CHAPTER 16

Global Warming, Part 2

Impacts, Adaptation, and Mitigation

Key Questions

- How is sea level projected to change over the next century?
- How will forests and other ecosystems respond to atmospheric CO_2 increases?
- How will global warming affect humans, and how will the effects vary in different parts of the world?
- How can one estimate the economic damages from global warming, along with the costs necessary to combat it? Should we start doing so now, or should we postpone action until the future?
- What specific policies might be adopted to reduce future CO_2 emissions?

Chapter Overview

The effects of climate change are likely to affect both abiotic and biological parts of the Earth system. Sea level is predicted to rise by 0.1–0.3 m over the next century from thermal expansion of seawater as the ocean warms. Much larger increases in sea level—from several meters to several tens of meters—could occur in the more distant future if sustained warm surface temperatures lead to melting of the Greenland and West Antarctic ice sheets. Future increases in atmospheric CO_2 concentrations and changes in climate are also likely to affect both natural and human ecosystems. Some of these changes may be difficult or impossible to counter, whereas humans may be able to simply adapt to other changes. Slowing or halting global warming will require widespread changes in modes of energy production and perhaps (although not necessarily) in lifestyles, as well. Specific policies that might be implemented to make this happen include taxes on carbon emissions and tax incentives for renewable energy resources and for fuel-efficient vehicles. The long-term nature of the global warming problem means that policy decisions made today will affect the lives and welfare of future generations in the United States and elsewhere. Hence, issues of international and intergenerational equity must be considered.

INTRODUCTION

In the last chapter, we saw that both atmospheric CO_2 concentrations and global surface temperatures are predicted to rise over the next few centuries if fossil fuels continue to be burned in large quantities. We saw also that these changes may be accompanied by changes in the distribution and intensity of rainfall and in ocean circulation. But the climate system itself is not the only thing that concerns us. Rather, it is the predicted changes in sea level and effects on ecosystems, both natural and human, that are of primary importance. What are the most significant impacts expected to be, and how might we adapt to them? Even more importantly, if we decide that these impacts are unacceptable, how might we go about slowing or halting global warming? Here, we explore some of these questions, along with specific policies that might be adopted, both nationally and globally, to solve this problem.

CHANGES IN SEA LEVEL

How concerned should we be about the prospect of future global warming? The answer depends not only on the magnitude and rate of the climate change itself, but also on the effects of that change on other parts of the Earth system. One factor that we must consider in any discussion of long-term global warming is sea level. But before we consider how sea level might change in the future, we must backtrack momentarily and see what we understand about sea-level changes in the recent past.

Sea-Level Change during the 20th Century

Researchers have estimated that sea level has increased by approximately 20 cm since 1880 (Figure 16-1). The data come from tide gauges on various shorelines around the world and, more recently (since 1992), from satellite altimetry. The satellite data are the most accurate, but the record is short, only about 17 years. Interpreting the tide gauge measurements is complicated, because the solid Earth itself is moving up or down in some locations. Parts of Canada and Europe, for instance, are moving upward at a rate of a few centimeters per century, because they are still rebounding from the weight of the great ice sheets that covered these regions as recently as 11,000 years ago. In contrast, the Nile River delta is subsiding, because silt from the Nile has increased the loading in this region. These localized trends in land surface elevation must be subtracted from the tide gauge data before we can draw any inferences about sea-level change.

The increase in global sea level during the 20th century parallels the rise in global mean surface temperature (see Figure 15-5). Indeed, approximately half of the rise in sea level can be attributed to simple **thermal expansion** of surface-ocean water. Water, like most other materials, normally expands as it warms. (More correctly, pure water expands when it warms except when its temperature is between 0 and 4°C, when warming causes it to contract. Seawater, however, does not exhibit this unusual behavior.) Because the lateral boundaries of the ocean are largely fixed, any expansion of ocean volume must result in a rise in sea level. The 0.8°C atmospheric temperature rise during the 20th century is expected to have warmed the surface ocean by this same amount, which should have increased sea level by about 8 cm. An increase of 0.8°C in the temperature of the deep ocean would cause a much larger increase in sea level, but such a change would take many centuries to occur, because the thermohaline circulation is very slow. Changes in deep-ocean temperatures caused by Milankovitch cycles may be responsible for periodic sea-level fluctuations of about 5 m that are recorded in carbonate platforms formed during the Mesozoic and Paleozoic eras.

Most of the remaining increase in sea level during the 20th century is thought to have been caused by melting of **mountain glaciers**, ice fields formed on the cold, upper reaches of mountains (Figure 16-2). Several glaciers in the Alps are known to have retreated during the past two centuries as Earth emerged from the Little Ice Age. Glaciers in the high Andes Mountains in Peru are also known to be receding rapidly at present. If this trend were to continue, sea level might eventually rise by another 40 cm from this source alone.

Sea-Level Rise in the Future

A serious concern for the future is that the polar ice caps will begin to melt. Only the ice that is now on land is important in this respect. The melting of sea ice does not

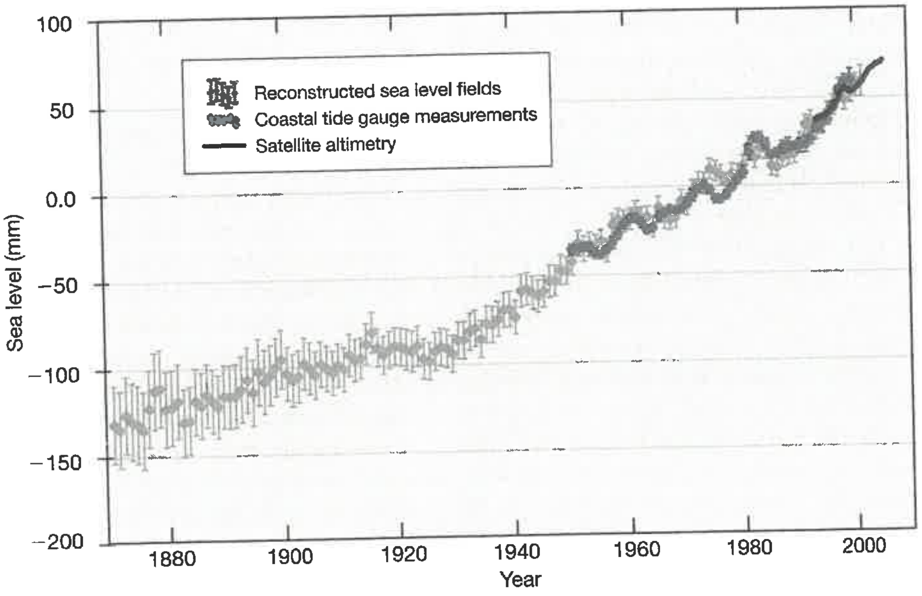

FIGURE 16-1 Global sea-level rise since 1880 (relative to the interval 1961–1990). Most of the data come from tide gauges. The last 15 years are from satellite altimetry. (*Source:* IPCC 2007, Chapter 5, Fig. 5.13.)

FIGURE 16-2 A mountain glacier. (*Source:* Gilbert S. Grant/Photo Researchers.)

increase sea level, because floating ice displaces an amount of seawater that is precisely equal to its mass. Recall from Chapter 1 that this may be thought of as an application of Archimedes' principle.

Today, large continental ice sheets are found on Greenland and Antarctica. The Greenland ice sheet contains enough water to raise sea level by approximately 7 m, were it to melt entirely. The Antarctic ice sheet contains much more water—some 60 to 70 m of equivalent sea-level rise. However, these two ice sheets are expected to behave quite differently as the climate warms. The island of Greenland extends to lower latitudes than does the continent of Antarctica, so the climate in southern Greenland is considerably warmer than the Antarctic climate. The Greenland ice sheet is therefore much more likely to experience increased melting as the climate warms than is the Antarctic ice sheet. Over most of Antarctica increased snowfall (resulting from warmer ocean temperatures and increased evaporation rates) is expected to cause the ice sheet to thicken over the next 50 to 100 years. This phenomenon could, paradoxically, cause global sea level to decrease as atmospheric CO_2 levels increase. However, it is likely to be outweighed in importance by melting that occurs in other regions.

The West Antarctic Ice Sheet

The actual situation in Antarctica is even more complicated than we have indicated. The Antarctic ice sheet can be divided geographically into an eastern and a western part. (See Figure 1-6a in Chapter 1.) The East Antarctic ice sheet contains most of the water (about 60 m of equivalent sea level) and is the part that might thicken as the climate warms. The West Antarctic ice sheet contains less water (about 5 to 6 m of equivalent sea level), but its response to greenhouse warming is expected to be quite different. This ice sheet flows primarily into the Ross and Weddell seas, where it forms **ice shelves**, large expanses of floating sea ice formed at the margins of continents. That in the Ross Sea is called the Ross Ice Shelf, and that in the Weddell Sea is called the Filchner-Ronne. Both ice shelves are grounded at several points on offshore islands.

Glaciologists have speculated that an increase in water temperature of just a few degrees in the Ross and Weddell seas could melt enough ice off the bottom of these ice shelves to cause them to become completely free-floating. As a result of this melting, those parts of the West Antarctic ice sheet that feed these shelves might flow much more rapidly, because the contact with the offshore islands currently inhibits the glaciers' flow. Such a sudden, rapid increase in a glacier's flow rate is called a **glacial surge**. Glacial surges are occasionally observed in mountain glaciers, and there is indirect evidence (from ice-rafted debris in North Atlantic sediments) that they occur in continental-scale glaciers as well. Once started, a glacial surge tends to perpetuate itself, because the increased flow rate causes frictional heating at the base of the glacier. This heating, in turn, produces a thin layer of water that allows the glacier to slide more smoothly over the surface. If such a positive feedback process were to be triggered by global warming, the West Antarctic ice sheet might thin relatively rapidly and could contribute significantly to sea-level rise over the next few centuries.

Projections of Future Sea-Level Rise

Given all these possible effects, what can we say about sea-level change in the near future? Will the observed upward trend of the 20th century continue?

The IPCC's projections of possible sea-level increase during the 21st century are shown in Figure 16-3. The curve shown is for the A1B or medium-emissions scenario. These calculations take into account thermal expansion of the oceans and melting of mountain glaciers, along with a minimal contribution from polar ice-sheet melting. The projected increases in sea-level range from 20 to 50 cm for this medium-emissions scenario. These rates of increase are two to three times faster than the rate of increase that occurred in the 20th century. Sea-level increases of this magnitude could pose problems for low-lying areas such as the Gulf coast of North America, Bangladesh, and numerous islands in the South Pacific and Indian oceans.

