of all people who get malignant melanoma have an inherited gene that makes them especially susceptible to the disease.

Figure 19-F lists ways for you to protect yourself from harmful UV radiation.

Critical Thinking

Which three of the measures listed in Figure 19-F do you think are the most important? Why? Which ones do you take?

WHAT CAN YOU DO?

Reducing Exposure to UV Radiation

- Stay out of the sun, especially between 10 A.M. and 3 P.M.
- Do not use tanning parlors or sunlamps.
- When in the sun, wear protective clothing and sunglasses that protect against UV-A and UV-B radiation.
- Be aware that overcast skies do not protect you.
- Do not expose yourself to the sun if you are taking antibiotics or birth control pills.
- When in the sun, use a sunscreen with a protection factor of at least 15.
- Examine your skin and scalp at least once a month for moles or warts that change in size, shape, or color and sores that keep oozing, bleeding, and crusting over. If you observe any of these signs, consult a doctor immediately.

Figure 19-F **Individuals matter:** ways to reduce your exposure to harmful UV radiation as suggested by dermatologists (skin experts).

We Can Reverse Stratospheric Ozone Depletion

According to researchers in this field, we should immediately stop producing all ozone-depleting chemicals (**Concept 19-4B**). However, models indicate that even with immediate and sustained action, it will take about 60 years for the earth's ozone layer to recover the levels of ozone it had in 1980, and it could take about 100 years for recovery to pre-1950 levels. Scientists have also discovered an important connection between warming of the troposphere and repair of the ozone layer. Warming of the troposphere makes the stratosphere cooler, which slows down the rate of its ozone repair.

In 1987, representatives of 36 nations met in Montreal, Canada, and developed the *Montreal Protocol.* This treaty's goal was to cut emissions of CFCs (but not other ozone-depleting chemicals) by about 35% between 1989 and 2000. After hearing more bad news about seasonal ozone thinning above Antarctica in 1989, representatives of 93 countries met in London in 1990 and then in Copenhagen, Denmark, in 1992. They adopted the *Copenhagen Protocol,* an amendment that accelerated the phase-out of key ozone-depleting chemicals. These landmark international agreements, now signed by 191 countries, are important examples of global cooperation in response to a serious global environmental problem. If nations continue to follow these agreements, ozone levels should return to 1980 levels by 2068 (18 years later than originally projected) and to 1950 levels by 2108 (**Concept 19-4B**).

The ozone protocols set an important precedent by using *prevention* to solve a serious environmental problem (**Concept 1-4**, p. 16). Nations and companies agreed to work together to solve this global problem for three reasons. *First,* there was convincing and dramatic scientific evidence of a serious problem. *Second,* CFCs were produced by a small number of international companies. *Third,* the certainty that CFC sales would decline over a period of years unleashed the economic and creative resources of the private sector to find even more profitable substitute chemicals.

CONCEPT LINK

Good news. Substitutes are available for most uses of CFCs, and others are being developed (see Individuals Matter, p. 459). However, the most widely used substitutes, such as HCFC-22, cause some ozone depletion. In 2007, delegates from 191 nations met in Montreal, Canada, and agreed to phase out the production of HCFCs by 2020 in developed countries and by 2030 in developing nations—10 years earlier than they had agreed to under the 1992 Copenhagen Protocol. On its trip to the stratosphere, a typical HCFC molecule helps warms the troposphere by as much as 10,000 times more than does a molecule of CO_2. Thus, phasing out HCFCs to help protect the stratosphere will also help us to reduce global warming in the troposphere.

REVISITING Volcanic Eruptions, Climate Change, Ozone Depletion and Sustainability

CORE CASE STUDY

SUSTAINABILITY

In this chapter, we have seen that humans play a major role in changing the earth's climate by emitting huge quantities of chemicals that warm the troposphere and deplete ozone in the stratosphere. Occasional large volcanic eruptions also emit CO_2 and other pollutants into the lower atmosphere (**Core Case Study**). But about three-fourths of current emissions of CO_2 come from human activities, especially the burning of fossil fuels. Thus, energy policy (Figure 16-33, p. 432) and climate policy (Figures 19-13, 19-14, and 19-17) are closely connected.

