chapter 20

The Atmosphere: Climate, Climate Change, and Ozone Depletion

Key Topics

1. Atmosphere and Weather
2. Climate
3. Global Climate Change
4. Response to Climate Change
5. Depletion of the Ozone Layer

El Niño has become a household name. Beginning in April 1997 and extending through the spring of 1998, an especially intense El Niño linked the world together. In California and Oregon, unusually severe storms battered the coastline, causing major coastal erosion and flooding rivers (Fig. 20–1). On the eastern seaboard and the Gulf of Mexico, residents relaxed through a hurricane season that was the mildest in many years. By contrast, rainfall at least five times the normal deluged East Africa, often a region of drought. Fires blackened 1,400 square miles of drought-affected forests in Indonesia, creating huge clouds of smoke that blanketed much of Southeast Asia. In New Guinea, the lack of rain brought crop failures, necessitating a massive effort in food relief in order to prevent famine. Record crop harvests were enjoyed in India, Australia, and Argentina. Unusual rainfall in California and Florida triggered lush growth of vegetation.

Development of the 1997–2000 El Niño–La Niña **Satellite images of the central Pacific Ocean from May 25 (upper left) and December 18 (upper right), 1997, showing El Niño conditions, and from June 26, 1998 (lower left), and March 10, 1999, (lower right), showing La Niña conditions. (White is warmest, red is next, and blue is coldest.)**

La Niña. Shortly after El Niño was officially declared over in May 1998, the world began to hear about La Niña, as weather conditions shifted 180°. Florida was hit by hot, dry weather, triggering wildfires that swept through woods and suburbs, fueled by the lush vegetation nurtured by El Niño. Heavy rains returned to drought-ridden areas, and Venezuela, China, and Mozambique experienced disastrous floods. The tropical Atlantic spawned an unusual number of strong hurricanes. By the spring of 2000, La Niña had dissipated and weather conditions had returned to normal. With global damage estimated upwards of $36 billion, and with over 22,000 deaths, the 1997–2000 El Niño–La Niña has been a lesson in global climate the world will not soon forget. The atmosphere and oceans teamed up to produce a reminder that we live at the mercy of a system we neither control nor understand.

What caused these incredible changes in weather over so much of the globe? Briefly, El Niño occurs


(a)
(b)
(c)
(d)

Figure 20–1 Impacts of El Niño. (a) Landslides on the California coast. (b) Food relief in New Guinea. (c) Smoke and fires in Indonesia. (d) Flooding in Kenya.

when a major shift in atmospheric pressure over the central equatorial Pacific Ocean leads to a reversal of the trade winds that normally blow from an easterly direction. Warm water spreads to the east, the jet streams strengthen and shift from their normal courses, patterns in precipitation and evaporation are affected, and the system is usually sustained for more than a year. La Niña conditions are just the reverse: The easterly trade winds are reestablished with even greater intensity, upwelling of colder ocean water in the eastern Pacific from the depths replaces the surface water blown westward, the jet streams are weakened, and weather patterns are again affected.

Meteorologists are quite good at explaining what El Niño and La Niña are and where and how they may influence the different continents and oceans, but they are still unable to explain why they happen. What we do know, however, is that they are occurring at an unprecedented frequency. In the past 15 years, for example, there have been six El Niños. The latest was in 2002, a short-term and less intense event. If such changes in major weather patterns persist, we will in fact be experiencing a climate change. The El Niño–La Niña phenomenon has revealed to people everywhere that the atmosphere, oceans, and land are linked together and that, when normal patterns are disrupted, the climate on the whole Earth can be affected. Could it be that the warming trend now evident in global temperatures is responsible for these changes? Are we in for a major climate change? Indeed, what does control the climate?

We will seek answers to these questions as we investigate the atmosphere, how it is structured, and how it brings us our weather and climate. Then we will consider the evidence for global climate change, finishing with a look at what is happening to ozone in the upper atmosphere.

20.1 Atmosphere and Weather

Atmospheric Structure

Recall from Chapter 3 that the atmosphere is a collection of gases that gravity holds in a thin envelope around Earth. The gases within the lowest layer, the **troposphere,** are responsible for moderating the flow of energy to Earth and are involved with the biogeochemical cycling of many elements and compounds—oxygen, nitrogen, carbon, sulfur, and water, to name the most crucial ones. The troposphere ranges in thickness from 10 miles (16 km) in the tropics to 5 miles (8 km) in higher latitudes, due mainly to differences in heat energy budgets. This layer contains practically all of the water vapor and clouds in the atmosphere; it is the site and source of our weather. Except for local temperature inversions, the troposphere gets colder with altitude (Fig. 20–2). Air masses in this layer are well mixed vertically, so pollutants can reach the top within a few days. Substances entering the troposphere—including pollutants—may be changed chemically and washed back to Earth's surface by precipitation (Chapter 21). Capping the troposphere is the **tropopause.**

Higher. Above the tropopause is the **stratosphere,** a layer within which temperature *increases* with altitude, up to about 40 miles above the surface of Earth. The temperature increases primarily because the stratosphere contains ozone (O_3), a form of oxygen that absorbs high-energy radiation emitted by the Sun. Because there is little vertical mixing of air masses in the stratosphere and no precipitation from it, substances that enter it can remain there for a long time. Beyond the stratosphere are two more layers, the *mesosphere* and the *thermosphere,* where the ozone concentration declines and only small amounts of oxygen and nitrogen are found. Because none of the reactions we are concerned with occur in the mesosphere or thermosphere, we shall not discuss those two layers. Table 20–1 summarizes the characteristics of the troposphere and stratosphere.

Weather

The day-to-day variations in temperature, air pressure, wind, humidity, and precipitation—all mediated by the atmosphere—constitute our **weather. Climate** is the result of long-term weather patterns in a region. The scientific study of the atmosphere—both of weather and of climate—is **meteorology.** It is fair to think of the atmosphere–ocean–land system as an enormous weather engine, fueled by the Sun and strongly affected by the rotation of Earth and its tilted axis. Solar radiation enters

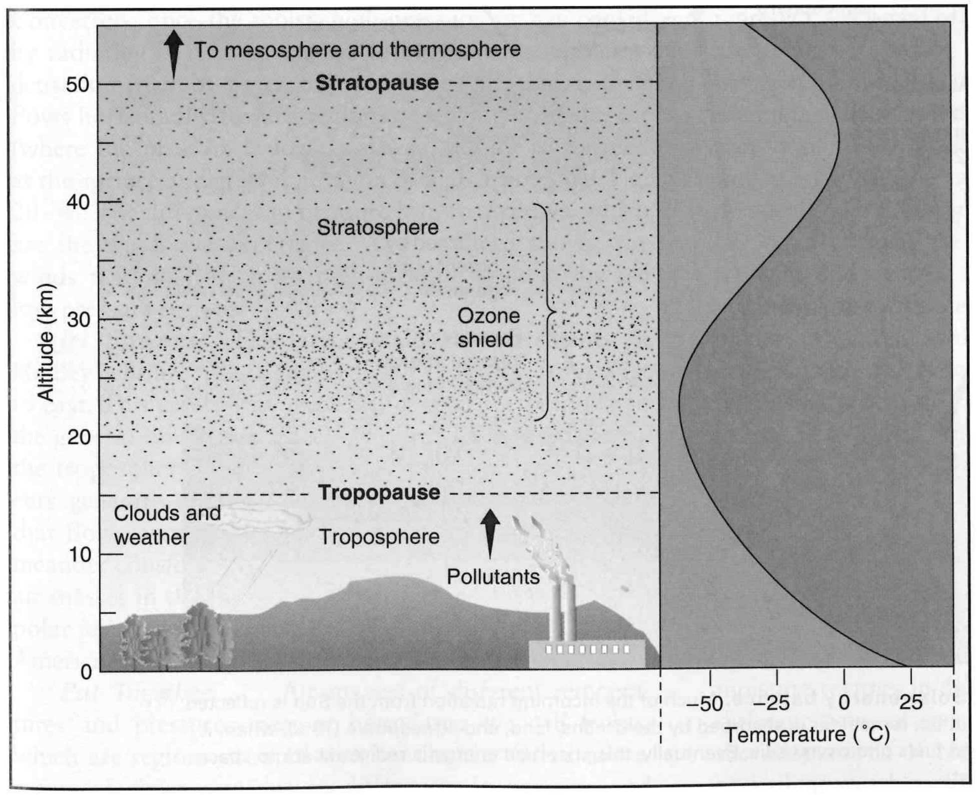

Figure 20–2 Structure and temperature profile of the atmosphere. The left-hand plot shows the layers of the atmosphere and the ozone shield, while the plot on the right shows the vertical temperature profile.

table 20-1 Characteristics of Troposphere and Stratosphere

Troposphere	Stratosphere
Extent: Ground level to 10 miles (16 km)	Extent: 10 miles to 40 miles (16 km to 65 km)
Temperature normally decreases with altitude, down to −70°F (−59°C)	Temperature increases with altitude, up to +32°F (0°C)
Much vertical mixing, turbulent	Little vertical mixing, slow exchange of gases with troposphere, via diffusion
Substances entering may be washed back to Earth	Substances entering remain unless attacked by sunlight or other chemicals
All weather and climate take place here	Isolated from the troposphere by the tropopause

the atmosphere and then takes a number of possible courses (Fig. 20–3). Some is reflected by clouds and Earth's surfaces, but most is absorbed by the atmosphere, oceans, and land, which are heated in the process. The land and oceans then radiate some of their heat back upward as infrared energy.

Flowing Air. Some of the heat that is radiated back is transferred to the atmosphere. Thus, air masses will grow warmer at the surface of Earth and will tend to expand, becoming lighter. The lighter air will then rise, creating *vertical* air currents. On a large scale, this movement creates the major *convection currents* we encountered in Chapter 7 (Fig. 7–6). Air must flow in to replace the rising warm air, and the inflow leads to *horizontal* airflows, or wind. The ultimate source of the horizontal flow is cooler air that is sinking, and the combination produces the Hadley cell (Fig. 7–6). As discussed in Chapter 7, these major flows of air create regions of high rainfall (equatorial), deserts (25° to 35° north and south of the equator), and horizontal winds (trade winds).