A potentially more serious problem is the change that might occur in the more distant future. (Indeed, some glaciologists believe that such changes might begin to occur within the next century as a consequence of nonlinear ice-sheet dynamics that are not included in the IPCC projections.) The amount of water now tied up in polar ice is so large, and the projected time scale for global warming is so long, that sea level could ultimately increase by many meters. As one concrete example, Chapter 10 of the 2007 IPCC report discussed one particular simulation in which an AOGCM was coupled to a model of the Greenland ice sheet. The atmospheric CO_2 concentration was held constant at four times the preindustrial value, and the two models were run together for a total time of 1,760 years. The resulting behavior

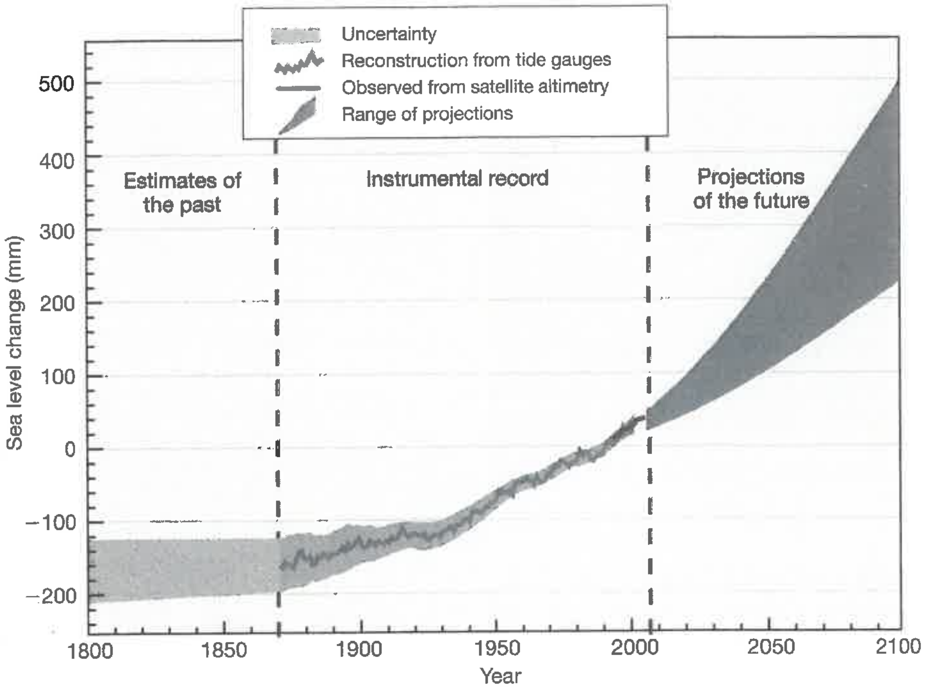

FIGURE 16-3 Predicted changes in sea level over the next century for the medium-emissions case shown in Figures 15-8 and 15-12. (*Source:* IPCC 2007, FAQ5.1, Fig. 1.)

of the ice sheet is shown in Figure 16-4. By the end of the first 270 years, the ice sheet has lost 20% of its volume. This would correspond to a sea-level rise of a little over 1 m. The next 20% of the ice sheet disappears by year 710. By the end of the simulation, only 20% of the ice-sheet remains, so sea level should be higher by about 4–5 m.

Although these projected future changes in Greenland ice-sheet volume are highly speculative, there is reason to believe that such behavior is not impossible. Sea level during the previous interglacial period (termed the Eemian), about 125,000 years ago, is thought to have been about 6 m higher than today. Evidence from ice cores in south Greenland suggests that ice may not have been present in this region and that as much as half of the 6-m sea-level increase may have been caused by melting of the Greenland ice cap. This interpretation is disputed by some glaciologists, and so it should not be blindly accepted. Global surface temperatures during the Eemian, however, were only about 1°C warmer than today, based on oxygen isotopes (see Chapter 14). Could the Greenland (and West Antarctic) ice sheets be less stable than we think? This is a research question that clearly deserves further study.

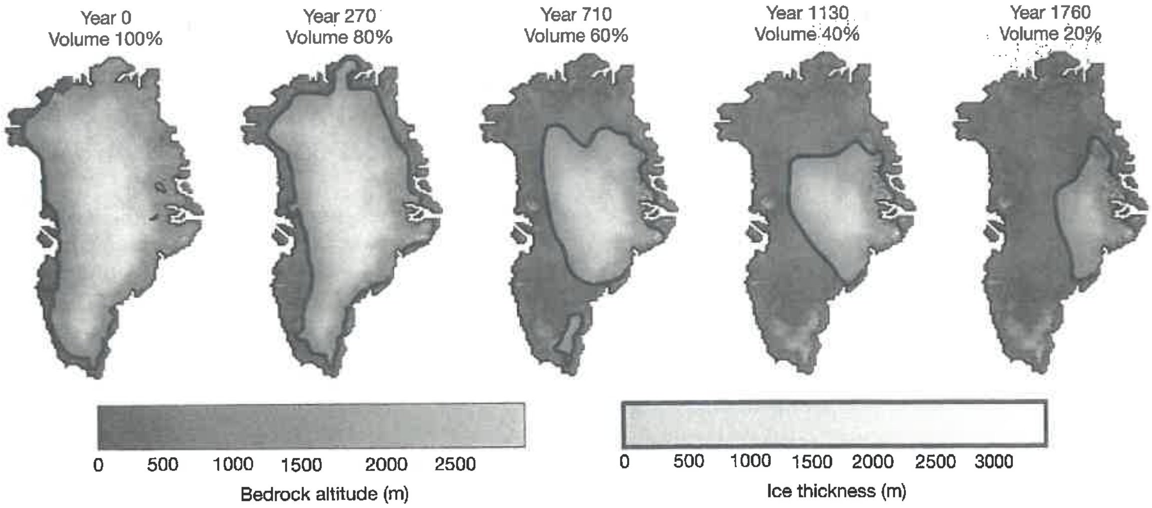

FIGURE 16-4 Predictions of Greenland ice-sheet mass for a climate simulation in which the atmospheric CO_2 concentration was held constant at four times its preindustrial value. (*Source:* IPCC 2007, Chapter 10, Fig. 10.38.)

How serious would such a change be if it were to happen today? A sea-level increase of this magnitude would wreak havoc with Earth's present geography. A 6-m rise in sea level, like the one that occurred during the Eemian, would submerge the southernmost one-third of Florida. In the very long term (thousands of years in the future), it is conceivable that the polar caps could melt entirely if we were to consume all of the available fossil fuels. This melting would increase sea level by 70 to 80 m and would submerge roughly 20% of the present continents. So, our decisions about fossil-fuel usage over the next few centuries could have major repercussions for our descendants.

EFFECTS ON ECOSYSTEMS

We have already mentioned several effects of increased CO_2 on terrestrial and marine ecosystems. Higher atmospheric CO_2 concentrations are expected to cause increased rates of plant growth. Plants are also expected to use water more efficiently at high CO_2 levels, because they do not need to open their stomata as wide to obtain CO_2 for photosynthesis and because stomatal density also decreases in plants grown under elevated CO_2. This increased efficiency might be offset in some regions by decreased soil moisture during the summertime growing season.

If we examine ecosystems in more detail, the possible changes induced by higher CO_2 levels and higher temperatures become more and more complex. This should not come as too much of a surprise, as biological systems are incredibly complicated by comparison with most physical systems. Here, we mention only a few of the many changes that are expected to take place. We expand upon this topic in Chapter 18.

C_3 and C_4 Plants

Different types of plants have different mechanisms of **carbon fixation**, the biochemical process that occurs during photosynthesis by which atmospheric CO_2 is converted to organic carbon. Most photosynthetic organisms alive today (about 95% of all terrestrial plants) fix carbon by a biochemical pathway called the **Calvin cycle**. The first step of this cycle involves the production of a stable, intermediate compound (3-phosphoglyceric acid) that contains three carbon atoms. Hence, this process is called *C_3 photosynthesis*, and plants that metabolize in this way are termed **C_3 plants.**

Some plants, however, including corn, sugarcane, and many tropical grasses, begin the photosynthetic process by producing a four-carbon compound. (Actually, corn and sugarcane are themselves species of grasses, although we do not usually think of them as such.) Plants of this type are termed **C_4 plants**. As a consequence of biochemical modifications, C_4 plants are able to photosynthesize at much lower CO_2 concentrations than are C_3 plants. Indeed, C_4 plants became widespread only about 7 or 8 million years ago, possibly in response to decreased atmospheric CO_2 levels caused by the uplift and weathering of the Himalayan Mountains (see Chapter 12). Also, C_4 plants are much less responsive to CO_2 increases than are C_3 plants (See the Box "A Closer Look: Physiological versus Ecological Optima for Growth" in Chapter 9). Thus, whereas CO_2 fertilization might have an important effect on the growth rate of C_3 plants, it is not expected to have a large effect on C_4 plants. Certain agricultural crops, such as corn, could be at a disadvantage compared with C_3 weeds in a high-CO_2 world.

Changes in Speciation within Forests

Even within the C_3 world, different types of plants are expected to exhibit different responses to changes in temperature and moisture availability that might accompany CO_2 increases. Figure 16-5 shows the predicted response of various tree species in Minnesota to estimated climate

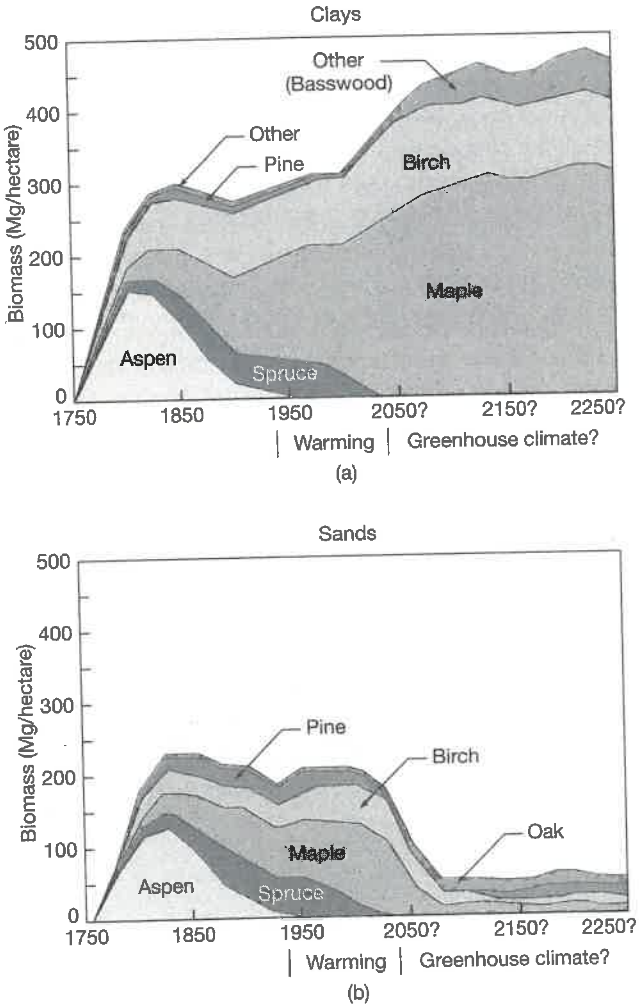

FIGURE 16-5 Predictions of species composition, in terms of (aboveground) biomass in Minnesota forests under doubled-CO_2 conditions, (a) for a clay soil, with a high water-holding capacity, and (b) for a sandy soil, with a low water-holding capacity. (*Source:* IPCC, *Climate Change: The IPCC Scientific Assessment*, Cambridge: Cambridge University Press, 1990.)

changes since 1750 and projected to A.D. 2250. The results depend strongly on whether the local soil has a high water-holding capacity (Figure 16-5a) or a low one (Figure 16-5b). In the first case, some species (maple and birch) thrive at high CO_2 levels, whereas others (aspen and spruce) decline when the temperature becomes too warm. In the second, all species do poorly after A.D. 2050 because the soil becomes too dry to support them. A general conclusion that we can reach, irrespective of the details of the calculation, is that species distributions within ecosystems are likely to change as the global climate warms.