The four **scientific principles of sustainability** (see back cover) can be applied to help reduce the harmful effects of global climate change and stratospheric ozone depletion. We can reduce inputs of greenhouse gases and ozone-depleting chemicals into the atmosphere by relying more on direct and indirect forms of solar energy than on fossils fuels; reducing the waste of matter and energy resources and recycling and reusing matter resources; mimicking biodiversity by using a variety of carbon-free renewable energy resources determined partly by local and regional availability; and reducing human population growth and wasteful resource consumption. We can also find substitutes for ozone-depleting chemicals and emphasize pollution prevention.

According to the scientific consensus, we need to implement known solutions to the problems of climate change and ozone depletion, and we must do this globally and on an emergency basis. Each of us has an important role to play in protecting the atmosphere—an irreplaceable resource that sustains all life on earth.

The atmosphere is the key symbol of global interdependence.
If we can't solve some of our problems
in the face of threats to this global commons,
then I can't be very optimistic
about the future of the world.

MARGARET MEAD

REVIEW

1. Review the Key Questions and Concepts for this chapter on p. 497. Describe how a major volcanic eruption (**Core Case Study**, Figure 19-1) allowed scientists to test the validity of climate models. CORE CASE STUDY
2. Describe global warming and cooling over the past 900,000 years and during the last century. How do scientists get information about past temperatures and climates? What is the greenhouse effect and why is it so important to life on the earth? What is the scientific consensus about global temperature change during the last half of the 20th century and about projected temperature changes during this century?
3. How can positive feedback loops affect future temperature changes and thus global climate? Give two examples of such loops. Describe the role played by oceans in the regulation of atmospheric temperatures. What are three factors that could decrease its effect in moderating temperature increases?
4. Describe how each of the following might affect global warming and its resulting effects on global climate: **(a)** cloud cover and **(b)** air pollution. Briefly describe the projections of scientists on how global warming is likely to affect: drought; ice cover; flooding; sea levels; permafrost; ocean currents; extreme weather; biodiversity; crop yields; and human health during this century.
5. What are five reasons for the fact that it is difficult to deal with the problem of climate change due to global warming caused mostly by human activities? What are four major strategies for slowing projected climate change? What is **carbon capture and storage (CCS)?** Describe six problems associated with capturing and storing carbon dioxide emissions.
6. List four things that governments could do to help slow projected climate change. What are the pros and cons of the Kyoto Protocol? What have the U.S. state of California and the U.S. city of Portland, Oregon, done to help reduce their greenhouse gas emissions?
7. Give two examples of what some major corporations and some schools have done to reduce their carbon footprints. List five ways in which you can reduce your carbon footprint. List five ways in which we can prepare for the possible long-term harmful effects of climate change.

8. Describe how human activities have depleted ozone in the stratosphere, and list five harmful effects of such depletion. Describe how scientists Sherwood Roland and Mario Molina helped to awaken the world to this threat. Describe the relationships between higher UV levels and three types of skin cancer. What has the world done to help reduce the threat from ozone depletion in the stratosphere?

9. Describe how the four **scientific principles of sustainability** can be applied to deal with the problems of climate change (**Core Case Study**) and ozone depletion.

SUSTAINABILITY

CORE CASE STUDY

Note: Key Terms are in **bold** type.

CRITICAL THINKING

1. What might happen to the earth's climate if several large-scale eruptions like the one on Mount Pinatubo in 1991 (**Core Case Study**) took place at the same time?

CORE CASE STUDY

2. A top U.S. presidential economic adviser once gave a speech in Williamsburg, Virginia (USA), to representatives of governments from a number of countries. He told his audience not to worry about global warming because the average global temperature increases predicted by scientists were much less than the temperature increase he had experienced that day in traveling from Washington, D.C., to nearby Williamsburg. What was the flaw in his reasoning? Write an argument that you could use to counter his claim.