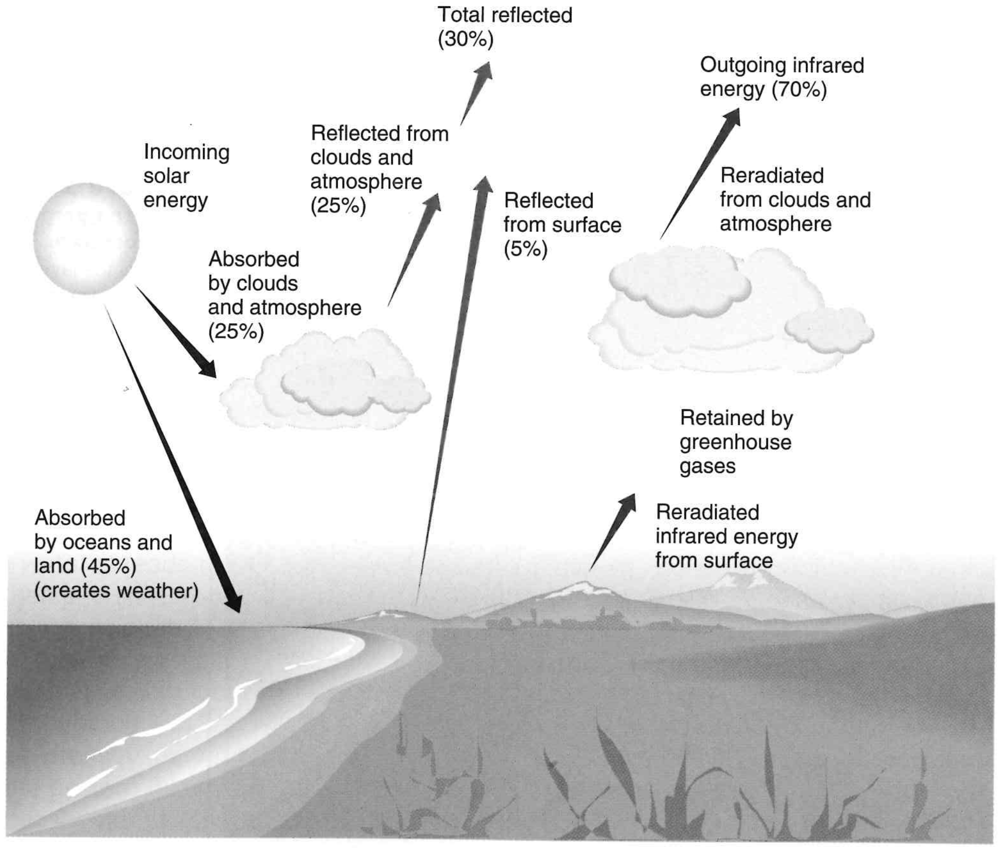

Figure 20–3 **Solar-energy balance.** Much of the incoming radiation from the Sun is reflected back to space (30%), but the remainder is absorbed by the oceans, land, and atmosphere (70%), where it creates our weather and fuels photosynthesis. Eventually, this absorbed energy is radiated back to space as infrared energy (heat).

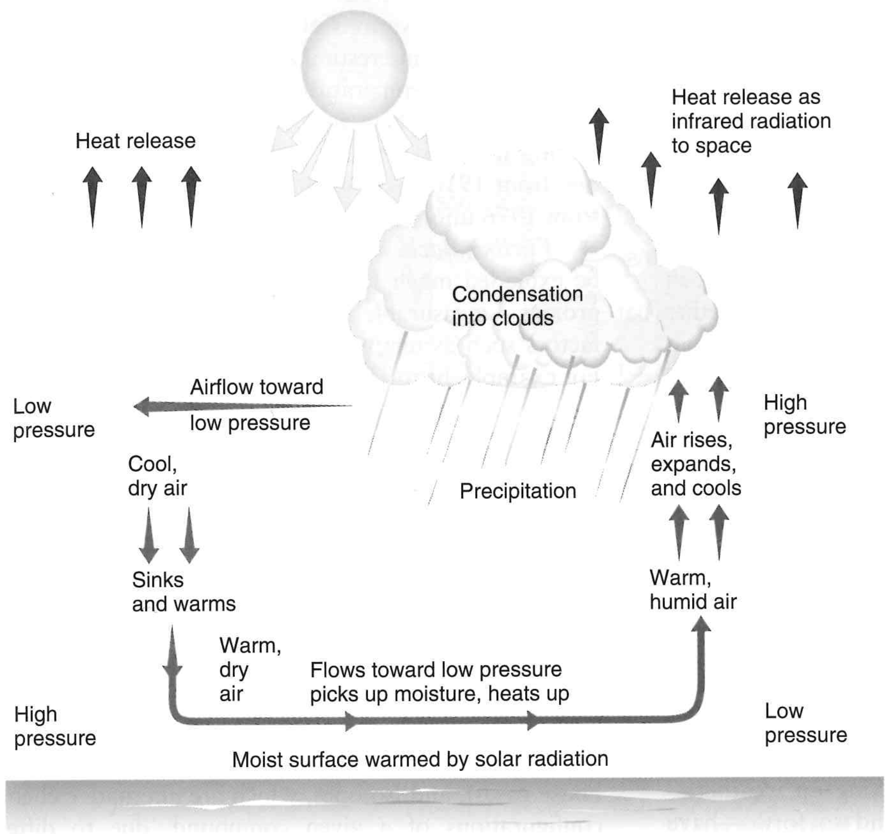

Figure 20–4 **A convection cell.** Driven by solar energy, these cells produce the main components of our weather as evaporation and condensation occur in rising air and precipitation results, followed by the sinking of dry air. Horizontal winds are generated in the process.

Convection. On a smaller scale, **convection currents** bring us the day-to-day changes in our weather as they move in a general pattern from west to east. Weather reports inform us of regions of high and low pressure, but where do these come from? Rising air (due to solar heating) creates high pressure up in the atmosphere, leaving behind a region of lower pressure close to Earth. Conversely, once the moist, high-pressure air has cooled by radiating heat to space and losing heat through condensation (thereby generating precipitation), the air then flows horizontally toward regions of sinking cool, dry air (where the pressure is lower). There, the air is warmed at the surface and creates a region of higher pressure (Fig. 20–4). The differences in pressure lead to airflows, which are the winds we experience. As the figure shows, the winds tend to flow from high-pressure regions toward low-pressure regions.

Jet Streams. The larger scale air movements of Hadley cells are influenced by Earth's rotation from west to east. This creates the trade winds over the oceans and the general flow of weather from west to east. Higher in the troposphere, Earth's rotation and air-pressure gradients generate veritable rivers of air, called **jet streams,** that flow eastward at speeds of over 300 mph and that meander considerably. Jet streams are able to steer major air masses in the lower troposphere. One example is the polar jet stream, which steers cold air masses into North America when it dips downward in latitude.

Put Together. . . . Air masses of different temperatures and pressures meet at boundaries we call **fronts,** which are regions of rapid weather change. Other movements of air masses due to differences in pressure and temperature include hurricanes and typhoons and the local, but very destructive, tornadoes. Finally, there are also major seasonal airflows: the **monsoons,** which often represent a reversal of previous wind patterns. Monsoons are created by major differences in cooling and heating between oceans and continents. The summer monsoons of the Indian subcontinent are famous for the beneficial rains they bring and notorious for the devastating floods that can occur when the rains are heavy. Putting these movements all together—taking the general atmospheric circulation patterns and the resulting precipitation, then adding the wind and weather systems generating them, and finally mixing all this with the rotation of Earth and the tilt of the planet on its axis, which creates the seasons—yields the general patterns of weather that characterize different regions of the world. In any given region, these patterns are referred to as the region's **climate.**

20.2 Climate

Climate was described in Chapter 2 as the average temperature and precipitation expected throughout a typical year in a given region. Recall that the different temperature and moisture regimes in different parts of the world "created" different types of ecosystems called *biomes*, representing the adaptations of plants, animals, and microbes to the prevailing weather patterns, or climate, of a region. The temperature and precipitation patterns themselves are actually caused by other forces, namely, the major determinants of weather previously outlined. Humans can adjust to practically any climate (short of the brutal conditions on high mountains or burning deserts), but this is not true of the other inhabitants of the particular regions we occupy. If other living organisms in a region are adapted to a particular climate, then a major change in the climate represents a major threat to the structure and function of the existing ecosystems. The subject of climate change is such a burning issue today because we depend on these other organisms for a host of vital goods and services without which we could not survive (Chapter 3). If the climate changes, can these ecosystems change with it in such a way that the vital support they provide us is not interrupted? How rapidly can organisms and ecosystems adapt to changes in climate? How rapidly do climates change? One way to answer these questions is to look into the past, which may harbor "records" of climate change.

Climates in the Past

Searching the past for evidence of climate change has become a major scientific enterprise, one that becomes more difficult the further into the past we try to search. Systematic records of the factors making up weather—temperature, precipitation, storms, and so forth—have been kept for little more than a hundred years. Nevertheless, these records already inform us that our climate is far from constant. The record of surface temperatures, from weather stations around the world and from literally millions of observations of temperatures at the surface of the sea, tells an interesting story (Fig. 20–5): Since 1855, global average temperature has shown periods of cooling and warming, but, in general, has increased 0.6°C (1°F). During the 20th century, two warming trends occurred, one from 1910 to 1945 and the latest dramatic increase from 1976 until the present.

Further Back. Observations on climatic changes can be extended much further back in time with the use of **proxies**—measurable records that can provide data on factors such as temperature, ice cover, and precipitation. For example, historical accounts suggest that the Northern Hemisphere enjoyed a warming period from 1100 to 1300 A.D. This was followed by the "Little Ice Age," between 1400 and 1850 A.D. Additional proxies include tree rings, pollen deposits, changes in landscapes, marine sediments, corals, and ice cores.

Some work done quite recently on ice cores has both provided a startling view of a global climate that oscillates according to several cycles and afforded some evidence that remarkable changes in the climate can occur within as little as a few decades. Ice cores in Greenland and the Antarctic have been analyzed for thickness, gas content (specifically, carbon dioxide (CO_2) and methane (CH_4), two greenhouse gases), and **isotopes,** which are alternative chemical configurations of a given compound, due to different nuclear components. Isotopes of oxygen, as well as isotopes of hydrogen, behave differently at different temperatures when condensed in clouds and incorporated into ice.