A particular concern related to this change in species distribution is whether midlatitude forests will be able to keep pace with the anticipated rate of climate change. Climatic warmings have occurred many times in the past, most recently at the end of the last glaciation around 12,000 years ago. However, the modern world is different from the postglacial world in several respects. Perhaps most importantly, forests in regions such as North America and Europe have been dissected by farms and highways, which tend to inhibit the migration of species. Thus, the poleward spread of species adapted to warmer climates might not occur fast enough to keep pace with the rate at which the climate warms. The extinction of many species of trees and animals could result unless humans intervene actively to facilitate the migration process.

Other Concerns

Accompanying the poleward migration of temperate and subtropical vegetation would be a migration of animal and insect species that live in warm climates. Insects, in particular, pose a significant problem for agriculture. If midlatitude winters become less severe, insect pests that are confined to the tropics today could expand their ranges to midlatitudes. For example, in the United States the potato leafhopper (Figure 16-6), a serious pest in soybean and other crops, is currently confined to a narrow band bordering the Gulf of Mexico. Warmer winters might allow this pest to double or triple its range. The expansion of insect ranges might well be one of the most economically damaging consequences of climate change.

FIGURE 16-6 A potato leafhopper. This insect, along with other agricultural pests, could expand its range poleward if the climate warms. (*Source:* Donald Specker/Animals Animals/Earth Scenes.)

Various human diseases, such as malaria, that are currently confined to the tropics might become a problem at midlatitudes as well. Malaria is spread by the *Anopheles* mosquito, whose life cycle does not allow it to survive cold winters. If wintertime temperatures remained above freezing in the continental United States, as might happen 100 to 200 years from now if atmospheric CO_2 levels continue to increase, malaria-bearing mosquitoes might be able to live there, presenting a whole new set of potential health problems.

Increased atmospheric CO_2 levels and associated global warming could also affect marine ecosystems. Aquatic photosynthesizers, which include both phytoplankton and larger, multicellular organisms such as kelp, are not expected to have increased growth rates from CO_2 fertilization because their growth rates are generally limited by other nutrients, especially phosphorus, nitrogen, and iron. Corals are likely to be directly affected by the acidification of the ocean that accompanies the buildup of atmospheric CO_2 (see Chapter 14). This stress on their ability to grow their calcium carbonate skeletons is in addition to the stress from elevated sea-surface temperatures that are already causing "bleaching events"—the loss of the corals' symbiotic algae. Warmer temperatures could also affect ocean currents and upwelling zones, for example, by stabilizing the water column against mixing and wind-driven upwelling. Upwelling of nutrient-rich deep water is the key factor that accounts for regions of high productivity in the modern oceans, such as the Grand Banks off the coast of Labrador or the fisheries off the coast of Peru. If the intensity or location of upwelling were to change as the climate warms, it could have major effects on both the high-productivity ecosystems themselves and on the fishing industry that takes advantage of them.

HUMAN IMPACTS OF GLOBAL WARMING

Floods, Droughts, and Freshwater

A likely consequence of increasing atmospheric carbon dioxide levels is an intensification of the hydrological cycle, that is, the global average rates of evaporation and precipitation. Climate models project that this will translate into a more complex geographical pattern of more frequent droughts and floods in areas already subject to these extreme climate events (see Chapter 15).

A reliable and clean drinking water supply is perhaps the most fundamental requirement of a healthy world population. Much of the current increase in population is occurring in regions that have marginal or unreliable water supplies. As a result, these supplies are already being taxed. Specific examples include:

- More frequent droughts in regions such as the southwestern United States are likely to exacerbate water-supply problems in the future.
- Nearly 15% of the world's population depends on seasonal melting of mountain glaciers for their drinking water supply, and these glaciers are disappearing at an alarming rate as a consequence of climate change.
- Sea-level rise causes saltwater intrusion into coastal aquifers, rendering them unusable to a growing coastal population.

Global Conflict

The risks from global warming extend well beyond the issues of ecosystem damage, sea-level rise, and food and water shortages. One key area of concern is national security. Our ongoing dependence on foreign oil is obviously of great concern to countries such as the United States that import most of their fossil fuel, and is one of the more immediate drivers for the development of alternative energy sources. A more subtle, but growing, concern is the opening of the Arctic Ocean, which has been becoming increasingly ice-free during the latter part of Northern Hemisphere summer. Nations now see opportunities for shipping through the Arctic Ocean during the summer and fall months, but they also recognize that they have new coastlines to protect. The Arctic seafloor is also thought to be rich in petroleum, and several countries are now jockeying for control of the mineral rights of this newly accessible real estate. In other parts of the world, climate change is already creating "environmental refugees" who are fleeing their drought-afflicted homelands. Such influxes of refugees across national boundaries can lead to unrest and discontent. Rainfall distributions, river courses, and groundwater resources know no political boundaries (except to the extent that they have already been modified by engineering activities designed to capture water). As water supplies diminish and populations grow, the potential for conflict continues to escalate.

Food Shortages

Amidst these dire predictions for the future is one positive consequence of the buildup of carbon dioxide: an increase in crop productivity for large regions of North America and Europe. Climate models predict that these regions should experience generally favorable shifts in precipitation, coupled with longer growing seasons. Furthermore, C_3 crops, which include most common food sources, will be "fertilized" by elevated carbon dioxide, a plant nutrient. However, other regions are likely to suffer reduced crop yields because of decreased rainfall. Moreover, the benefits in North America and Europe are projected to be only short term. Eventually, as CO_2 levels continue to increase and the global climate continues to warm, most of the agricultural regions of the world are expected to suffer reduced agricultural productivity. Moreover, marine fisheries are likely to be impacted by warming sea temperatures, resulting in reduced biological productivity and fish populations.

ADAPTING TO GLOBAL WARMING

According to the latest IPCC report (see Chapter 15), even if we were to stop burning fossil fuels and cutting down old-growth forests today, global temperature would increase by another 0.6°C by the end of the century because certain components of the climate system (*e.g.*, the oceans and glaciers/ice sheets) respond sluggishly to climate forcing. Moreover, as this chapter is being written, there is no sign that we will significantly reduce, let alone eliminate, anthropogenic greenhouse-gas emissions in the near future. Thus, some amount of adaptation to climate change will be necessary. Vulnerability to the detrimental effects of climate change differs among nations, and as it turns out, those regions most vulnerable (e.g., Africa) are often not the major contributors to the problem. Below we discuss two environmental changes to which society will need to adapt in the coming decades: sea-level rise and challenges to water supply and agriculture. In the next section we discuss the alternative to adaptation, namely, *mitigation*. Clearly, a measure of each of these approaches will be key to creating a sustainable human future.

Adapting to Sea-Level Rise

A significant problem facing society is that a large fraction of the world's population lives close to sea level. Researchers at Columbia University, who define low-elevation coastal zones (LECZs) as those with an elevation of less than 10 m above sea level, place this number at 10%. Of particular concern are the developing countries of Bangladesh and Vietnam, both of which have large numbers of people living in LECZs.

The developed world is also at risk. Consider the United States: many of its major urban centers, including parts of New York City, Miami, and Boston, where more than 20 million people live, are in LECZs (Figure 16-7). The Netherlands already has 60% of its population living in LECZs. Based on their experiences and on others we have learned quite a bit about which measures to protect LECZs work and which don't. With varying levels of success, inundated land has been reclaimed, and dikes and dams have been installed. These measures have their limits, though, and ultimately people living in LECZs will have to find ways to accommodate inundation. These include building flood-proof structures and using floating agricultural systems. Eventually, retreat to areas further inland may be the only adaptation available. The low slope