3. How might the earth's climate change if the land area of the planet were larger than the planet's ocean area?

4. List three ways in which you could apply **Concept 19-3A** to making your lifestyle more environmentally sustainable.

5. Explain why you agree or disagree with each of the proposals listed in Figure 19-13 for slowing projected climate change caused by atmospheric warming.

6. What changes might occur in **(a)** the global hydrologic cycle (Figure 3-17, p. 66) and **(b)** the global carbon cycle (Figure 3-18, p. 68) if the atmosphere experiences significant warming? Explain.

7. One way to slow the rate of CO_2 emissions is to reduce the clearing of forests—especially in tropical developing countries where intense deforestation is taking place. Should the United States and other developed countries pay poorer countries to stop cutting their forests? Explain.

8. What are three consumption patterns or other aspects of your lifestyle that directly add greenhouse gases to the atmosphere? Which, if any, of these habits would you be willing to give up to help slow projected climate change?

9. Congratulations! You are in charge of the world. List your three most important strategies for dealing with the problems of **(a)** global climate change due to atmospheric warming caused mostly by human activities and **(b)** depletion of ozone in the stratosphere.

10. List two questions that you would like to have answered as a result of reading this chapter.

Note: See Supplement 13 (p. S78) for a list of Projects related to this chapter.

ECOLOGICAL FOOTPRINT ANALYSIS

Largely because of the intense use of fossil fuels, per capita CO_2 emissions for the United States are nearly five times the world average. According to a recent report from the International Energy Agency, the average American is responsible for adding 19.6 metric tons (21.6 tons) of CO_2 per year to the atmosphere, compared with a world average of 4.23 metric tons (4.65 tons). The table on p. 530 is designed to help you understand the sources of your personal inputs of CO_2 into the atmosphere and how you can reduce your inputs.

Some typical data are provided in the "Typical Quantity per Year" column of the table. However, the calculations will be more accurate if you can substitute for these typical values information based on your own personal lifestyle, which you can enter in the blank "Personal Quantity" column. For example, you could add up your monthly utility bills for a year and divide the total by the number of persons in your household to determine your utility use, and you could analyze your driving habits to determine how much fuel you use in automobile transportation.

After completing the table, you can compare your emissions against the per capita U.S. average. Your answer should be considerably less—roughly half the per capita value, because this computation only accounts for direct emissions. For instance, CO_2 resulting from driving a car is included, but the CO_2 emitted in manufacturing or disposing of the car is not.

Finally, you can check your result against the greenhouse gas calculator provided on the web by the EPA at **epa.gov/climatechange/emissions/ind_calculator.html**.

	Units per Year	Personal Quantity per Year	Typical Quantity per Year	Multiplier	Emissions per Year (lbs. CO_2)
Residential Utilities					
Electricity	kwh		4,500	1.5	
Heating oil	gallons		37	22	
Natural gas	hundreds of cubic feet (ccf)		400	12	
Propane	gallons		8	13	
Coal	tons		–	4,200	
Transportation					
Automobiles	gallons		600	19	
Air travel	miles		2,000	0.6	
Bus, urban	miles		12	0.07	
Bus, intercity	miles		0	0.2	
Rail or subway	miles		28	0.6	
Taxi or limousine	miles		2	1	
Other motor fuel	gallons		9	22	
Household Waste					
Trash	pounds		780	0.75	
Recycled Items	pounds		337	−2	
				Total (pounds)	
				Total (tons)	
				Total (kilograms)	
				Total (metric tons)	

Source: This CO_2 calculator was developed by Thomas B. Cobb, Bowling Green State University, Bowling Green, Ohio (USA).