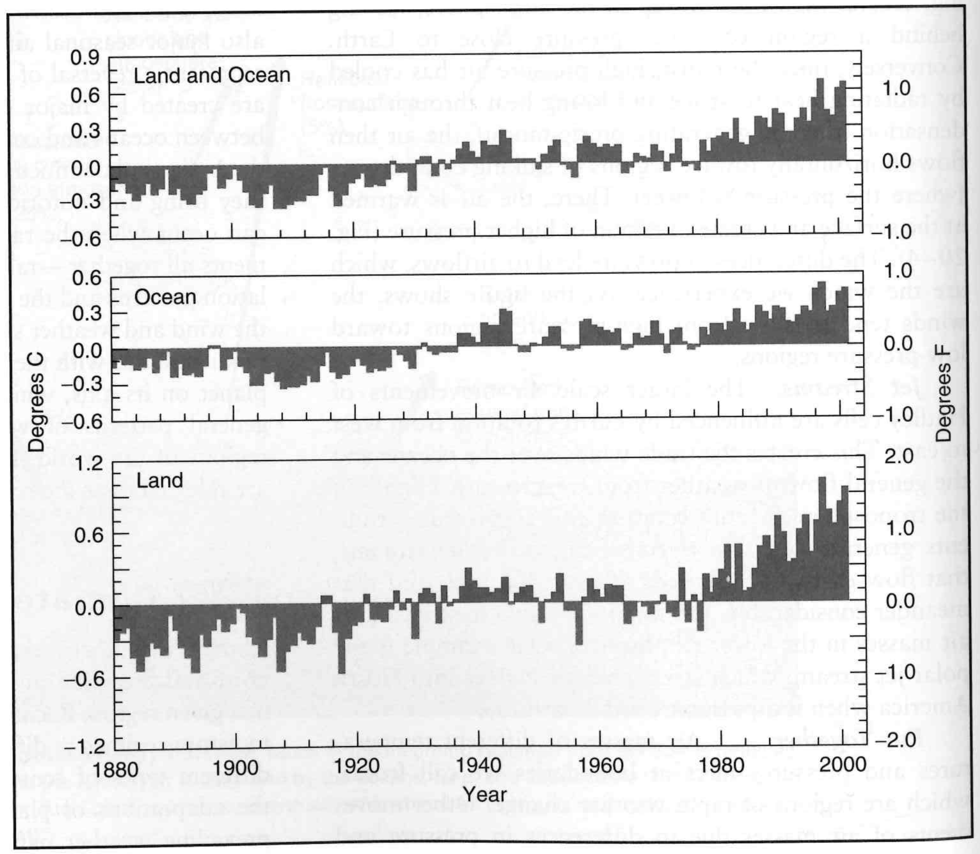

Figure 20–5 Annual mean global surface atmospheric temperatures. The baseline, or zero point, is the 1880–1999 long-term average temperature. The warming trend since 1970 is conspicuous. (*Source:* National Climatic Data Center, NOAA.)

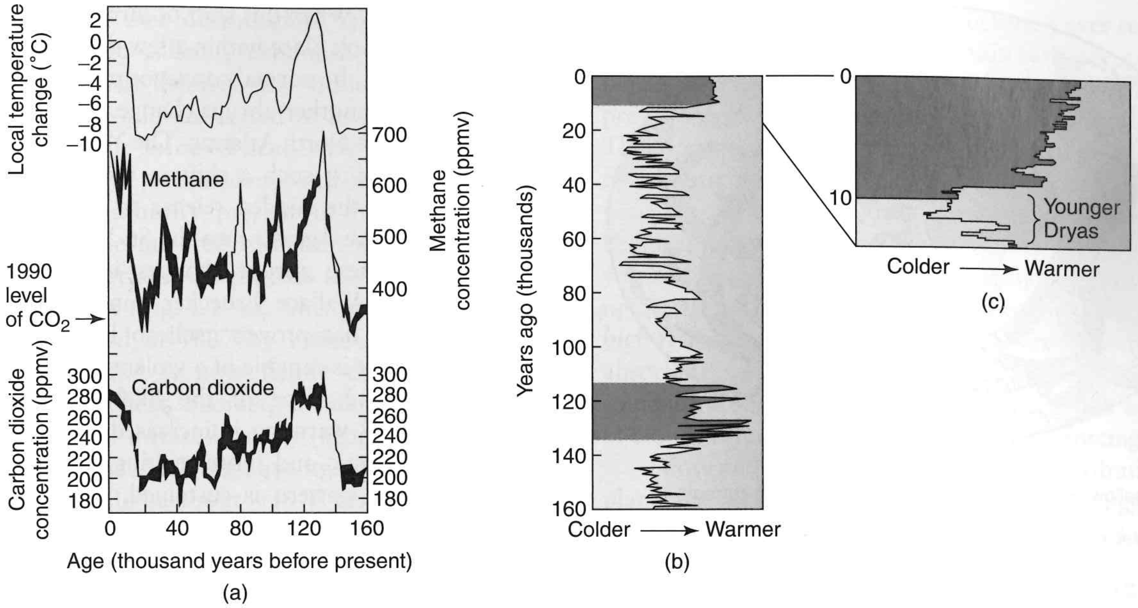

Figure 20–6 Past climates, as determined from ice cores. (a) Temperature, methane, and carbon dioxide data from Antarctic ice cores, covering the past 160,000 years. (b) Temperature patterns of the last 160,000 years, demonstrating climatic oscillations. (c) Higher resolution of the last 12,000 years. The "Younger Dryas" cold spell occurred at the start of this record. Note how rapidly the cold spell dissipated, at around 10,700 years before the present. [After Christopherson, Robert W., *Geosystems: An Introduction to Physical Geography,* 4th ed. (Upper Saddle River, NJ: Prentice Hall, 2000.)]

The record based on these analyses indicates that Earth's climate has oscillated between ice ages and warm periods (Fig. 20–6). During major ice ages, huge amounts of water were tied up in glaciers and ice sheets, and the sea level was lower by as much as 400 feet (120 m). The most likely explanation for these major oscillations is the existence of known variations in Earth's orbit, such that, in different modes of orbital configuration, the distribution of solar radiation over different continents and latitudes varies substantially. These oscillations take place according to several periodic time intervals, called **Milankovitch cycles** (after the Serbian scientist who first described them): 100,000, 41,000, and 23,000 years.

Rapid Changes. Superimposed on the major oscillations is a record of rapid climatic fluctuations during periods of glaciation and warmer times (Fig. 20–6c). One such rapid change, called the *Younger Dryas* event (*Dryas* is a genus of Arctic flower), occurred toward the end of the last ice age. Earth had been warming up for 6,000 years and then plunged again into 1,500 years of cold weather. At the end of this event, 10,700 years ago, Arctic temperatures rose 7°C in 50 years! The impact on living systems must have been enormous. It is unlikely that this warming was due to variations in solar output: There is simply no evidence that the Sun has changed over the last million years, let alone undergone major changes in just a few decades. Instead, scientists have narrowed the field of possible explanations to the link between the atmosphere and the oceans. We return now to this link, having already seen the crucial role played by the oceans in El Niño events.

Ocean and Atmosphere

Earth is mostly a water planet, covered more than two-thirds by oceans. Since we all live on land, it is hard for us to imagine that the oceans play a dominant role in determining our climate. Nevertheless, the oceans are the major source of water for the hydrologic cycle and the main source of heat entering the atmosphere. Recall from Chapter 9 that the *evaporation of ocean water* supplies the atmosphere with water vapor, and when water vapor condenses in the atmosphere (Fig. 7–6), it supplies the atmosphere with heat (latent heat of condensation). The oceans also play a vital role in climate because of their innate *heat capacity*—the ability to absorb energy when water is heated. Indeed, the entire heat capacity of the atmosphere is equal to that of just the top 3 m of ocean water! The well-known ameliorating effect of oceans on the climate of coastal land areas is a consequence of this property. Finally, through the movement of currents, the oceans *convey heat* throughout the globe.

Thermohaline Circulation. A thermohaline circulation pattern dominates oceanic currents, where *thermohaline* refers to the effects that temperature and salinity have on the density of seawater. This **conveyor** system (Fig. 20–7) acts as a giant, complex conveyor belt, moving water masses from the surface to deep oceans and back again, according to the density of the mass. A key area is the high-latitude North Atlantic, where salty water from the Gulf Stream moves northward on the surface and is cooled by Arctic air currents. Cooling increases the density of the water, which then sinks to depths of up to 4,000 m—the *North Atlantic Deep Water* (NADW). This

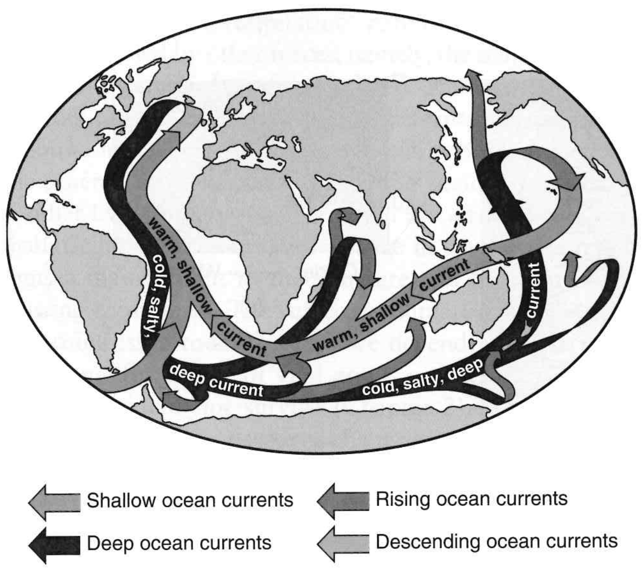

Figure 20–7 The oceanic conveyor system. Salty water flowing to the North Atlantic is cooled and sinks, forming the North Atlantic Deep Water system. This deep flow extends southward and is joined by Antarctic water, whereupon it extends into the Indian and Pacific oceans. Surface currents then proceed in the opposite direction, returning the water to the North Atlantic. (Adapted from Figure 3.15 from *Our Changing Planet,* 2d ed., by Fred T. MacKenzie. Copyright © 1998 by Prentice Hall, Inc. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ 07458.)

deep water spreads southward through the Atlantic to the southern tip of Africa, where it is joined by cold Antarctic waters. Together, the two streams spread northward into the Indian and Pacific oceans as deep currents. Gradually, the currents slow down and warm, becoming less dense and welling up to the surface, where they are further warmed and begin to move surface waters back again toward the North Atlantic. This movement transfers enormous quantities of heat toward Europe, providing a climate that is much warmer than the high latitudes there would suggest. The circulation pattern operates over a period of about 1,000 years for one complete cycle and is vital to the maintenance of current climatic conditions.

Abrupt Change. Recent evidence indicates that the conveyor system has been interrupted in the past, changing climate abruptly. One mechanism that could accomplish such a change is the appearance of unusually large quantities of fresh water in the North Atlantic, lowering the density of the water and therefore preventing much of the massive sinking that normally occurs there and blocking the northward movement of warmer, saltier water. North Atlantic marine sediments show evidence of the periodic invasion (six times in the last 75,000 years) of icebergs from the polar ice cap that supplied huge amounts of fresh water as they melted—called Heinrich events, after the scientist who first described them. The evidence indicates that these invasions coincided with rapid cooling, as recorded in ice cores, and suggests that the conveyor system shifted southward, with deep water forming nearer to Bermuda than Greenland. When this shift occurred, a major cooling of the climate took place within a few decades. Although it is not clear how, the normal conveyor pattern returned and brought about another abrupt change, this time warming conditions in the North Atlantic. The Younger Dryas event likely involved just such a shift in the conveyor system, brought on by the sudden release of dammed-up water from glacial Lake Agassiz into the St. Lawrence drainage. Referring to these abrupt changes in a recent article, oceanographer Wallace Broecker commented,[1] "Earth's climate system has proven itself to be an angry beast. When nudged, it is capable of a violent response."

What if...? One of the likely consequences of extended global warming is increased precipitation over the North Atlantic and more melting of sea ice and ice caps. If such a pattern is sustained, it could lead to a breakdown in the normal operation of the conveyor and a rapid change in climate, especially in the northern latitudes, a possibility that Broecker has called "The Achilles' heel of our climate system." Indeed, oceanographers have seen a gradual decline in the salinity of the northern seas consistent with known glacial melt and a thinning of the ice in the Arctic Ocean. Although it is too soon to know whether this freshening will affect the conveyor, the trend has raised concern over climate change another notch.