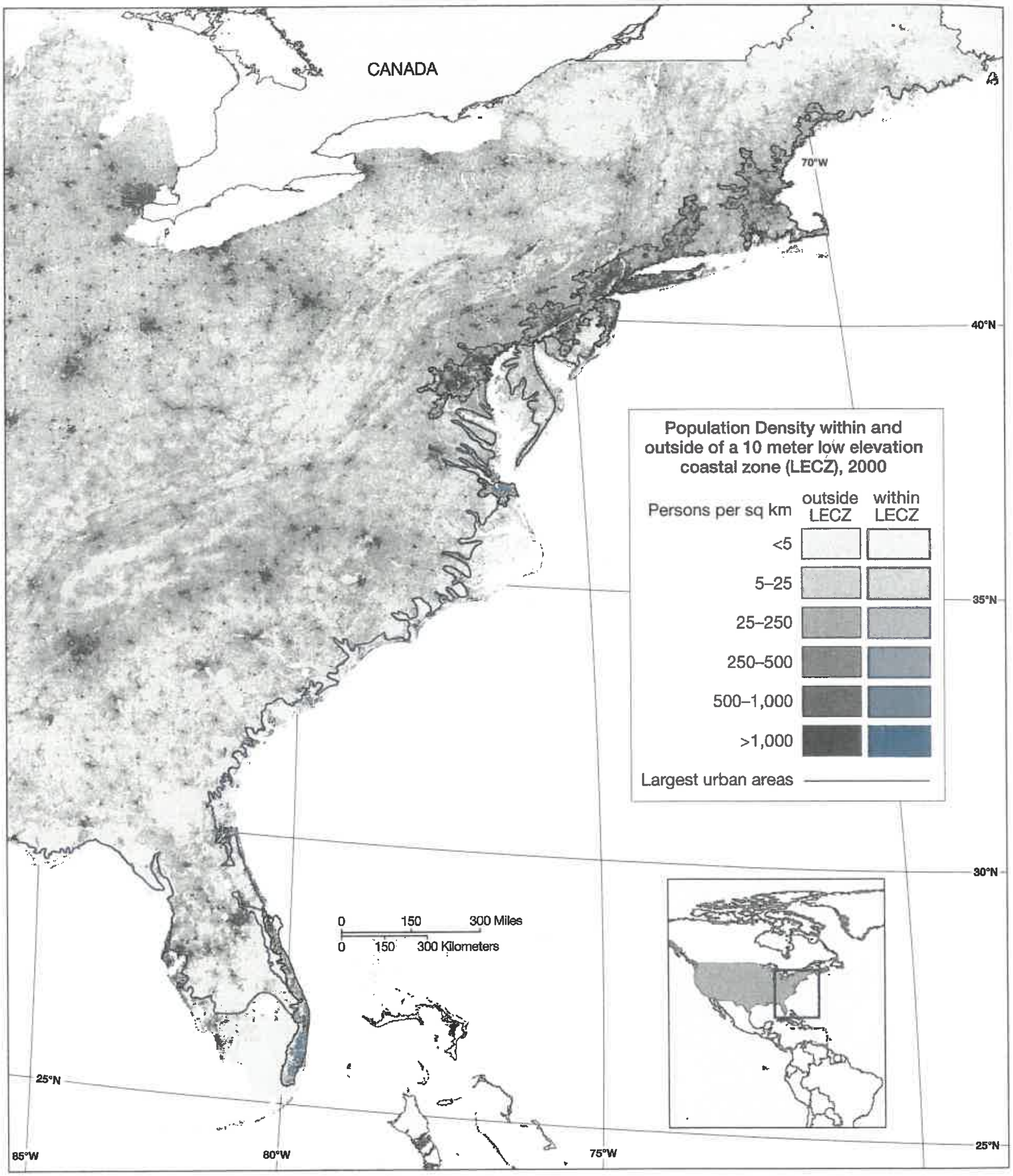

FIGURE 16-7 Map showing the low-elevation coastal zone (LECZ) along the east coast of the United States. An LECZ is defined as a region that is within 10 m of sea level. (*Source:* http://sedac.ciesin.columbia.edu/gpw/maps/lecz/USA_10m_LECZ_and_population_density.jpg.)

of coastal zones means that 1 m of sea-level rise could translate into a kilometer or more of required retreat.

Water Management

How do we ensure adequate and clean water for the burgeoning world population in a time when human-induced climate change is reducing the quantity and dependability of existing water supplies? A number of steps can be taken to both provide more water and to reduce demand. On the supply side, more effort can be placed on prospecting for groundwater, collecting rainwater, and building larger reservoirs for water storage. Seawater desalinization plants can be built in coastal areas, and more efficient water transport networks can be constructed. Demand can be reduced by recycling water and wastewater after treatment (so-called beneficial reuse). Cropping calendars, crop mixes, irrigation methods, and areas planted can all be adjusted to minimize irrigation demands on water. In urban areas, economic incentives including metering and higher pricing can be used to reduce water demand.

POLICIES TO SLOW GLOBAL WARMING

Should we take action now to slow or halt global warming? Whether immediate action is warranted is one of the most hotly debated political issues of our time. The theoretical argument that warming will eventually occur is rock solid. The evidence that CO_2-induced global warming has already started is also very strong, as we saw in Chapters 1 and 15. Because of the high cost of addressing the problem, however, there is an understandable reluctance in most societies to act hastily. The attitude of many citizens and some governments is to wait and see how bad the problem is before we commit any substantial resources to addressing it.

The Kyoto Protocol

In 1997, an international conference was convened in the city of Kyoto, Japan, for the purpose of creating an international treaty, or protocol, to regulate CO_2 emissions. The treaty called for economically developed countries, like the United States, Europe, and Japan, to roll back CO_2 emissions to 5% below 1990 levels. Since that time, 182 countries have ratified the **Kyoto Protocol**, including all members of the European Union, Russia, and Japan. Many developing countries, such as India, Brazil, and China, also ratified the treaty. This was easy for them to do, however, because the treaty did not require any emissions reductions from developing nations. The United States, notably, has *not* signed the Kyoto Protocol. There are several reasons for this—one of them being skepticism about climate science on the part of the Bush administration. To be fair, however, the Kyoto treaty was first proposed under the preceding Clinton administration, which also failed to take any action on it. Indeed, in 1997 the U.S. Senate (which must approve all international treaties) voted 95–0 against supporting any CO_2 treaty that did not include limits on emissions from developing nations. So, there has been bipartisan opposition to this treaty within the United States, even though many U.S. climate scientists (and former vice president Al Gore) strongly supported it.

Energy Conservation and Other "Soft" Measures

Whether or not the Kyoto treaty was worth signing, many U.S. citizens (including the authors of this textbook) are convinced that actions should be taken to reduce emissions of CO_2 and other greenhouse gases and to at least make a start in slowing the process of global warming. To begin, there are a number of "soft" measures that might be taken that would be relatively inexpensive and that would require little or no change in people's lifestyles. One step on which virtually everyone agrees is to encourage energy conservation. Every kilowatt-hour of electricity or gallon of gasoline saved is one less that contributes to CO_2 buildup in the atmosphere. Indeed, many conservation measures have already been implemented. Homes built in the United States today are typically much better insulated than were homes built a generation ago. New cars get significantly better fuel mileage than did cars built in the 1960s, although the trend toward larger cars and SUVs during the past two decades has rolled back some of the gains in fuel efficiency that had occurred during the 1970s and early 1980s. Gasoline prices near \$4 per gallon are now starting to push back car sales to smaller, more fuel-efficient vehicles. (Note added in proof: As a result of the 2008 recession, gas prices *fell* to below \$2 per gallon! However, they are creeping up again in early 2009, and we suspect that they will top \$4 per gallon again within the next year or two.)

Planting trees is another step that can be taken with which few people would disagree. As discussed in Chapter 8, trees take up CO_2 during the time that they are growing to maturity. This typically takes on the order of 50 to 100 years. Once a forest has reached steady state, however, then further CO_2 uptake is generally balanced by CO_2 released from the death and decomposition of older trees. Furthermore, living forests contain only about the same amount of carbon as does the atmosphere, whereas the amount of carbon potentially available from fossil fuels is much larger. So, this policy could potentially buy us some time, but it is not a long-term solution to the problem of global warming.

Energy-conservation and tree-planting measures are to be lauded, but those who have thought seriously about the global warming problem realize that these measures by themselves are not likely to solve it. One way of demonstrating this is by performing "inverse" calculations with carbon cycle models. In an inverse calculation, one *assumes* a specified stabilization level for atmospheric CO_2 and then calculates what level of CO_2 emissions would be required to produce it. For example, suppose we wanted to stabilize atmospheric CO_2 at 450 ppm. According to Figure 16-8, this stabilization would require a decrease in net CO_2 production from 6 Gton(C)/yr to just over 1 Gton(C)/yr by the year 2300. Cutting global fossil-fuel usage by this amount would be a daunting task. The task might be made somewhat easier if the terrestrial biosphere were still absorbing CO_2 at that time, but such absorption may or may not occur. Thus, we can conclude that large reductions in fossil-fuel consumption would be necessary to stabilize atmospheric CO_2 anywhere near its present value. With world population increasing, and with developing countries eager to raise their standard of living to levels comparable to those in the West, the demand for energy is likely to increase despite our best efforts to conserve. If we wish to fulfill this demand and still reduce CO_2 emissions, we will either have to develop nonfossil energy sources or figure out ways to capture and sequester CO_2.

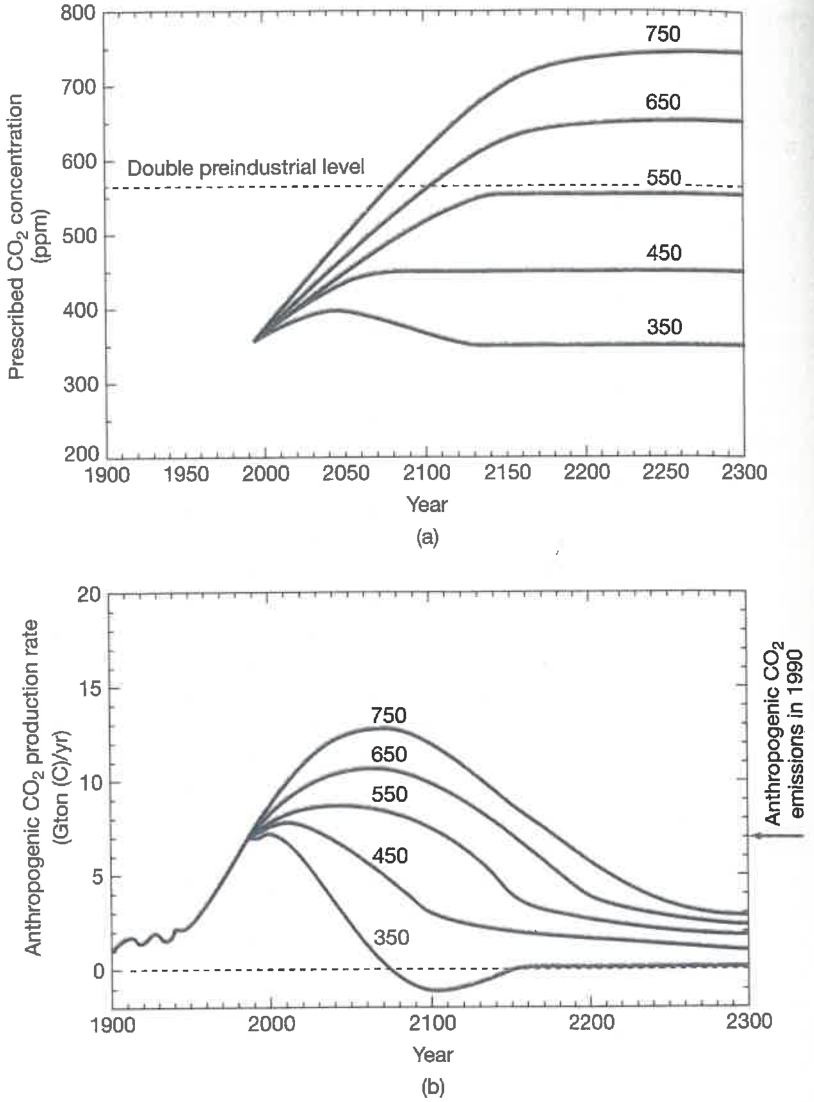

FIGURE 16-8 (a) Various prescribed levels of atmospheric CO_2. Stabilization at these levels requires (b) these new CO_2 emission rates. (*Source: Climate Change 1994: Radiative Forcing of Climate Change*, Cambridge: Cambridge University Press, 1994.)