1. Calculate your carbon footprint. To calculate your emissions, first complete the blank "Personal Quantity" column using your personal information (for a more accurate outcome) or using data from a typical utility bill and from other personally known information. If your information is not available, use the data listed in the "Typical Quantity" column. Then, for each activity, calculate your annual consumption (using the units specified in the "Units per Year" column), and multiply your annual consumption by the associated number in the "Multiplier" column to obtain an estimate of the pounds of CO_2 resulting from that activity. Finally, add the numbers in the "Emissions" column to find your carbon footprint, and express the final CO_2 result in both pounds and tons (1 ton = 2,000 lbs) and in kilograms and metric tons (1 kilogram = 2.2 pounds and 1 metric ton = 1.1 tons).
2. Compare your emissions with the per capita U.S. average of 19.6 metric tons (21.6 tons) of CO_2 per person per year and with those of your classmates.
3. Consider what actions you might take to reduce your carbon footprint by 20%.

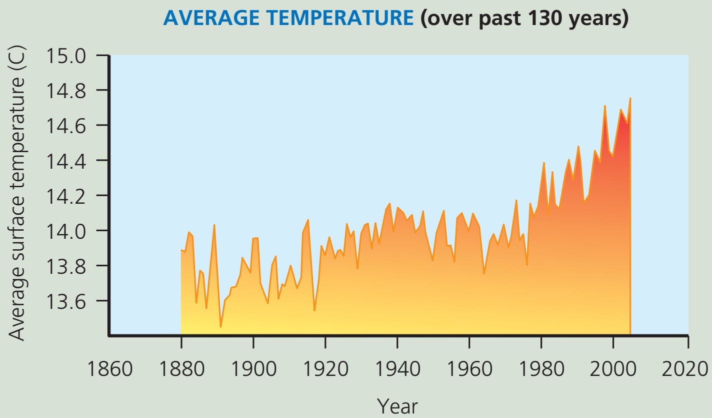
LEARNING ONLINE

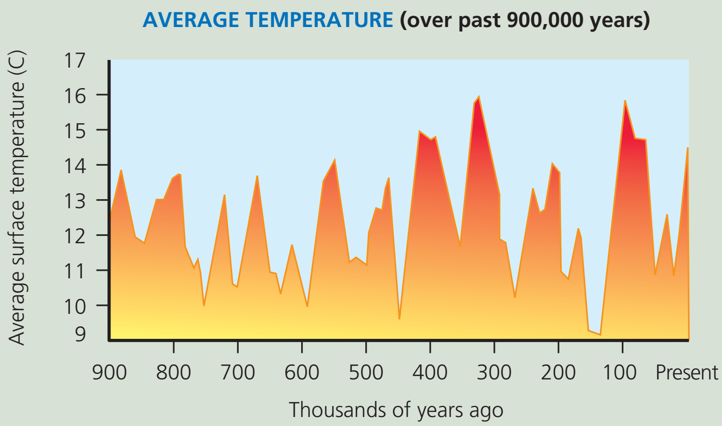
Log on to the Student Companion Site for this book at **academic.cengage.com/biology/miller**, and choose Chapter 19 for many study aids and ideas for further reading and research. These include flash cards, practice quizzing, Weblinks, information on Green Careers, and InfoTrac® College Edition articles.

AP* Review Questions for Chapter 19

1. What was one result for climatologists of the Mount Pinatubo eruption?
(A) Climatologists were unable to make any predictions about the effect of the eruption on global climate.
(B) Climatologists were able to assess their predictions of the eruption on global temperatures.
(C) Climatologists predicted no global changes from the eruption.
(D) Climatologists were not making predictions when Pinatubo erupted.
(E) Climatologists had to radically revise their predictions based on the eruption.

Questions 2 and 3 are based on the diagram below.





2. Which of the statements below about the earth's current warming trend is true based on the diagrams above?
(A) There has been a uniform warming of the earth since 1900.
(B) The temperature of the earth has been stable and unchanging over the previous centuries.
(C) Greenhouse gases have been slowly accumulating in the atmosphere promoting global warming.
(D) The earth has experienced many warming and cooling trends over the previous centuries.
(E) Humans have been influencing global temperatures for the last few centuries.