20.3 Global Climate Change

The Earth as a Greenhouse

Factors that influence the climate include interactive, *internal components* (oceans, the atmosphere, snow cover, sea ice, etc.) and *external factors* (solar radiation, the Earth's rotation, slow changes in our planet's orbit, and the gaseous makeup of the atmosphere). **Radiative forcing** is the influence a particular factor has on the energy balance of the atmosphere–ocean–land system. The factors can be *positive,* leading to *warming,* or *negative,* leading to *cooling,* as they affect the energy balance. If the factors change over time, they can lead to a change in the climate.

Warming Processes. The interior of a car heats up when the car is sitting in the Sun with the windows closed. This heating occurs because sunlight comes in through the windows and is absorbed by the seats and other interior objects, thus converting light energy into heat energy, which is given off in the form of infrared radiation. Unlike sunlight, infrared radiation is blocked by glass and so cannot leave the car. The trapped heat energy causes the interior air temperature to rise. This is the same phenomenon that keeps a greenhouse warmer than the surrounding environment.

Greenhouse Gases. On a global scale, water vapor, CO_2, and other gases in the atmosphere play a role analogous to that of the glass in a greenhouse. Therefore, they are called **greenhouse gases (GHGs).** Light energy comes through the atmosphere and is absorbed by Earth and converted to heat energy at the planet's surface. The infrared heat energy radiates back upward through the atmosphere and into space. The GHGs that are naturally present in the troposphere absorb some of the infrared radiation and reradiate it back toward the surface; other gases (N_2 and O_2) in the troposphere do not (Fig. 20–8). This greenhouse effect was first recognized in 1827 by French scientist Jean-Baptiste Fourier and is now firmly established. The GHGs are like a heat blanket, insulating Earth and delaying the loss of infrared energy (heat) to space (Fig. 20–8). Without this insulation, average surface temperatures on Earth would be about −19°C instead of +14°C, and life as we know it would be impossible. Therefore, our global climate depends on Earth's concentrations of GHGs. If these concentrations increase or decrease significantly, their influence as positive "forcing" agents will change, and our climate will change accordingly.

Cooling Processes. Earth's atmosphere is also subject to negative forcing factors. For example, on average, clouds cover 50% of Earth's surface and reflect some 21% of solar radiation away to space before it ever reaches the ground. Sunlight reflected in this way is called the **planetary albedo,** and it contributes to overall cooling by preventing a certain amount of warming in the first place. The effect of the albedo is especially true for *low-lying* clouds and can be readily appreciated if you think of how you are comforted on a hot day when a large cloud passes between you and the Sun. The radiation that was heating you and your surroundings is suddenly intercepted higher up in the atmosphere, and you feel cooler. However, *high-flying,* wispy clouds have a positive forcing effect, absorbing some of the infrared radiation and emitting some infrared themselves. Overall, the current net impact of clouds is judged to be slightly negative forcing.

Snow and ice also reflect sunlight, contributing to the planetary albedo. Recent work, however, suggests that this effect is reduced greatly by the widespread soot originating from anthropogenic sources. By darkening the snow and ice, the soot promotes the absorption of radiant energy rather than reflection.

Volcanoes. Volcanic activity can also lead to planetary cooling. When Mount Pinatubo in the Philippines erupted in 1991, some 20 million tons of particles and aerosols entered the atmosphere and contributed to a significant drop in global temperature as radiation was

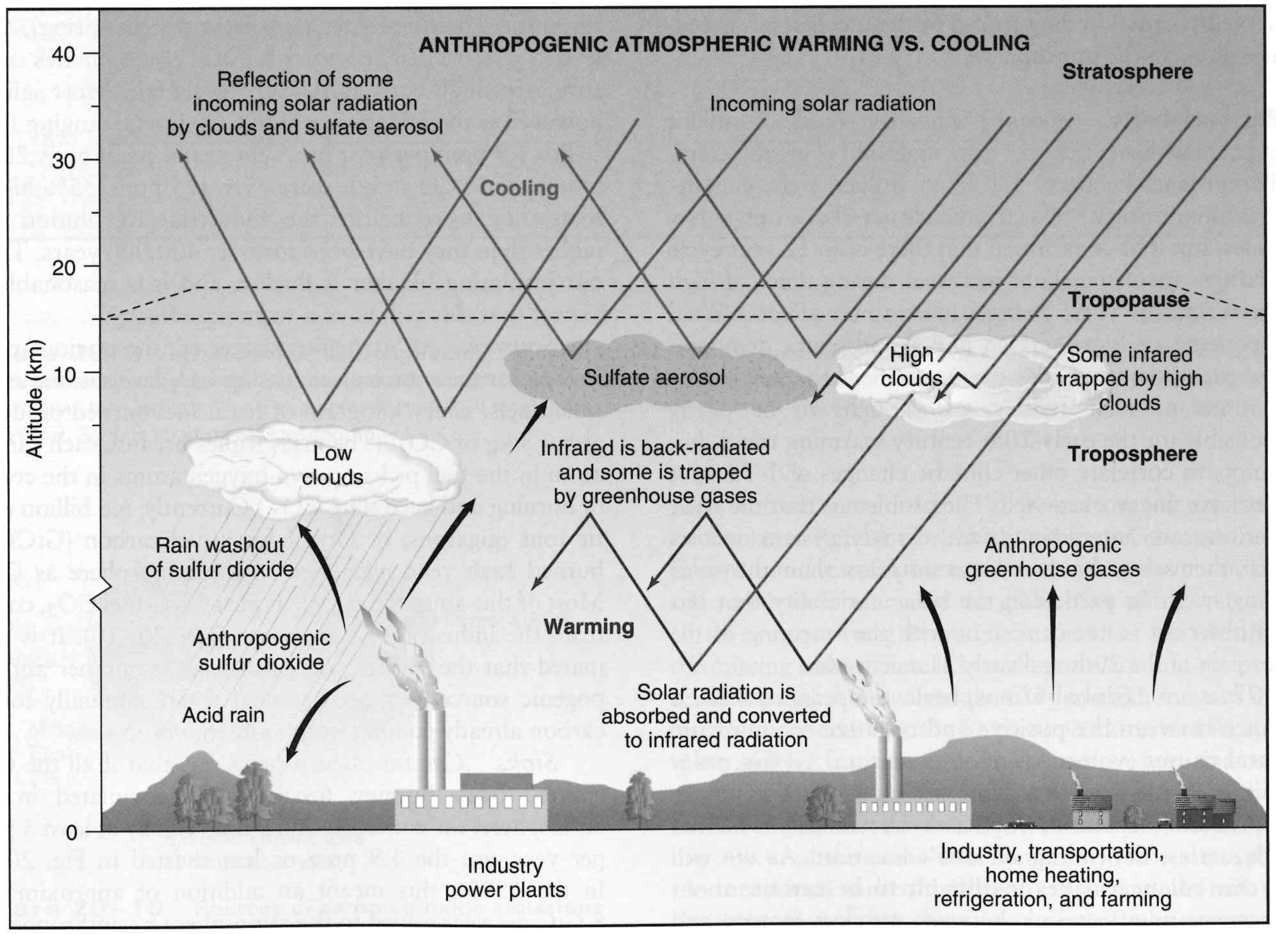

Figure 20–8 Global warming and cooling. Factors involved in atmospheric warming and cooling are illustrated. Greenhouse gases promote global warming; sulfur dioxide leads to cooling.

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[1] Broecker, W. S. "Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere?" *Science* 300 (June 6, 2003): 1519–1522.

reflected and scattered away. This global cooling effect lasted until the volcanic debris was finally cleansed from the atmosphere by chemical change and deposition, a process that took several years.

Aerosols. Climatologists have found that anthropogenic sulfate aerosols (from ground-level pollution) play a significant role in canceling out some of the warming from GHGs. Sulfur dioxide from industrial sources enters the atmosphere and reacts with compounds there to form a high-level aerosol—a sulfate haze. This haze reflects and scatters some sunlight and also contributes to the formation of clouds, with a concomitant increase in planetary albedo. The mean residence time of the sulfates forming the aerosol is about a week, so the aerosol does not increase over time, as the GHGs do. However, because anthropogenic sulfate is more than double that coming from natural sources, its effect is substantial and persistent. Climatologists estimate that the cooling effect of these pollutants has counteracted some 20–30% of the global warming in recent years. Newer findings indicate that sulfate aerosols and other pollutants can prevent precipitation from occurring within clouds, adding substantially to their impact on climate.

Ozone Depletion. Paradoxically, the depletion of the stratospheric ozone layer by anthropogenic sources (Section 20.5) has led to a cooling of the lower stratosphere. In turn, this cooling offsets about 20% of the observed positive forcing traced to the increases in greenhouse gases in the atmosphere.

Solar Variability. Since the Sun is the source of radiant energy that heats Earth, any variability in the sun's radiation reaching Earth will likely influence the climate. Direct monitoring of solar irradiance goes back only a few decades, but it has confirmed that there is an 11-year cycle of changes involving slight increases during times of high sunspot activity. These changes in turn may affect internal components such as surface and tropospheric temperatures, ocean currents, and the position of the jet stream. Variations in solar forcing are thought to be partly responsible for the early-20th-century warming trend, but attempts to correlate other climatic changes with sunspot cycles have not worked well. The problem is that the solar variations are interacting with climate system factors which themselves have stronger impacts than the solar forcing itself. In particular, the solar variability that has been observed is not consistent with the warming of the latter part of the 20th and early 21st centuries.

Thus. . . . Global atmospheric temperatures are a balance between the positive and negative forcing from natural causes (volcanoes, clouds, natural GHGs, solar irradiance) and anthropogenic causes (sulfate aerosols, soot, ozone depletion, increases in GHGs). The net result varies, depending on one's location. As we will see, this balance makes it difficult to be certain about the cause-and-effect link between forcing factors and climate parameters such as temperature, precipitation, and storm events. It also contributes much uncertainty to our predictions of what will happen in the future as GHGs continue to increase. Figure 20–8 depicts most of the natural and anthropogenic factors that interact to influence the temperature at any given location.

The Greenhouse Gases

Carbon Dioxide. More than 100 years ago, Swedish scientist Svante Arrhenius reasoned that differences in CO_2 levels in the atmosphere could greatly affect Earth's energy budget. Arrhenius suggested that, in time, the burning of fossil fuels might change the atmospheric CO_2 concentration, although he believed that it would take centuries before the associated warming would be noticeable. He was not concerned about the impacts of this warming, arguing that such an increase would be beneficial. (He lived in Sweden!)