Alternative Energy Sources

What alternative, nonfossil energy sources might we turn to? For the production of electricity, nuclear energy is one option that is currently available. Conventional nuclear power plants (Figure 16-9) produce energy from the **nuclear fission** of uranium atoms, the splitting of an atomic nucleus into two fragments, accompanied by the release of energy. This process, which is the basis for the atomic bomb, produces no CO_2 (although some CO_2 is produced in mining the uranium fuel by means of conventional, gasoline-powered machinery). Many environmentalists, however, feel that nuclear power poses its own threat to the global environment. A large part of their concern stems from the problem of disposal of long-lived radioactive wastes. Although several methods have been proposed for handling wastes, none of them is totally without risk. Nuclear waste disposal sites are vigorously opposed by citizens in areas where the potential sites are to be located. Local opposition has so far prevented the United States from opening its planned nuclear waste storage facility at Yucca Mountain in Nevada. Although many Nevadans see such a delay as positive, it is not without negative consequences. From a practical standpoint, most of the waste produced by existing nuclear reactors is still stored on-site in large underground "swimming pools" rather than in a long-term facility designed for that purpose.

Acceptance of nuclear power varies widely from one country to another. The United States produces about 20% of its energy from nuclear power, but no new nuclear plants have been ordered by utilities for more than 25 years, partly as a result of pressure from vocal antinuclear lobbying groups. Germany and Sweden have also almost abandoned this energy option. Conversely, both France and Japan have active nuclear programs, and both produce the majority of their electricity from nuclear power. One reason for their different outlook may lie in the fact that neither country has appreciable domestic reserves of coal or oil.

A second type of nuclear power that shows some hope for the future is **nuclear fusion**, the combining of

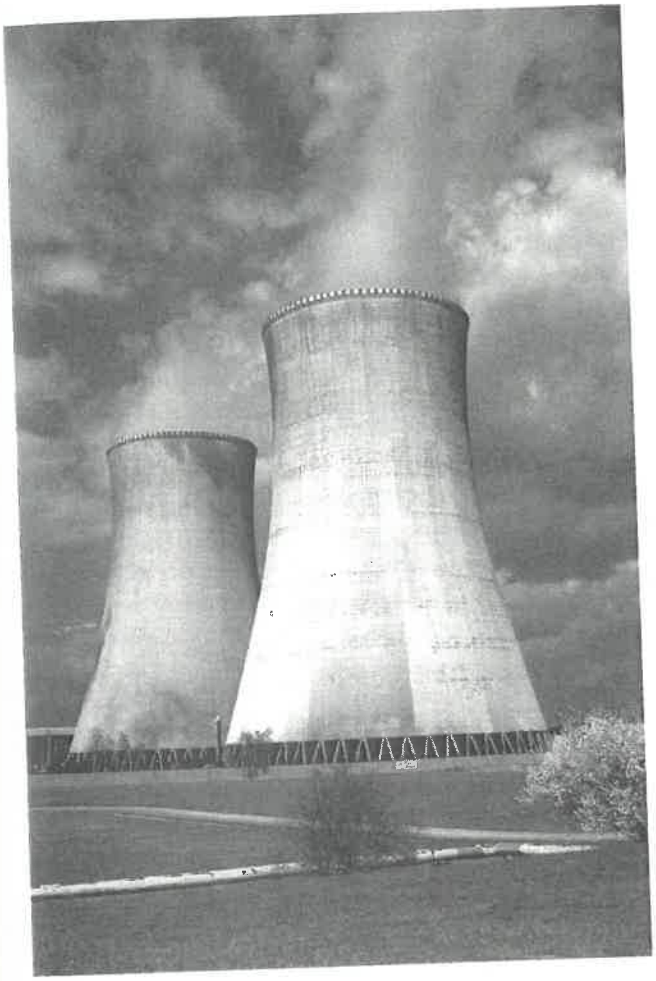

FIGURE 16-9 A nuclear power plant. (*Source:* Petr Student/iStockphoto.)

lightweight atomic nuclei into a heavier nucleus, with an accompanying release of energy. The fusion of hydrogen atoms into helium is the energy source that powers the Sun. Prototype fusion reactors on Earth use the hydrogen isotopes deuterium (^{2}H) and tritium (^{3}H) as fuel, because these atoms can fuse at lower temperatures than can the normal (^{1}H) isotope. Deuterium is fairly abundant on Earth; 16 of every 100,000 atoms of hydrogen in seawater consist of this isotope. Unfortunately, designing a successful fusion reactor is a technologically daunting task. As one wag put it, "nuclear fusion has been 30 years over the horizon for the last 50 years." If ongoing efforts to design fusion reactors succeed, this process could eventually be an important source of energy.

Other non-CO_2-producing energy sources include wind power, tidal power, geothermal power, and biomass-based fuels. **Wind power** generates electricity by means of windmills, which utilize Earth's solar-energy-driven winds. Wind power is "clean and green," but it is not a consistent source of energy because the wind does not blow all the time. Hence, it generally must be backed up with more reliable sources of power. **Tidal power** produces electricity by using long, floating booms to harness the energy of ocean tides. Its potential disadvantage is that it encroaches on coastal areas that often have many other uses, such as recreation. **Geothermal power** utilizes temperature gradients within the solid Earth as an energy source for generating electricity. It works best in places like Iceland, where hot magma is only a few kilometers beneath the surface.

Biomass-based fuels are liquid fuels, such as methanol (CH_3OH) or ethanol (C_2H_5OH), that are produced from fast-growing plants. **Ethanol** is produced from corn in the United States and from sugarcane in Brazil. **Biodiesel** is another biomass fuel that is produced from fats or oils (soybean oil, in particular) and that is widely available in Europe. These fuels deserve special attention because they can be (and are being) used to power vehicles, thereby supplementing or replacing conventional oil-based gasoline. Biomass fuels release CO_2 when they are burned, but the plants from which they are made absorb CO_2 while they are growing, so the net effect on the atmospheric CO_2 budget is zero. It would seem at first glance that these fuels are an unadulterated "plus" from an environmental standpoint. In reality, though, the story is more complicated. Corn-based ethanol actually reduces CO_2 emissions by only a small amount because of the large amount of energy needed to grow and harvest it. **Cellulosic ethanol** (ethanol produced from the woody cellulose part of plants) would be more efficient, but economical ways of producing it are still under development.

All biomass fuels suffer from another problem that is even more serious. Devoting land (and fertilizer) to growing them reduces the amount of land that is available to cultivate food crops. Production of corn-based ethanol in the United States has already driven up the price of corn by more than a factor of 2 over the past few years. The effects of this price increase have been felt not just in the United States, but also in countries such as Mexico that import U.S.-grown corn. Hence, the environmental benefits from the use of biomass fuels must be weighed against the negative impacts on food production and food prices. This does not mean that we should abandon biomass fuels, but it does indicate that we must carefully consider their overall impact on the global economy and on global welfare in general.

Perhaps the most promising energy source in the long term is solar energy. Sunlight is a clean and virtually inexhaustible energy source that is on the verge of becoming economically competitive. In some favorably situated areas, such as southern California, solar power is already competitive and contributes a substantial amount of electrical energy to local power grids. In sunny areas, **solar thermal power** is an efficient method for producing electricity (Figure 16-10). In this method, sunlight is used to heat a fluid that, in turn, drives a turbine. In more northern regions, the production of electricity from **photovoltaic cells**, specially designed panels that can directly convert sunlight into electricity, may be the most practical solution.

FIGURE 16-10 A solar thermal power plant. (*Source:* Hank Morgan/Photo Researchers.)

Photovoltaic cells, similar to those flown on satellites, are currently more expensive than conventional energy sources, however. Ultimately, huge orbiting **solar-power satellites** may collect the Sun's energy in space and beam it to Earth's surface as laser or microwave radiation. Another idea is to build solar-power collectors on the Moon and beam the energy back from there. (Surprisingly, this appears to be technologically feasible!) Such systems could be built by the more industrially developed nations to provide power across the entire globe. Much work would need to be done to determine whether space-based solar-power systems could be designed to be both economical and safe. They appear to be exorbitantly expensive today, but they might be more cost-effective in the future as space technology advances.

Carbon Capture and Storage

Another approach to CO_2-free electrical power generation is to continue to burn coal, but to trap the CO_2 that is produced and bury it underground, either in deep, land-based geological formations, the deep ocean, or the upper parts of the oceanic crust. This approach is termed **carbon capture and storage (CCS)** or, equivalently, **carbon sequestration**. There are several approaches to doing this. One is to burn the coal in pure O_2 rather than air. The exhaust is then composed of nearly pure CO_2 plus H_2O. The two gases can be easily separated by cooling because H_2O condenses at a higher temperature. The CO_2 can then be liquified and transported to the storage site by pipelines. A second approach is to run hot steam through the coal before it is burned. The coal is partially oxidized during this process and it releases **syngas**, which is a mixture of CO (carbon monoxide) and H_2. The CO is then oxidized to CO_2 by the **water–gas shift reaction**:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The net result of this process is the production of molecular hydrogen, H_2, which can be cleanly burned to produce H_2O as the only byproduct. CO_2 is generated in both steps of this process; however, it is in a nearly pure-CO_2 airstream and can be captured and sequestered, as before.

CCS technology is promising and is being further developed by a number of different countries. If it proves to be commercially feasible, it would allow us to continue to use our abundant coal reserves as a source of energy without exacerbating the problem of global warming. There are downsides to this process, however. For one, the technology is relatively expensive. It has been estimated that implementing CCS would increase the cost of electrical power generation by at least 50% for new coal-fired plants and by as much as a factor of 2 for existing plants that would need to be retrofitted. Although painful, these additional costs might well be worth bearing if they allowed us to protect the environment. A more serious issue with CCS is that the long-term effects of CO_2 sequestration are largely unknown. Injection of CO_2 into the deep ocean could contribute to ocean acidification, which is a hazard to marine life. CO_2 storage on land could result in highly acidic groundwater, which might then leach out of confinement and create problems with groundwater supplies in nearby areas. Neither of these problems appears insurmountable; however, the environmental effects of CO_2 sequestration clearly require further study. If CCS can be done in an environmentally friendly way, then perhaps this technology will play an important role in satisfying our long-term energy requirements.