3. Calculate the average annual change in temperature from 1900 to 2000.
(A) .006
(B) .06
(C) .6
(D) 6
(E) 60

4. Which of the factors described below was not utilized to generate the data shown in the graphs above?
(A) Bubbles of ancient air found in ice cores
(B) Pollen samples taken from the bottoms of lakes
(C) Dust samples from the ozone layer
(D) Historical records
(E) Pollen and minerals in different layers of bat dung

5. Which of the factors below has a cooling effect on the earth's atmosphere?
(A) Particulate matter from burning grasslands and forests
(B) Aerosols such as sulfate particles
(C) Carbon particles from diesel exhaust
(D) Carbon dioxide from burning fossil fuels
(E) Condensation trails left by jet planes

6. Which of the effects below is unavoidable due to the current warming trend of the earth?
(A) Flooding of low lying cities and island nations
(B) Melting of the permafrost and tundra that releases methane gas
(C) Premature extinction of 20–30% of plant and animal species
(D) Bleaching of coral reefs and spread of deserts
(E) Collapse of the Amazon rain forest

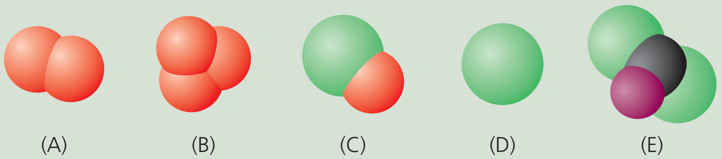
7. Which of the events below is a positive feedback mechanism that could be accelerating the warming of the earth's atmosphere?
(A) Absorption of CO_2 by the oceans
(B) Increase in severe weather in certain areas
(C) Severe drought causing the earth to be browner and absorb more radiation
(D) Spraying of sulfate particles in the atmosphere that reflect light
(E) Changing of ocean currents that carry heat to different places

8. A 2007 IPCC report stated that the world's oceans are very likely to rise 18–59 cm during this century. The majority of this rise will occur as
(A) increased rainfall.
(B) the melting of the Arctic ice sheet.
(C) the melting of icebergs.
(D) the melting of land-based ice.
(E) the expansion of water as it warms.

9. Which of the means below is **NOT** a way of reducing the release of greenhouse gases into the atmosphere?
(A) Utilizing cleaner burning natural gas with less sulfur
(B) Increasing the production of energy with nuclear power
(C) Using conservation tillage on all cropland
(D) Increasing the efficiency of coal fired plants
(E) Shifting to renewable energy sources

10. Which of the effects below is **NOT** a result of ozone depletion in the stratosphere?
(A) Increased sunburns
(B) Increased skin cancers
(C) Disrupted populations of phytoplankton
(D) Increased asthma and bronchitis problems
(E) Degradation of outdoor paints and plastics

11. Which of the diagrams below is an appropriate representation of the ozone molecule?



12. Which of the statements below is **NOT** true of CFC molecules as they rise through the atmosphere?
(A) CFCs remain in the atmosphere for extended periods of time.
(B) CFCs rise through the atmosphere via convection currents.
(C) CFCs are broken down by UV radiation releasing chlorine atoms.
(D) CFC atoms can last in the atmosphere hundreds of years.
(E) CFC atoms are no longer a danger to ozone after UV light breaks them down.

13. Many climate-change analysts believe that because of the difficulty in making large reductions in greenhouse gases, we need to prepare for the harmful effects of large-scale climate warming and change. Which of the methods below is a means of preparing for long-term harmful effects of climate change?
(A) Replace incandescent light bulbs with compact fluorescents
(B) Plant trees to shade houses and absorb CO_2 from the atmosphere
(C) Buy products from companies that are actively reducing their carbon footprints
(D) Walk, bike, carpool, or utilize mass transit
(E) Connect wildlife reserves with corridors and move people inland