Monitoring. In 1958, Charles Keeling began measuring CO_2 levels on Mauna Loa, in Hawaii. Measurements there have been recorded continuously, and they reveal a striking increase in atmospheric levels of the gas (Fig. 20–9). The concentrations increased exponentially until the energy crisis in the mid-1970s and have been rising more or less linearly ever since. The data also reveal an annual oscillation of 5–7 ppm, which reflects seasonal changes of photosynthesis and respiration in terrestrial ecosystems in the Northern Hemisphere. When respiration predominates (late fall through spring), CO_2 levels rise; when photosynthesis predominates (late spring through early fall), CO_2 levels fall. Most salient, however, is the relentless rise in CO_2 levels, ranging from 0.8 to 1.9 ppm per year in recent years. As of early 2004, atmospheric CO_2 levels were over 375 ppm, 35% higher than they were before the Industrial Revolution and higher than they have been for over 400,000 years. Thus, our insulating blanket is thicker, and it is reasonable to expect that this will have a warming effect.

Sources. As Arrhenius suggested, the obvious place to look for the source of increasing CO_2 levels is our use of fossil fuels. Every kilogram of fossil fuel burned produces about 3 kg of CO_2. (The mass triples because each carbon atom in the fuel picks up two oxygen atoms in the course of burning and becoming CO_2.) Currently, 6.6 billion metric tons (gigatons, or Gt) of fossil-fuel carbon (GtC) are burned each year, all added to the atmosphere as CO_2. Most of this amount, as well as past fossil-fuel CO_2, comes from the industrialized countries (Fig. 20–10). It is estimated that the burning of forest trees is another anthropogenic source that adds some 1.6 GtC annually to the carbon already coming from industrial processes.

Sinks. Careful calculations show that if all the CO_2 emitted from burning fossil fuels accumulated in the atmosphere, the concentration would rise by at least 3 ppm per year, not the 1.9 ppm or less charted in Fig. 20–9. In the 1990s, this meant an addition of approximately 8 GtC per year added to the atmosphere by anthropogenic sources, yet only 3.2 GtC per year actually accumulated. Thus, there must be carbon "*sinks*" that absorb CO_2 and keep it from accumulating at a more rapid rate in the atmosphere. Recent work with stable carbon and oxygen isotopes and careful measurements of atmospheric CO_2 from 120 stations around the globe have brought us much closer to quantifying annual fluxes in CO_2 and identifying the missing sinks. There is broad agreement that the oceans serve as a sink for much of the CO_2 emitted; some of this is due to the uptake of CO_2 by phytoplankton and its subsequent sinking, and some is a consequence of the undersaturation of CO_2 in seawater. There are limitations to the ocean's ability to absorb CO_2, however, because only the top 300 m of the ocean is in contact with the atmosphere. (As mentioned earlier, the deep ocean layers do mix with the upper layers, but the mixing time is over a thousand years.) Calculations indicate that, in the 1990s, the ocean sink accounted for an uptake of 2.0 (±0.6) GtC annually.

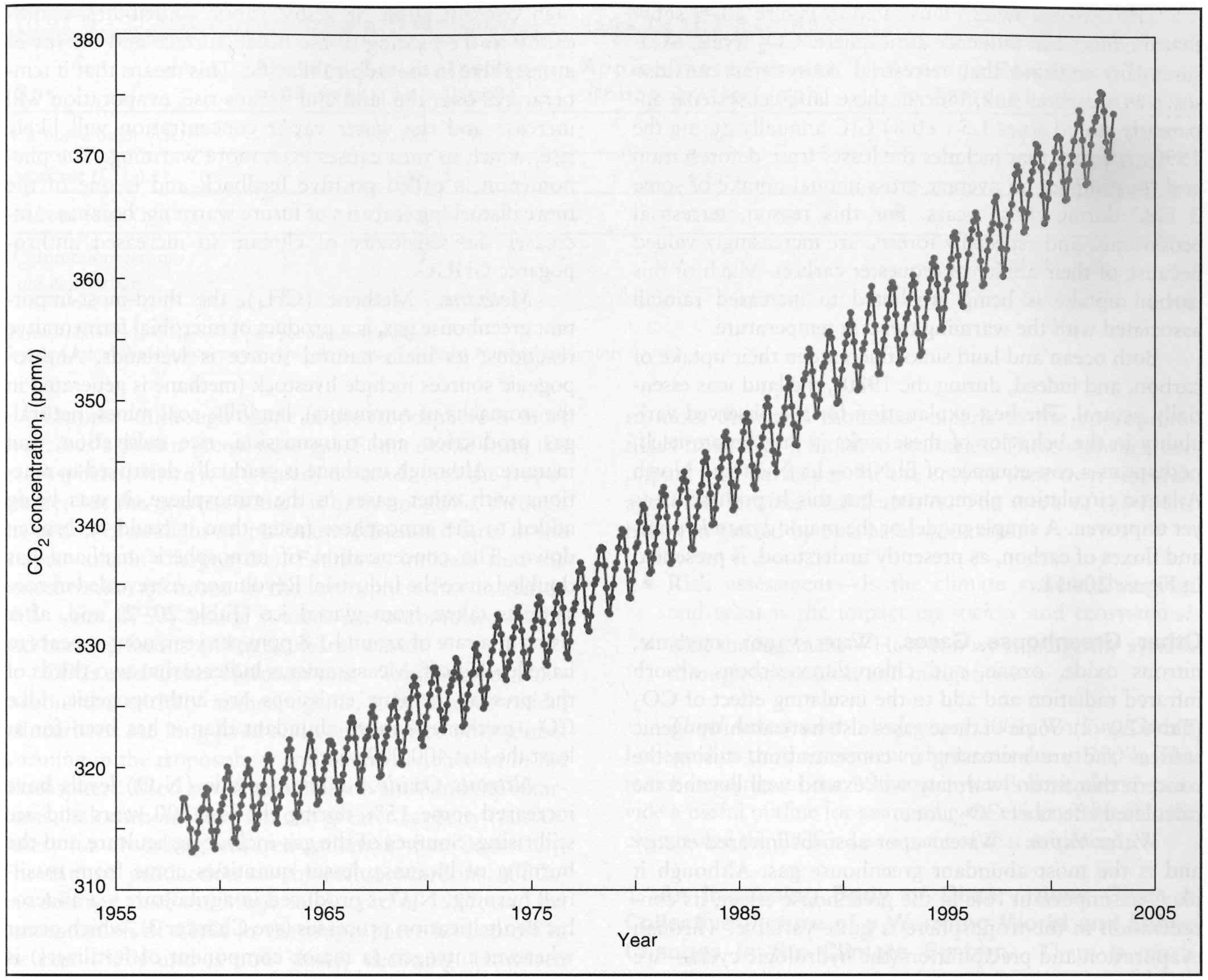


Figure 20–9 Atmospheric carbon dioxide concentrations. The concentration of CO_2 in the atmosphere fluctuates between winter and summer because of seasonal variation in photosynthesis. The average concentration is increasing owing to human activities—in particular, burning fossil fuels and deforestation. (All measurements made at Mauna Loa Observatory, Hawaii, by Dave Keeling and Tim Whorf, Scripps Institute of Oceanography.)

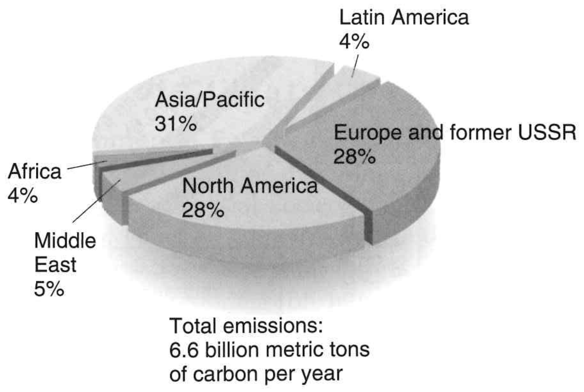


Figure 20–10 Sources of carbon dioxide emissions from fossil-fuel burning. Total emissions in 2001 were approximately 6.6 GtC, or 24 billion metric tons of CO_2. (*Source:* Data from U.S. Energy Information Agency.)

The seasonal swings illustrated in Figure 20–9 show that the biota can influence atmospheric CO_2 levels. Measurements indicate that terrestrial ecosystems can also serve as a carbon sink. Indeed, these land ecosystems apparently stored a net 1.5 (±0.8) GtC annually during the 1990s, a figure that includes the losses from deforestation and thus implies an average gross annual uptake of some 3 GtC during those years. For this reason, terrestrial ecosystems, and especially forests, are increasingly valued because of their ability to sequester carbon. Much of this carbon uptake is being attributed to increased rainfall associated with the warming trend in temperature.

Both ocean and land sinks fluctuate in their uptake of carbon, and indeed, during the 1980s, the land was essentially neutral. The best explanation for the observed variability in the behavior of these sinks is the climate itself, perhaps as a consequence of El Niño–La Niña and North Atlantic circulation phenomena, but this hypothesis is as yet unproven. A simple model of the major dynamic pools and fluxes of carbon, as presently understood, is presented in Figure 20–11.

Other Greenhouse Gases. Water vapor, methane, nitrous oxide, ozone, and chlorofluorocarbons absorb infrared radiation and add to the insulating effect of CO_2 (Table 20–2). Some of these gases also have anthropogenic sources and are increasing in concentration, raising the concern that future warming will extend well beyond the calculated effects of CO_2 alone.

Water Vapor. Water vapor absorbs infrared energy and is the most abundant greenhouse gas. Although it plays an important role in the greenhouse effect, its concentration in the troposphere is quite variable. Through evaporation and precipitation (the hydrologic cycle—see Chapter 7), water undergoes rapid turnover in the lower atmosphere, and water vapor does not tend to accumulate over time. Water vapor does, however, appear to be a major factor in what has been called the "supergreenhouse effect" in the tropical Pacific Ocean. As it traps energy that has been radiated back to the atmosphere, the high concentration of water vapor contributes significantly to the heating of the ocean surface and the lower atmosphere in the tropical Pacific. This means that if temperatures over the land and oceans rise, evaporation will increase and the water vapor concentration will likely rise, which in turn causes even more warming. The phenomenon is called **positive feedback** and is one of the more disturbing features of future warming, because it increases the sensitivity of climate to increased anthropogenic GHGs.

Methane. Methane (CH_4), the third-most-important greenhouse gas, is a product of microbial fermentative reactions; its main natural source is wetlands. Anthropogenic sources include livestock (methane is generated in the stomachs of ruminants), landfills, coal mines, natural-gas production and transmission, rice cultivation, and manure. Although methane is gradually destroyed in reactions with other gases in the atmosphere, it was being added to the atmosphere faster than it could be broken down. The concentration of atmospheric methane has doubled since the Industrial Revolution, as revealed in core samples taken from glacial ice (Table 20–2) and, after rising at a rate of around 1.8 ppm per year, now appears to have leveled off. Measurements indicate that two-thirds of the present methane emissions are anthropogenic. Like CO_2, methane is more abundant than it has been for at least the last 400,000 years.