Geoengineering of Global Climate

Even more exotic approaches have been discussed to combat global warming. Perhaps the most extreme idea is to allow greenhouse gases, including CO_2, to accumulate, but then to counteract their effects by artificially cooling the climate. This class of solutions is referred to as **geoengineering**. This sounds difficult, and indeed it would be, but there may be ways to do this using current technology. The idea that has received the most attention so far is to purposely seed the stratosphere with sulfate aerosol particles. This could be done, for example, by building large guns at many different locations around the globe and using them to shoot sulfate-filled explosive capsules up into the stratosphere. As we saw in Chapter 1, sulfate aerosols cool the climate by reflecting some of the incident solar energy back to space, that is, by increasing Earth's albedo. Aerosol particles remain in the stratosphere for only a few months; hence, they would need to be continually injected in order for this mechanism to work.

While this class of solutions deserves careful study, there are reasons to think that this approach is of questionable value. Stratospheric aerosol particles would be unlikely to remain evenly distributed from one location to another; hence, they might alter global weather patterns in ways that are difficult to predict. Aerosol particles can also serve as surfaces that liberate chlorine from unreactive compounds and convert it into forms that can destroy ozone (see Chapter 17). Paul Crutzen, a famous atmospheric chemist who received the Nobel Prize for his work on ozone depletion, has pointed out that this should not necessarily pose a problem, because stratospheric chlorine levels should be significantly lower by the end of this century as a result of ozone protection policies that have already been enacted. Still, one wonders whether there might be other such reactions that might become important should the stratosphere become loaded with aerosol particles.

An additional objection that applies to other geoengineering approaches as well is that, while they address the problem of global warming, they do not address the related problem of ocean acidification. As we saw in the previous chapter, atmospheric CO_2 concentrations could approach 2000 ppm if we burn an appreciable fraction of the available fossil fuels. This could cause an appreciable drop in surface-ocean pH, and that in turn could result in the dissolution of many species of calcareous plankton and corals. So, even if a geoengineered climate was deemed acceptable by humans, the effects on marine ecosystems might be so severe that this option would be rejected for other reasons.

Specific Policies That Might Be Adopted

How could a shift to nonfossil energy sources be promoted if such action is deemed necessary? More generally, what types of policies might be adopted that would reduce greenhouse gas emissions by whatever mechanism?

One way of reducing carbon dioxide emissions is by the imposition of direct governmental regulations. An example that is already in effect in the United States is the **CAFÉ** (Combined Automobile Fleet Emissions) **standard** that governs cars sold. Each manufacturer's fleet must meet an average fuel economy rating specified by the federal government. These standards may well be raised in the near future if Congress decides that more fuel-efficient cars should be available. There is a downside to this, though. In the past, auto manufacturers have circumvented the rules by helping to get SUVs classified as "light trucks," for which the fuel-efficiency standards are less strict. And, although the CAFÉ standards undoubtedly increase the number of small, fuel-efficient cars that are sold, they do little to encourage people to drive less or to live closer to their workplace. If one drives 75 minutes each way to work—which is the average commute in both Los Angeles and Atlanta—then even if one is driving a Prius, the amount of CO_2 released will still be relatively large.

A more efficient mechanism for reducing CO_2 emissions would be to impose a tax on any energy source that produces CO_2. Such a **carbon tax** would make other forms of energy more economically competitive and, hence, more likely to be exploited. It would, for example, favor nuclear- or wind-based production of electricity as opposed to coal-fired power plants. It would also encourage people to drive cars that are fuel efficient and to commute shorter distances to work. The carbon tax could be augmented by a "gas-guzzler" tax on fuel-inefficient automobiles. Such taxes need not represent an additional burden on the average citizen, because all or part of the revenue that they generate could be returned to the public in the form of income tax breaks. Some of the proceeds might also be used to construct better rail systems so that more people and goods could be moved by trains (which could be designed to be entirely electric). A carbon tax would be costly to some industries and localities, however, particularly those involved in mining coal or in producing oil. In the United States, the energy-rich western states, along with some eastern coal-producing states, including Pennsylvania and West Virginia, might lose jobs if such a policy were implemented. Thus, measures such as this are not likely to be accepted unless the population at large becomes alarmed about global warming.

ECONOMIC CONSEQUENCES OF GLOBAL WARMING

How can we decide which policy would best deal with global warming? Should we take strong steps now, or should we wait and see for a while longer and see how things develop? One approach that is certain to be used to address this question is to analyze the problem from an economic standpoint. Each of the physical effects that we have talked about will have some effect on the future economy of the United States and of the world as a whole. Agricultural output, for example, is almost certain to be affected. Some of the changes, such as decreased soil moisture in continental interiors, will be detrimental to agricultural output while other changes, CO_2 fertilization of plant growth for example, are expected to be beneficial. By now, many economists have developed forecast models that attempt to calculate how the projected changes in CO_2 and climate will affect the global economy.

Cost–Benefit Analysis

The way that such calculations are typically done is by what is often termed **cost–benefit analysis**. At least some of the changes anticipated from global warming are likely to cost money to deal with. Relocating cities away from continental coastlines is one obvious example. On the other hand, reducing CO_2 emissions is likely to cost money, too. As discussed further below, alternative means of producing energy are available, but none of these is currently as convenient or inexpensive as fossil fuels. Thus, if society chooses to reap the economic benefits of limiting climate change, certain costs will be incurred. The goal of economic models of global warming is to determine how these projected costs and benefits balance out. From an economic standpoint, the optimum solution is one in which the benefits less the costs is at a maximum.

A detailed analysis of such economic models is beyond the scope of the present discussion. It may nonetheless be useful to make a few comments about them because of their importance to climate policy. The first comment is that all of the economic models are highly uncertain—more so, even, than the physical models of global warming. This should come as no surprise. Predicting the behavior of humans is inherently more difficult than predicting the behavior of physical systems. This does not mean that economic models are of no use, however. As with physical models that contain large inherent uncertainties (clouds in climate models, for example), we can still use these models to help guide our choices.

Economic models, however, often contain value judgments in addition to other uncertainties. As an example, consider the ongoing debate about how much money to put into (or pay out of) the Social Security system. Social Security is predicted to go bankrupt sometime before the middle of this century unless Social Security taxes are raised or benefits are reduced. The government could fix this problem by taking one or both of these actions now, or it could postpone dealing with the problem until 10 or 20 years from now. In the first case, the present generation of taxpayers and beneficiaries would be affected. In the second case, the future beneficiaries of the system would bear the costs. Which course should government take? The answer involves a value judgment. One has to decide how much economic hardship is worth putting up with now in order to avoid economic hardship for a somewhat different group of people several decades in the future.

The Stern Review on the Economics of Global Warming

Within the last few years, the debate about the economic effects of global warming has heated up (just as Earth itself has done!). In late 2006 the British government released a report from a committee led by the economist Nicholas Stern; hence, it is referred to as the *Stern Review on the Economics of Global Warming*. In it, Stern and his colleagues used a collection of different models to estimate the economic impact of global warming. They concluded that by the end of the next century (i.e., by the year 2200) the potential damages could be enormous—as much as 30% of the world per capita GDP (see Figure 16-11). **Gross domestic product (GDP)** is the total amount of money generated by all of the world's people. The term **per capita** simply means "per person." Not all of their predictions were this dire. In a more conservative case, the damages were only about 5% of world GDP. Even this, though, is an enormous amount of money. Stern's group went on to recommend a variety of strict measures to reduce greenhouse gas buildup, including high taxes on carbon emissions to discourage the use of fossil fuels. Such a carbon tax is a policy favored by many economists as an efficient tool to combat global warming.

Not all economists agreed with Stern's analysis, however. Indeed, many of them, including the influential Yale economist William Nordhaus, thought that Stern's economic assumptions were flawed and that his policy recommendations were therefore invalid. Nordhaus advocates carbon taxes as well; however, he thinks that Stern's proposed tax would be far too high.

Why would two different, well-educated economists disagree so strongly on global warming economic policy? The reason is primarily due to their different approaches to **economic discounting**. Because this concept is critical to making decisions about climate policy, or any other long-term environmental problem, we discuss it further below.

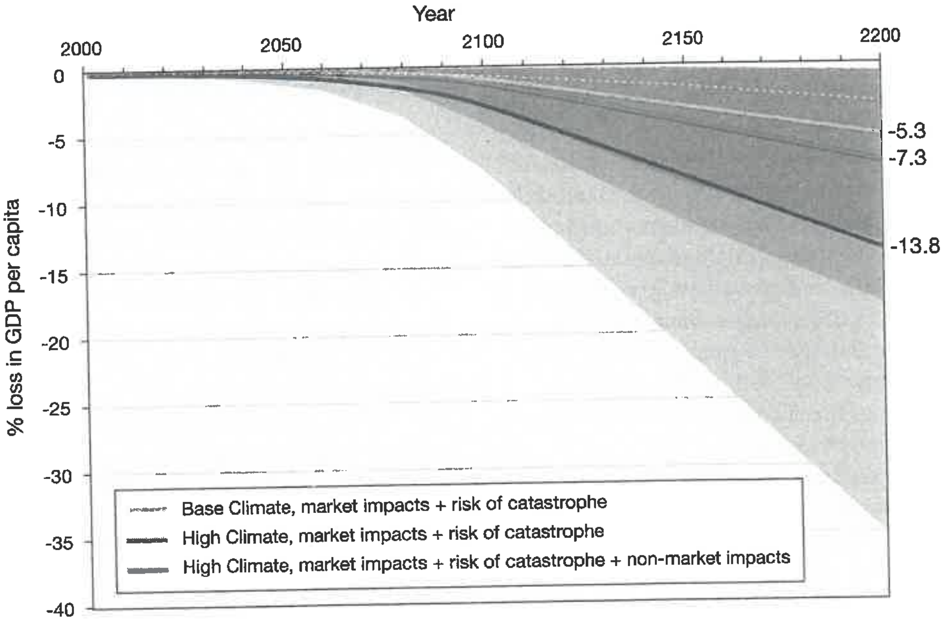

FIGURE 16-11 Projected future decreases in per capita GDP (gross domestic product) for three different global warming scenarios. The shaded regions show the uncertainty in the calculations. (*Source:* N. H. Stern, *The Economics of Climate Change: The Stern Review,* Cambridge: Cambridge University Press, available online at http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm.)

Economic Discounting

In economic models of global warming, the key question is: How much should we pay now in order to avoid damages that may be incurred in the distant future? Global warming is a slow process. As we have already seen earlier in this chapter, the biggest changes in climate, and hence the largest economic damages, are not likely to occur until more than 100 years from now. In a typical cost–benefit analysis, such as one to decide whether or not to build a dam or a powerplant, future damages or benefits are *discounted* at a rate of as much as 10% a year. That is, a benefit of \$100 that is realized 1 year from now is valued at only \$90.91 [= $\$100/(1 + 0.1)$]. The same benefit reaped 2 years from now is valued at \$82.64 [= $\$100/(1 + 0.1)^2$], and so forth. This **discount rate** takes into account two factors: (1) If one saves money now by not building the dam, one could invest this money somewhere else and make a profit. This is called *growth discounting*. (2) Most people would rather have a dollar today than a dollar 10 years from now (after adjustment for inflation). This is called *time preference discounting*.

In models of global warming, growth discounting is generally accounted for in one way or another. This makes a certain amount of sense: If society is richer 100 years from now than it is today, then people at that time can afford to pay more than they can at present. (On the other hand, if the change one is considering is essentially irreversible, like sea-level rise, then no amount of economic growth may compensate for it.) Economic models of global warming usually include time preference discounting as well. According to analyses of past economic behavior, societies as a whole exhibit a preference for having money right now, as opposed to receiving it sometime in the future. The Yale economist William Nordhaus, mentioned earlier, has studied investment behavior in U.S. society over the past 40 years and has determined that the *pure rate of social time preference*, as it is formally termed, is about 3% per year. Thus, a benefit (or cost) that was worth \$100 today would be valued at \$97.08 one year from now, \$94.26 two years from now, and so on.

A discount rate of 3% per year may not sound like much, and indeed significantly larger discount rates (7–10%/yr) are often used in short-term cost–benefit analyses. Consider what happens over long time spans, however. In 50 years, the assigned value of a \$100 benefit (or damage) would be $\$100/(1 + 0.03)^{50} = \$22.81$. In 100 years, the value drops to \$5.20. In 200 years, it is \$0.27. Thus, even if some truly catastrophic change were predicted to occur 200 years from now, its influence on a typical cost–benefit analysis would be minimal. The damages could be real and could be large in real economic terms, but time preference discounting ensures that they would be essentially neglected.

Cost–Benefit Calculations with Different Discount Rates: Nordhaus versus Stern

As a concrete example of the importance of discounting, let us examine some calculations performed by Nordhaus using his Dynamic Integrated Climate-Economy (DICE) model. The DICE model is typically run over a time span that extends 400 years into the future. It attempts to predict global economic growth, taking into account such factors as increases in population, new developments in technology, and climate change. Then, by performing a cost–benefit analysis, the model generates numbers that can be used to calculate the optimal amount of money that should be devoted to reducing greenhouse gases. Or, alternatively, it can be used to estimate the optimal carbon tax that would produce this result and, at the same time, do minimal damage to the world economy.

Figure 16-12 shows the results of two such calculations over the next century. Figure 16-12a shows the optimal carbon tax for Nordhaus's standard DICE model (bottom curve) and for Stern's more aggressive approach to combating global warming. Figure 16-12b shows the global CO_2 emissions that would result from these two different policies. Also shown in (b) are three other scenarios: (1) a "business as usual" scenario in which fossil-fuel emissions are not reduced at all; (2) a curve showing what would have happened if the 1997 Kyoto Protocol had been signed and implemented by all nations that attended the conference (which did *not* happen in reality); and (3) another ambitious strategy for CO_2 emissions reductions suggested by former U.S. vice president Al Gore. Figure 16-13 shows what would happen to atmospheric CO_2 levels and to global temperatures over the next two centuries, were any of these particular policy recommendations to be followed.

Let us start by looking at Figure 16-13. In the "business as usual" scenario, atmospheric CO_2 levels would increase to over 1100 ppm before the year 2200, while global temperatures would rise by approximately 5°C (9°F). The Kyoto Protocol, had it been fully implemented, would have done little to alter this outlook, largely because developing nations such as India and China were exempted from its regulations. By contrast, Nordhaus's prescription would keep atmospheric CO_2 concentrations below 700 ppm and would limit the temperature increase to about 3.5°C. Both Stern's and Gore's proposals would keep CO_2 levels below 450 ppm and would allow a surface temperature increase of only about 1.5°C.

Look next at the CO_2 emissions required to achieve each of these scenarios. In the business-as-usual scenario, CO_2 emissions increase from about 8 Gton(C)/yr today to almost 20 Gton(C)/yr in 2100. Nordhaus's prescription would hold CO_2 emissions to less than 10 Gton(C)/yr, declining back to 6 Gton(C)/yr in 2100. The latter number is approximately equal to 1990 consumption levels. By contrast, Gore's proposal would reduce emissions to less than 1 Gton(C)/yr by 2050 and hold them there indefinitely. Stern's proposal would

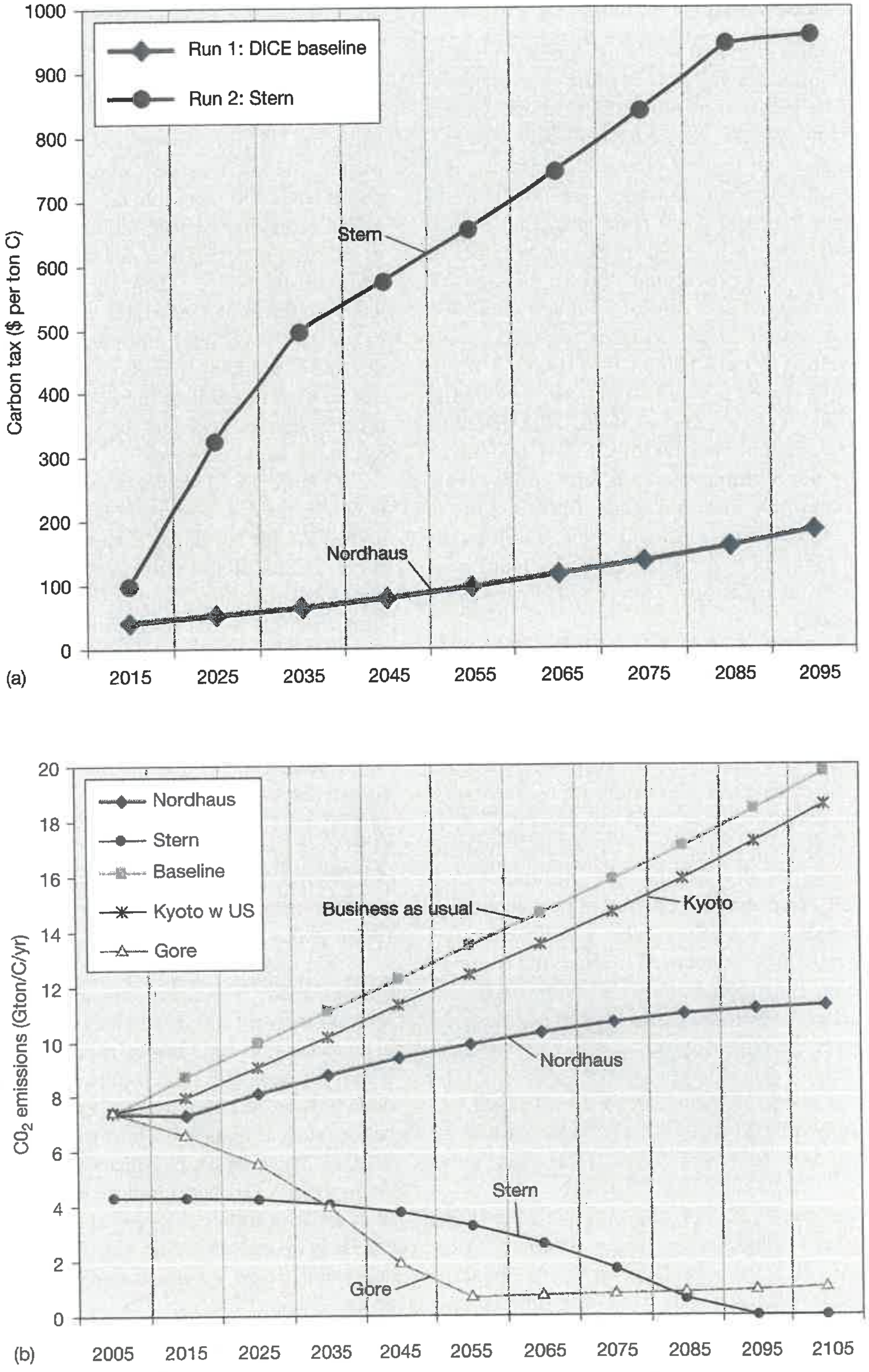

FIGURE 16-12 (a) Optimal carbon tax (in $US/ton) predicted by the economic models of Stern and Nordhaus. (b) The projected CO_2 emissions corresponding to these two models. Also shown in (b) are the projected emissions for a "business as usual" scenario, a scenario based on enactment of the 1990 Kyoto Protocol, and a scenario based on a proposal by former U.S. vice president Al Gore. (*Source:* William Nordhaus, *The Challenge of Global Warming: Economic Models and Environmental Policy,* New Haven, CT: Yale University Press, July 24, 2007.)