Nitrous Oxide. Nitrous oxide (N_2O) levels have increased some 15% during the last 200 years and are still rising. Sources of the gas include agriculture and the burning of biomass; lesser quantities come from fossil-fuel burning. N_2O is produced in agriculture via anaerobic denitrification processes (see Chapter 3), which occur wherever nitrogen (a major component of fertilizers) is highly available in soils. The buildup of nitrous oxide is particularly unwelcome, because its long residence time (114 years) makes the gas a problem in not only the troposphere, where it contributes to warming, but also the stratosphere, where it contributes to the destruction of ozone.

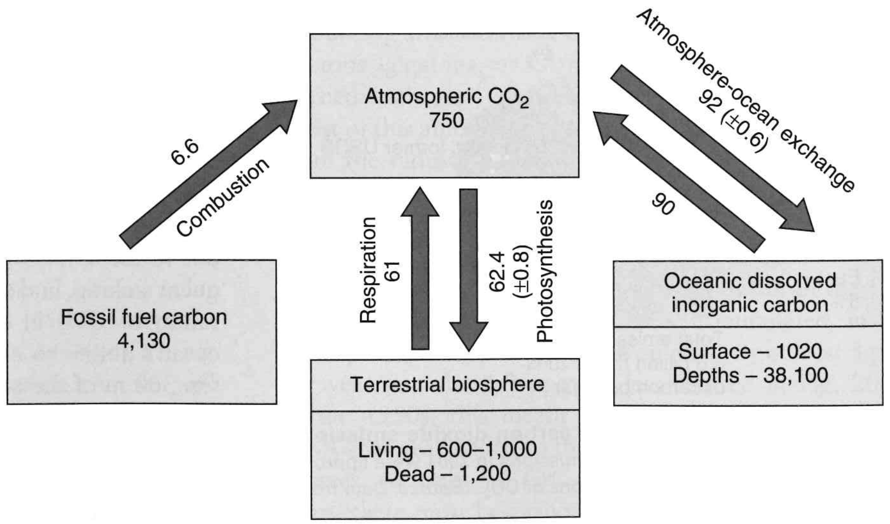


Figure 20–11 Global carbon cycle. Data are given in GtC (billion metric tons of carbon). Pools are in the boxes, and fluxes are indicated by the arrows. (*Data sources:* Various.)

table 20-2 Anthropogenic Greenhouse Gases in the Atmosphere

Gas	Average Concentration 100 years ago (ppb)[1]	Approximate Current Concentration (ppb)	Average Residence Time in Atmosphere (years)
Carbon dioxide (CO_2)	288,000	375,000	120
Methane (CH_4)	848	1,850	12
Nitrous oxide (N_2O)	285	316	114
Chlorofluorocarbons and halocarbons	0	1.2	50–100

[1] Parts per billion; 1,000 ppb = 1 part per million (ppm).
(*Source:* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.)

Ozone. Although ozone in the troposphere is short lived, it is a potent greenhouse gas. Some ozone from the stratosphere (where it is formed) descends into the troposphere, but the greatest source is anthropogenic, through the action of sunlight on pollutants (discussed later in the chapter and in Chapter 21). Estimates indicate that the concentration of ozone in the atmosphere has increased 36% since 1750. Major sources are automotive traffic and burning forests and agricultural wastes.

CFCs and Other Halocarbons. Emissions of halocarbons are entirely anthropogenic. Like nitrous oxide, halocarbons are long lived and contribute to both global warming in the troposphere and ozone destruction in the stratosphere. Used as refrigerants, solvents, and fire retardants, halocarbons have a much greater capacity (10,000 times) for absorbing infrared radiation than does CO_2. The rate of production of chlorofluorocarbons (CFCs) has declined since the Montreal Accord of 1987, and the concentration of CFCs in the troposphere leveled off in the late 1990s and is now slowly declining. However, these gases are highly stable and will continue to exert their warming effects for many decades.

Together, the other anthropogenic GHGs are estimated to trap as much infrared radiation as CO_2 does. Although the tropospheric concentrations of some of these gases are rising, it is hoped that they will gradually decline in importance because of steps being taken to reduce their levels in the atmosphere, leaving CO_2 as the primary greenhouse gas to cope with in the future.

Evidence of Climate Change

Intergovernmental Panel on Climate Change. In 1988, the United Nations Environment Program and the World Meteorological Society established the Intergovernmental Panel on Climate Change (IPCC) in order to provide accurate and relevant information that would lead to an understanding of human-induced climate change. The IPCC has established three working groups: one to assess the scientific issues (Working Group I), another to evaluate the impact of global climate change and the prospects for adapting to it (Working Group II), and a third to investigate ways of mitigating the effects (Working Group III). The IPCC working groups consist of more than two thousand experts in the appropriate fields from over a hundred countries. These stalwarts are unpaid and participate at the cost of their own research and other professional activities. The work of the IPCC has been guided by two basic questions:

- **Risk assessment**—Is the climate system changing, and what is the impact on society and ecosystems?
- **Risk management**—How can we manage the system through adaptation and mitigation?

Third Assessment. In January 2001, Working Group I released its third assessment (the next is due in 2007). The major headings of the "Summary for Policymakers" provide a useful outline for examining the evidence for climate change and the IPCC's assessment of that evidence:

1. An Increasing Body of Observations Gives a Collective Picture of a Warming World and Other Changes in the Climate System. There is much natural variation in weather from year to year, and local temperatures do not necessarily follow globally averaged ones. It is a fact, however, that 17 of the hottest years on record have occurred since 1980 (Fig. 20–5); indeed, 1990–2000 was the hottest decade ever recorded—and that in spite of two cooler years following the eruption of Mount Pinatubo in the Philippines in 1991. After the debris from Mount Pinatubo was cleansed from the atmosphere, we returned to the warming trend that was evident in the 1980s. The years 1997, 1998, 2001, and 2002 set new records for global temperatures, adding further compelling evidence for global warming.

Correlation? Scientists have puzzled over the absence of a more direct correlation between CO_2 and global atmospheric temperatures over the last several decades. Calculations, for example, predict significantly higher increases in temperature than have actually occurred. Critics have used this discrepancy to bolster their arguments that global warming is, so to speak, a lot of "hot air." Recent work has addressed the problem. First, it is apparent that sulfate aerosol in the industrialized regions of the Northern Hemisphere appears to be canceling out much of the greenhouse warming over those regions. The cooling effects of the aerosol occur over the very regions most responsible for greenhouse gas emissions. However, scientists point out that the aerosol cooling effect is temporary. As the industrialized nations continue to reduce sulfate emissions (because of acid rain and its impacts on human health), and as GHGs continue to build up, the Northern Hemisphere will likely experience its own share of warming.

The second finding confirms what climatologists have thought, but, until now, have never been able to prove: The oceans are absorbing much of the heat, slowing down the rate at which the atmosphere is warming. Recently, oceanographers analyzed millions of oceanic temperature records from 1950 to 1995 and found that, between 1970 and 1995, the heat content of the global oceans increased dramatically. Indeed, the heat record in the oceans follows the same general trend as that in the atmosphere, having accelerated during the 1990s (Fig. 20–12).

Satellites? An interesting and controversial aspect of the warming trend has arisen with measurements of tropospheric temperatures (from Earth's surface to 8 km) made by 13 different satellites over two decades. Two early analyses of the data indicated either virtually no increase (+0.01°C per decade) or a significant increase (+0.10°C per decade), the latter consistent with the +0.17°C-per-decade warming found in the surface temperature measurements. Much has been made of the first group's apparent discrepancy with the surface temperature trends, especially by skeptics eager to disprove global warming. A National Research Council panel examined this discrepancy and concluded both that the surface warming was real and that satellite records should be used with caution. A more recent analysis of the satellite data corrected for seasonal and diurnal effects, instrument biases, and orbital discrepancies and found a trend of +0.22–0.26°C per decade. If anything, the tropospheric temperatures appear to be rising even more rapidly than the surface temperatures.

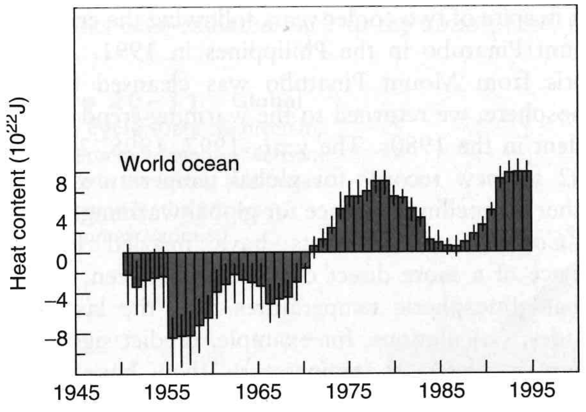


Figure 20–12 Heat capture by the oceans. The plot shows the changes in heat content of the upper 3,000 meters of the world's oceans, based on an analysis of millions of temperature data points. (*Source:* Reprinted with permission from *Warming of the World Ocean* by S. Levitus et al. in *Science,* 287, March 24, 2000. Copyright © 2000 by American Association for the Advancement of Science. Reprinted by permission.)

Other Changes. Other significant impacts of global climate change were noted by the IPCC. One is the retreat of glaciers. The World Glacier Monitoring Service has followed the melting and slow retreat of mountain glaciers all over the world. The response time of glaciers to climatic trends is slow—10 to 50 years—but the data collected show a wide-scale recession of glaciers over the past hundred years, consistent with an increase in GHGs. Another impact is the thinning of polar ice. Recent work has documented large decreases in the thickness and extent of sea ice in the Arctic. The polar ice cap has lost nearly 20% of its volume in the last two decades, and permafrost has been melting all over the polar regions, lifting buildings, uprooting telephone poles, and breaking up roads. During 2002 and 2003, the largest ice shelf in the Arctic (150 square miles) was broken up. The Greenland Ice Sheet, a huge reservoir of water, is melting at unprecedented rates, undoubtedly a response to the rise in temperatures in the northern latitudes. While overall global temperature has increased a moderate 1°F, temperatures in Alaska, Siberia, and northwest Canada have risen 5°F in summer and 10°F in winter. Indeed, winters above 40° north latitude have been shortened by an average of two weeks.

The weather has been changing. Further impacts reported by the IPCC include a significant increase in precipitation—especially heavy precipitation; a reduction in the frequency of very low temperatures; a greater frequency of El Niño events; and more frequent and intense droughts in parts of Asia and Africa. In July 2003, the World Meteorological Society issued a bulletin to the effect that the world's weather has seen record-breaking extremes during the late spring, in the form of heat waves, rainfall, and tornadoes, and linked them to climate change.

Sea Level. By far the most ominous of the impacts is the *rise in sea level.* With global warming, the sea level has been rising due to two factors: thermal expansion as ocean waters warm, and the melting of glaciers and ice fields. Sea level has risen between 0.1 and 0.2 meter during the 20th century and is continuing to rise at rate of 2 mm per year. As we have noted, the oceans are clearly warming (Fig. 20–12).

2. Emissions of GHGs and Aerosols Due to Human Activities Continue to Alter the Atmosphere in Ways That Are Expected to Affect the Climate. The IPCC examined long-term records of GHGs and sulfate aerosols and demonstrated that these agents were on the increase in the atmosphere (Fig. 20–13) and were exerting a predictable forcing impact on the climate system—positive for the GHGs and negative for the aerosols. All of these trends and impacts are the result of human activities, and are all currently increasing. The combined radiative forcing of these and other anthropogenic and natural factors of the climate are shown in Figure 20–14. Note that the level of scientific certainty for some of these factors is low, but it is high for the GHGs, whose positive radiative forcing is highly significant.

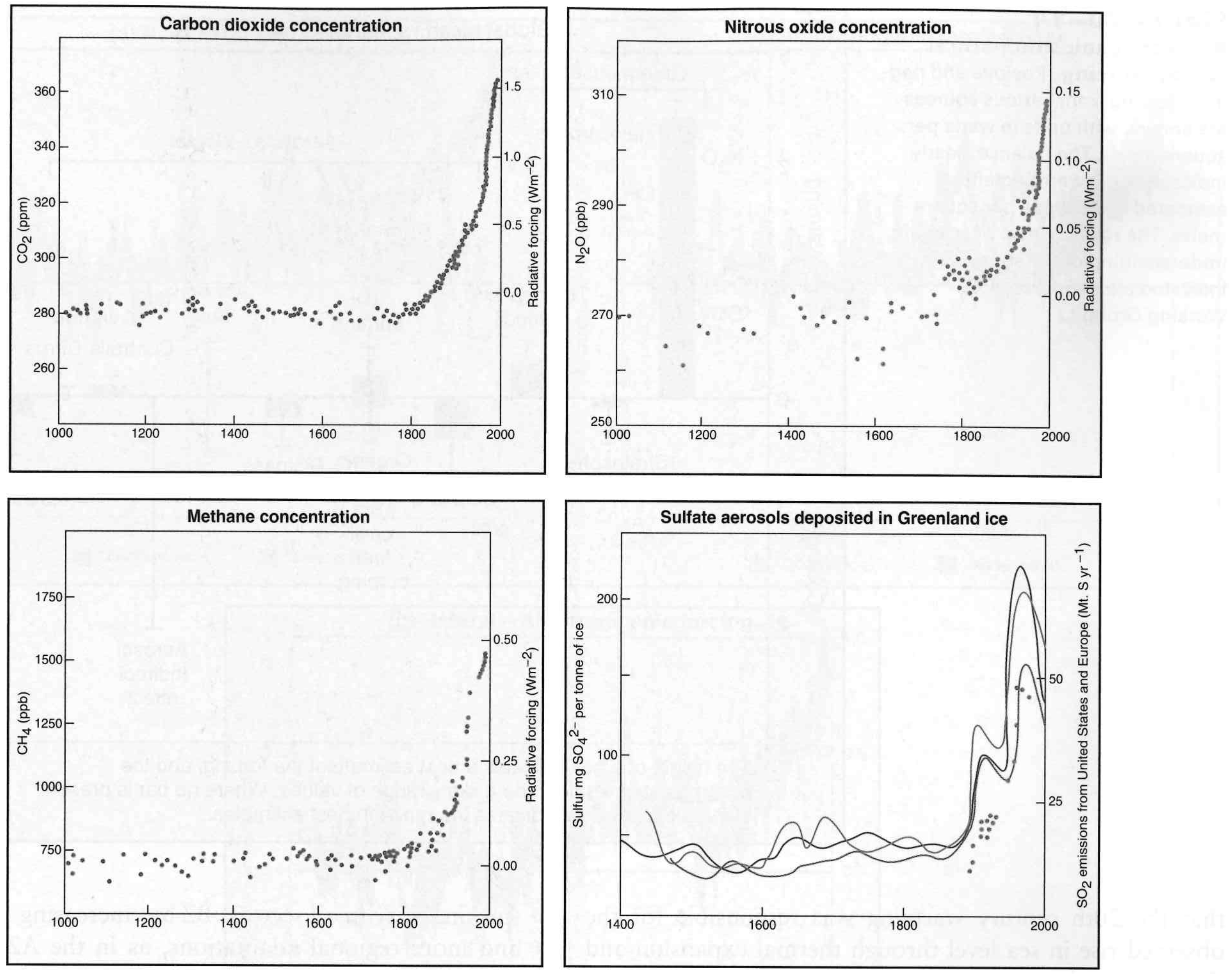


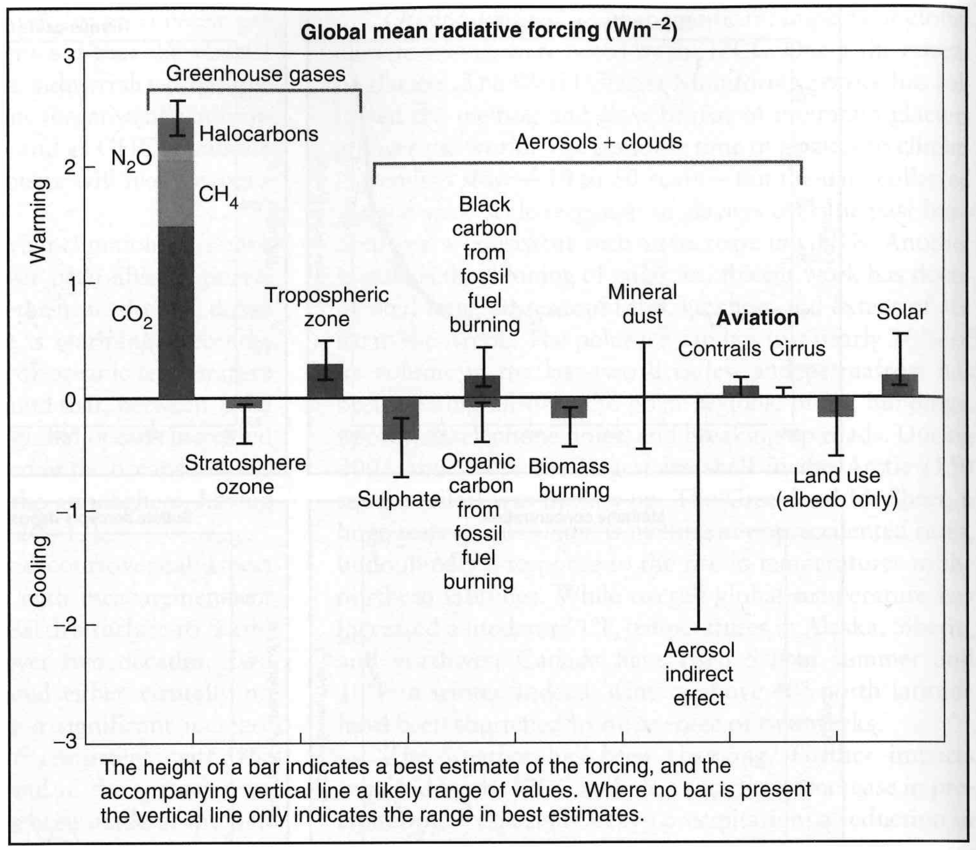
Figure 20–13 Human influence on the atmosphere during the industrial era. The plots show concentrations of the greenhouse gases carbon dioxide, methane, and nitrous oxide as they have risen since the early 1800s. Sulfate aerosols are also shown. The lines depict three ice core measurements (left axis), while the dots show levels of sulfate emissions from the U.S. and Europe (right axis). (*Source:* IPCC Working Group I.)

3. Confidence in the Ability of Models to Project Future Climate Has Increased. Weather forecasting employs powerful computers capable of handling large amounts of atmospheric data and applying appropriate mathematical equations modeling the processes taking place in the atmosphere, oceans, and land. Forecasts of conditions for 72 hours or more have become quite accurate. Even though computing power has increased greatly in recent years, the somewhat chaotic behavior of weather parameters prevents more long-term forecasting.

Modeling climate is an essential strategy for exploring the potential future impacts of rising GHGs. Climatologists employ the same powerful computers used for weather forecasting and have combined global atmospheric circulation patterns with ocean circulation and radiation feedback from clouds to produce *coupled general circulation models* (CGCMs) that are capable of simulating long-term climatic conditions. Fourteen centers around the world are now intensely engaged in exploring climate change by running models coupling the atmosphere, oceans, and land. The latest information on the cooling effects of sulfate aerosols has been incorporated into current simulations, giving modelers more confidence in their results. Figure 20–15 is taken from the IPCC assessment and indicates simulated global mean temperatures based on natural and known anthropogenic forcings. Note how well the combined model simulates the observed temperature changes. Many models have now successfully simulated past climates on the basis of known differences in Earth's orbit and ocean–atmosphere coupling. The most complex models, requiring supercomputers, recently scored a major triumph in predicting the intensity and locations of the latest El Niño. As we will see, the main purpose of the models is to project the future global climate.

4. There Is New and Stronger Evidence That Most of the Warming Observed Over the Last 50 Years Is Attributable to Human Activities. In 1995, in its second assessment report, the IPCC stated cautiously, "The balance of evidence suggests a discernible human influence on global climate." (See "Ethics" essay, p. 556.) In the panel's third assessment, the tone of consensus had shifted, to the more definite statement that anthropogenic GHGs have "contributed substantially to the observed warming over the last 50 years." The panel also concluded

Figure 20–14 **Anthropogenic and natural climate forcing.** Positive and negative forcing from various sources are shown, with units in watts per square meter. The balance clearly indicates a net warming effect, estimated at 1.6 watts per square meter. The relative level of scientific understanding of the sources is indicated also. (*Source:* IPCC Working Group I.)



The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates.

that the 20th century warming was responsible for the observed rise in sea level through thermal expansion and the extensive loss of glaciers and sea ice.

5. Human Influences Will Continue to Change Atmospheric Composition Throughout the 21st Century. The coupled general circulation models were employed to examine the changes that might take place over the 21st century. A number of assumptions about greenhouse gas emissions were combined with a range of responses of climate to greenhouse gas concentrations (climate sensitivity) to project some 35 scenarios of 21st-century climate changes. All scenarios project a rise in CO_2 as a consequence of burning fossil fuels. The IPCC expects that this one greenhouse gas will be the dominant influence on climate. Figure 20–16 shows several of the scenarios as they play out in the models; the rising CO_2 emissions and atmospheric concentrations are clearly indicated.

Assumptions. The assumptions underlying the scenarios are critical. The A1 scenarios reflect a world in which population reaches its peak in midcentury and then declines, economic growth is rapid, and new technologies are employed. A1F1 shows a fossil-fuel-intensive society, A1T reflects shifts to non-fossil-energy sources, and A1B is a balance across all energy sources. The A2 series reflects a world of independent countries going their own way, with increasing population and varied economic growth and technological change. B1 reflects a world with population developments as in A1, but with rapid changes in economies and effective global cooperation to reach sustainability in all sectors. B2 has increasing populations and more regional adaptations, as in the A2 series, but with significant efforts to achieve sustainability. IS92a is a scenario carried over from the second IPCC assessment, for comparison purposes. Notably, none of the scenarios includes specific adjustments based on the targets of the Framework Convention on Climate Change or the Kyoto Protocol (discussed shortly).