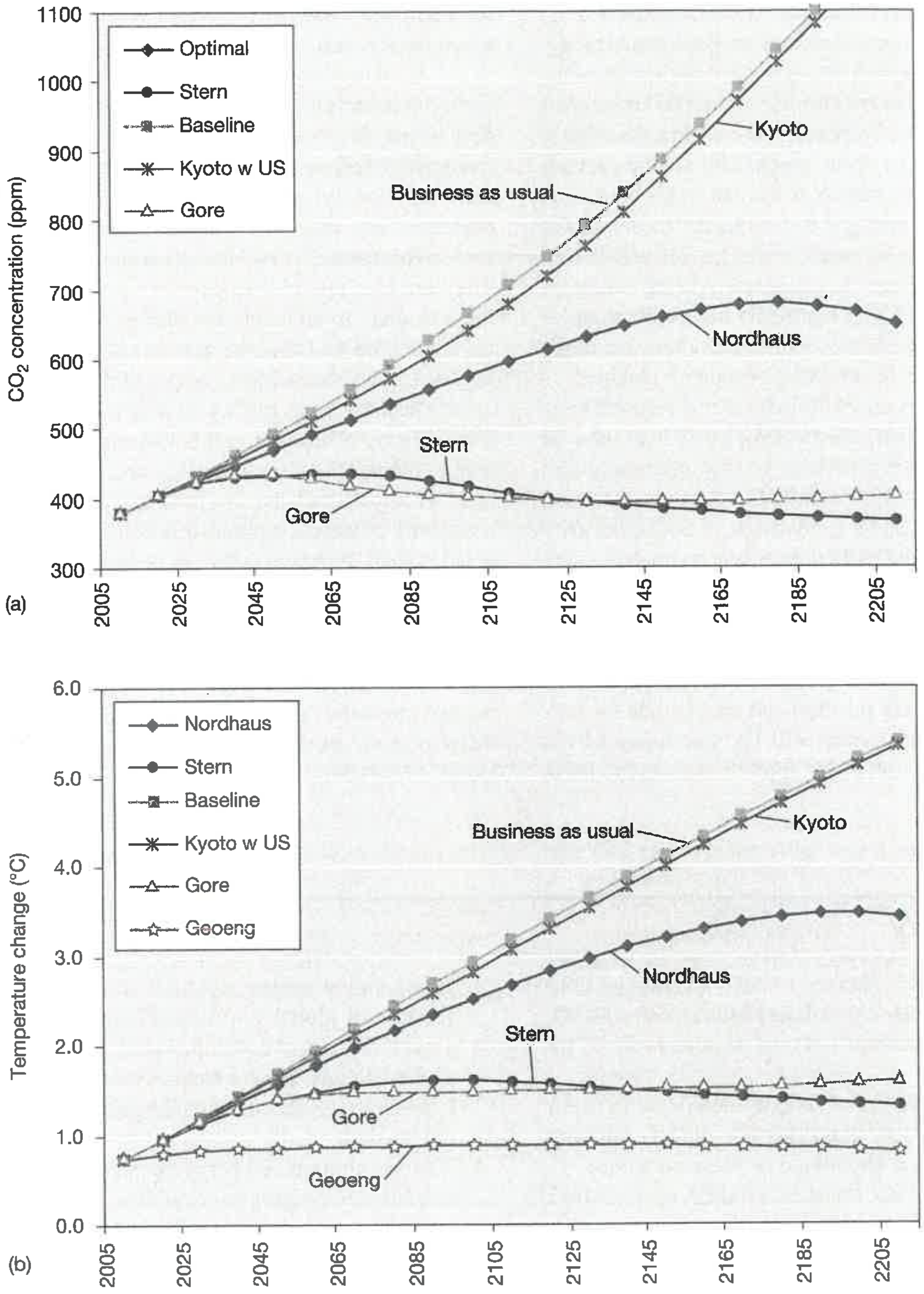

FIGURE 16-13 Projected atmospheric CO_2 concentrations (a) and surface temperature increases (b) for the emissions scenarios shown in Figure 16-8b. The bottom curve shows a geoengineered climate solution. (*Source:* William Nordhaus, *The Challenge of Global Warming: Economic Models and Environmental Policy,* New Haven, CT: Yale University Press, July 24, 2007.)

reduce emissions somewhat more slowly, but would eventually achieve even lower emission levels.

Many environmentalists think that we will ultimately need to reduce CO_2 emissions by large amounts, as suggested by Stern and Gore. But what type of economic policy would be required to do that? The carbon tax necessary to encourage this kind of behavior is shown in Figure 16-12a. It starts at about \$100 per ton of carbon initially and rises to about \$950 per ton within 100 years. In terms of commodities that people buy, the initial \$100/ton tax would be equivalent to about a \$0.30 per gallon tax on gasoline, or about a 3¢/kilowatt-hour tax on electricity (about 30% of its current market price). The proposed gasoline tax is less than 10% of the current market price, which is just under \$4/gallon as this chapter is being drafted. But this would rise to about \$3/gallon by 2100, effectively doubling the price of gas for citizens of the United States. Most Europeans already pay prices this high or higher because of gas tax policies enacted for other reasons.

The economically "optimal" model advocated by Nordhaus would also impose a carbon tax, but it would be significantly smaller: about \$30 per ton of carbon initially, increasing to \$200 per ton by 2100. The initial tax on gasoline would amount to about 9¢ per gallon—within the weekly fluctuations of gas prices at the pump. This solution sounds relatively painless, as Nordhaus points out in his books and papers. But is it really enough? In Nordhaus's model, global temperatures increase by as much as 3.5°C, or about 6°F. That is a lot! Are the economic damages really being estimated correctly in this model? And is it really acceptable to allow these damages to occur, as they will affect not us, but rather our children, or perhaps our children's children's children?

This last thought raises an issue that is referred to as **intergenerational equity**. How justified is it to pass on economic costs to future generations? This question relates directly to the question of economic discounting, discussed previously. And it is similar to the issue of Social Security benefits, also mentioned earlier. How much should we pay now in the United States to ensure that future generations of Americans will be able to retire comfortably? There is no simple answer to this question, just as there is no simple answer to the economics of global warming. We have to debate the merits of each position and then decide for ourselves what our own answer will be. For many of us, though, the old Boy Scout creed applies: We want to leave our campsite—the Earth, in this case—cleaner than it was when we arrived.

A related concept that is important for the global warming issue is that of **international equity**. The countries that stand to lose the most from global warming—low-lying Pacific island nations, Bangladesh (which is also extremely low-lying), nations in central Africa where temperatures are already high—are not the ones that are responsible for the bulk of the human-related CO_2 emissions. They are also less able to pay for costs that might enable them to adapt to future climate change, if it is even possible for them to do so. Don't the more developed nations, including the United States, have a responsibility to see that others are not hurt by things that we do at home? Of course we do. But it is easy to say that, and not so easy to ensure that this idea is incorporated in our energy and environmental policies. We do, after all, live in a democracy, and it is only when a majority of people agree that action should be taken that policies such as carbon taxes can be implemented. Our own perception is that people in the United States are not quite ready to take costly steps to slow the process of global warming. But that perception is also changing on a yearly basis as more and more people become educated about global warming and about the options that are available to combat it. For this reason, we are optimistic that solutions will eventually be found, even if they are not yet in sight.

Chapter Summary

1. Global warming is expected to have a variety of consequences for both natural and human ecosystems. Sea-level rise is perhaps the most serious problem for humans.
   a. Sea-level increases of several meters could occur over the next few centuries if extensive melting were to occur on Greenland or West Antarctica.
   b. Melting of the East Antarctic ice sheet would deliver many tens of meters of sea-level rise, but this change would require many centuries even if the climate were to warm significantly.
2. Natural ecosystems could be affected by global warming in many ways.
   a. Higher CO_2 levels will favor C_3 plants over C_4 plants. This could affect agriculture, as well, because corn and sugarcane are C_4 plants, whereas most weeds are C_3 plants.
   b. The speciation of trees in forests is expected to change as deciduous forests expand their range poleward.
   c. Insect pests, including mosquitos that carry diseases such as malaria, may expand their range from tropical regions to midlatitudes.
   d. In the oceans, coral growth could be inhibited by warming seawater and ocean acidification.
3. International agreements have been proposed to slow the rate of global warming. The Kyoto Protocol was signed by most developed nations but not by the United States. Future treaties that include all major CO_2-emitting nations, including developing countries, are needed.
4. Various alternative energy sources can be developed to reduce our dependence on fossil fuels.
   a. Electricity can be generated by wind, solar, geothermal, and nuclear power, thereby displacing electricity produced by burning of coal, oil, and natural gas.
   b. Biomass fuels, including (but not restricted to) ethanol, can be used to replace gasoline and diesel fuel.
   c. A tax on carbon would be an efficient method of encouraging the development of alternative energy sources.
5. There are ways to continue to burn fossil fuels and yet to reduce or eliminate their effects on climate.
   a. Carbon capture and storage (CCS) can be employed to sequester CO_2 in underground reservoirs.
   b. Earth's climate can be deliberately "geoengineered" by methods such as stratospheric aerosol injection.

6. Economic cost–benefit analyses of global warming reach different conclusions because of different assumptions in the models.
   a. Most models predict that at least a modest carbon tax should be imposed in the near future to help reduce the economic costs of future global warming.
   b. Models in which the discount rate is set to a low value suggest that higher carbon taxes are needed. The discount rate determines how much costs or benefits in the future matter compared to the same costs or benefits today.

Key Terms

biodiesel
biomass-based fuels
C_3 plants
C_4 plants
CAFÉ standard
Calvin cycle
carbon capture and storage (CCS)
carbon fixation
carbon sequestration
carbon tax
cellulosic ethanol
cost–benefit analysis
discount rate
economic discounting
ethanol
geoengineering
geothermal power
glacial surge
gross domestic product (GDP)
ice shelves
intergenerational equity
international equity
Kyoto Protocol
mountain glaciers
nuclear fission
nuclear fusion
per capita
photovoltaic cells
solar-power satellites
solar thermal power
syngas
thermal expansion
tidal power
water–gas shift reaction
wind power

Review Questions

1. What processes contribute to increases in global sea level, and by how much has it gone up in the recent past?
2. Why is predicting future sea-level change such a tricky task?
3. How are changes in climate predicted to affect natural ecosystems, including forests and insects?
4. What are some of the predicted effects of global warming on human populations?
5. What provisions did the Kyoto Protocol make to slow global warming, and why did the United States decline to sign it?
6. What role can energy conservation play in combating global warming?
7. What are some alternative energy sources that might be used to replace fossil fuels?
8. How can carbon capture and storage be used to burn coal in an environmentally safe way?
9. What are some ways in which Earth's climate might be "geo-engineered"?
10. What do economists mean by the term "cost–benefit analysis"?
11. What role does economic discounting play in cost–benefit analyses of global warming?
12. What specific differences in global warming policy are advocated by William Nordhaus and Nicholas Stern?

Critical-Thinking Problems

1. Write a two- or three-page typewritten, double-spaced essay on the following topic: Should the world collectively take immediate action to limit CO_2 emissions? If so, what steps should be taken in the United States and abroad to deal with this issue? Is nuclear power an acceptable option for producing electricity, or should we rely on renewable energy resources such as wind and solar power? Should we impose a carbon tax in the United States? Should developing nations such as China and India be required to cut emissions as well? If so, how might they be induced to do so? If immediate action is not warranted, what might be the best ways to deal with the anticipated effects of global warming? Do any of the proposed *geoengineering* solutions appear viable? In short, what would *you* do about global warming if you were president of the United States?

Further Reading

Nordhaus, W. D. 2008. *A question of balance: Weighing the options on global warming policies* (p. 234). New Haven, CT: Yale University Press.

Stern, N. H. 2007. *The economics of climate change: The Stern review* (p. 692). Cambridge: Cambridge University Press.