The IPCC scenarios demonstrate the crucial importance of energy choices. The great range of CO_2 emissions and consequent atmospheric concentrations (540–970 ppm) in the scenarios reflect the range of energy options from "business as usual" fossil-fuel use (A1F1) to a shift to renewable energy (B1). Even the most optimistic scenario pictures a doubling of atmospheric CO_2 over preindustrial levels. The most important issue here is that of stabilizing atmospheric CO_2 concentrations. It will be necessary to bring CO_2 emissions below 1990 levels (The Kyoto Protocol target) within a few decades, to stabilize CO_2 at 450 ppm, but if it took a century to achieve the 1990 target, CO_2 would be at 650 ppm, and if it took two centuries, 1,000 ppm would be the ambient CO_2 concentration.

6. Global Average Temperature and Sea Level Are Projected to Rise Under All IPCC Scenarios. The major consequence of rising greenhouse gas levels during the 21st century is rising temperatures—the amount of rise again depending on the energy choices and other factors, such as population growth. Rising global temperatures are linked to two major impacts: *regional climatic changes* and *a rise in sea level* (Fig. 20–17a). Both of these effects show up in all of the models and are expected to become evident in a matter of a few decades. The IPCC assessment states, "The globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100." This projection is based on the range of scenarios and numerous climate models. For doubled CO_2 (560 ppm), the best estimate is a temperature rise of 2.5°C. The difference in temperature between an ice age and the warm period following is only 5°C, so in a century, unless some drastic measures are taken, Earth's climate will change rapidly. Responding to these changes will likely involve unprecedented and costly adjustments. The impact on natural ecosystems could be highly destabilizing.

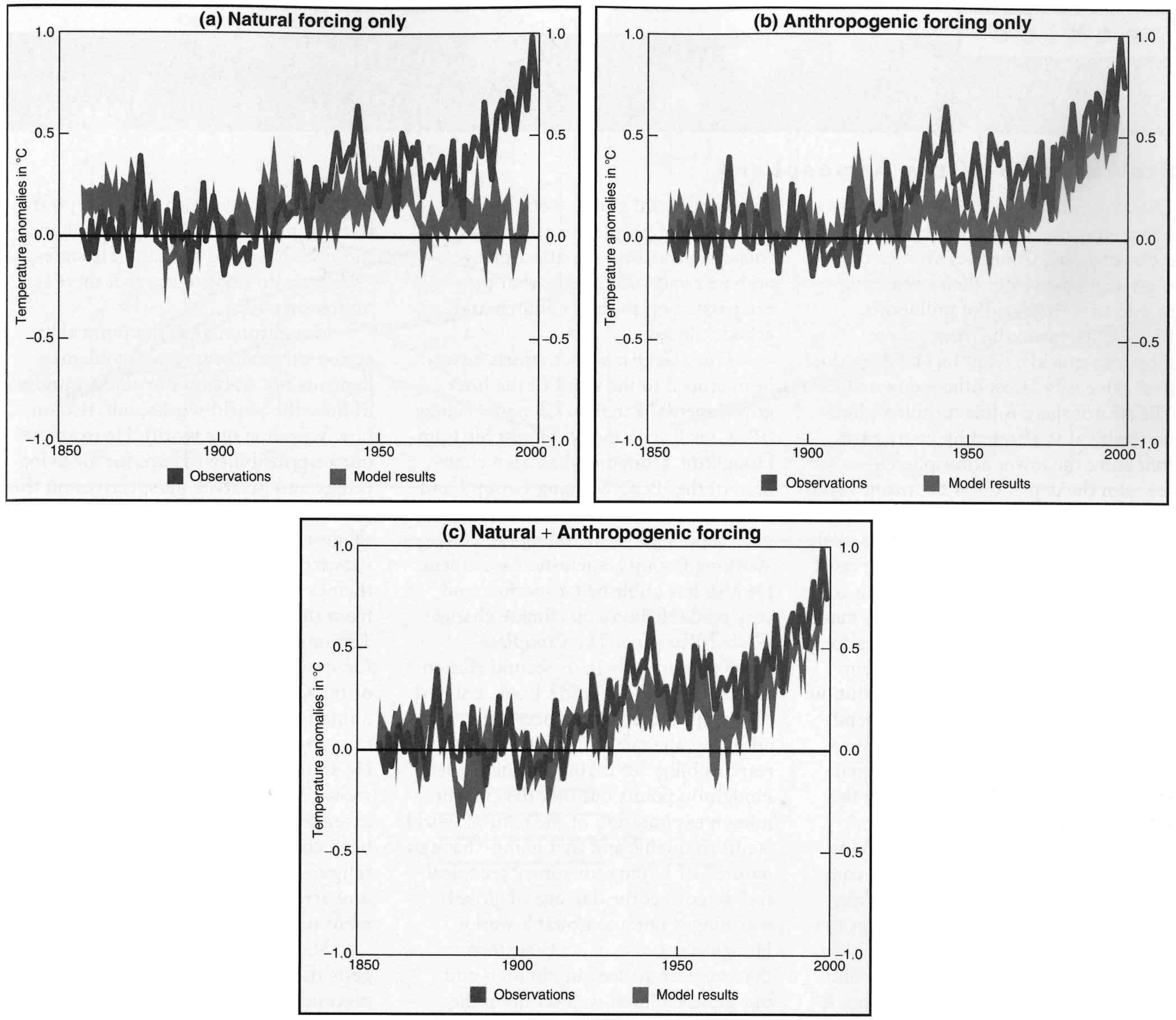


Figure 20–15 **Comparison between modeled and actual data on temperature rise since 1860.** (a) Model results with only natural forcing. (b) Model results with only anthropogenic forcing. (c) Model results combining natural and anthropogenic forcing. Note how well the latter follows the actual temperature data. (*Source:* IPCC Working Group I.)

Climate Changes. Warming will seriously affect rainfall and agriculture. The present-day difference between temperatures at the poles and those at the equator is a major force driving the atmospheric circulation. The warming associated with a doubling of greenhouse gas levels is likely to be more pronounced in polar regions (as much as 10°C) and less pronounced in equatorial regions (1 to 2°C). Greater heating at the poles than at the equator will change atmospheric circulation patterns, as well as rainfall distribution patterns. Higher temperatures promote more evaporation and a greater ability of the atmosphere to hold moisture, which can enhance precipitation. Some regions will be drier, and some will be wetter. The frequency of droughts is expected to increase, as well as the frequency and intensity of rainstorms (and, therefore, floods). Further changes in climate could be initiated by alterations in the global oceanic circulation, which could be brought on by greenhouse warming. Oceanographers fear that if the ocean's conveyor goes into a stall, sudden shifts in land temperature may occur in the northern hemisphere.

ethics

Stewardship of the Atmosphere

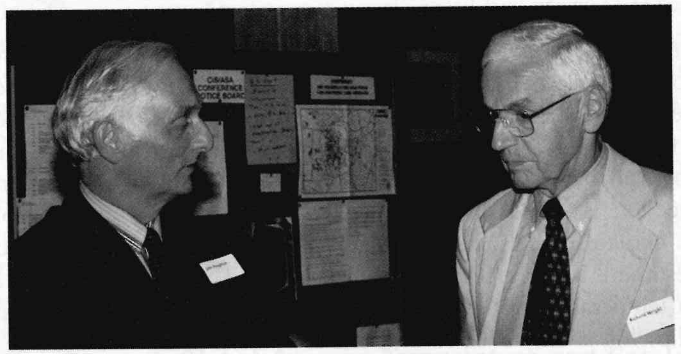
The atmosphere is a global commons—a resource used by all countries, yet not owned by any. Countries are free to draw from it to meet their needs and to add to it to get rid of pollutants. Because the air in the troposphere moves so quickly, what one country does to it can easily affect others downwind. The stratosphere is less turbulent, but inevitably it is affected by many gases that enter the lower atmosphere—as we see with the depletion of the ozone layer. Managing a global commons presents a difficult problem: Treaties must be made between countries and compliance must be assured if the global commons is to be protected. Some progress has been made in forging international agreements to curb acid emissions, which represent one form of transboundary air pollution. The Montreal Protocol and its amendments represent the most far-reaching and potentially effective international effort to protect a global resource: the stratospheric ozone layer.

Taking action on ozone-depleting chemicals is child's play, however, compared with what lies ahead in dealing with global climate change. Perhaps the most challenging aspect of the problem is that what we do about it now will do little to affect the present generation. It will likely take several generations for greenhouse gas concentrations to come to a doubling of preindustrial levels, with almost certain profound impacts. Thus, our dilemma is this: Shall we take action *now* to restrain our use of fossil fuels in order to benefit *future* generations? Increasing numbers of people are answering this question with a definite *yes*! For example, more than 2,000 economists agreed that there are many policies to reduce greenhouse gas emissions for which the total benefits outweighed the costs. Over 1,500 scientists, including 104 Nobel laureates, signed a statement urging government leaders attending the 1997 Kyoto conference to "act immediately to prevent the potentially devastating consequences of human-induced global warming." In fact, these people are assuming the role of stewards of the atmosphere and are concerned about what they are passing on to their children and grandchildren.

One scientist whose efforts have been crucial to the work of the Intergovernmental Panel on Climate Change (IPCC) is British meteorologist Sir John Houghton. Houghton has been chairman of the IPCC Working Group I and chief editor of four of the group's published reports, including the 2001 Working Group I Scientific Assessment. He also has published a succinct and very readable book on climate change: *Global Warming: The Complete Briefing*, currently in its second edition. Chapter 8 of Houghton's book, entitled "Why Should We Be Concerned," addresses the question of human responsibility for caring for the planet. Houghton points out that the current human exploitation of the natural world is unsustainable and that going "back to nature" or hoping for some "technical fix" to correct the damage of global warming is not a reasonable option. Houghton speaks of "a basic instinct that we wish to see our children and our grandchildren well set up in the world and wish to pass on to them some of our most treasured possessions," in particular "an earth that is well looked after and which does not pose to them more difficult problems than those we have had to face." He states, "We have no right to act as if there is no tomorrow."

Houghton makes the point that action on environmental problems depends not only on our understanding of how the world works, but also on how we value our world. He examines our responsibility to care for all living things and presents perspectives on this view from a number of the world's religions. He speaks of the concept of stewardship—one of the continuing themes of this text—that is derived from the Judaeo–Christian Old Testament. He recommends as a model for stewardship the biblical picture of the Garden of Eden, where the first humans were placed "to work and take care of it," as Genesis puts it. He states, "At the basis of this stewardship should be a principle extending what has traditionally been considered wrong—or in religious parlance as sin—to include unwarranted pollution of the environment or lack of care for it."

Stewardship of the atmosphere suggests that the world's nations act on the precautionary principle and begin to curb greenhouse gas emissions now and more deeply in the future. What do you think, and what will you do?



Sir John Houghton (left) and text author Richard Wright (right) discuss global climate change at a conference in Cambridge, UK.

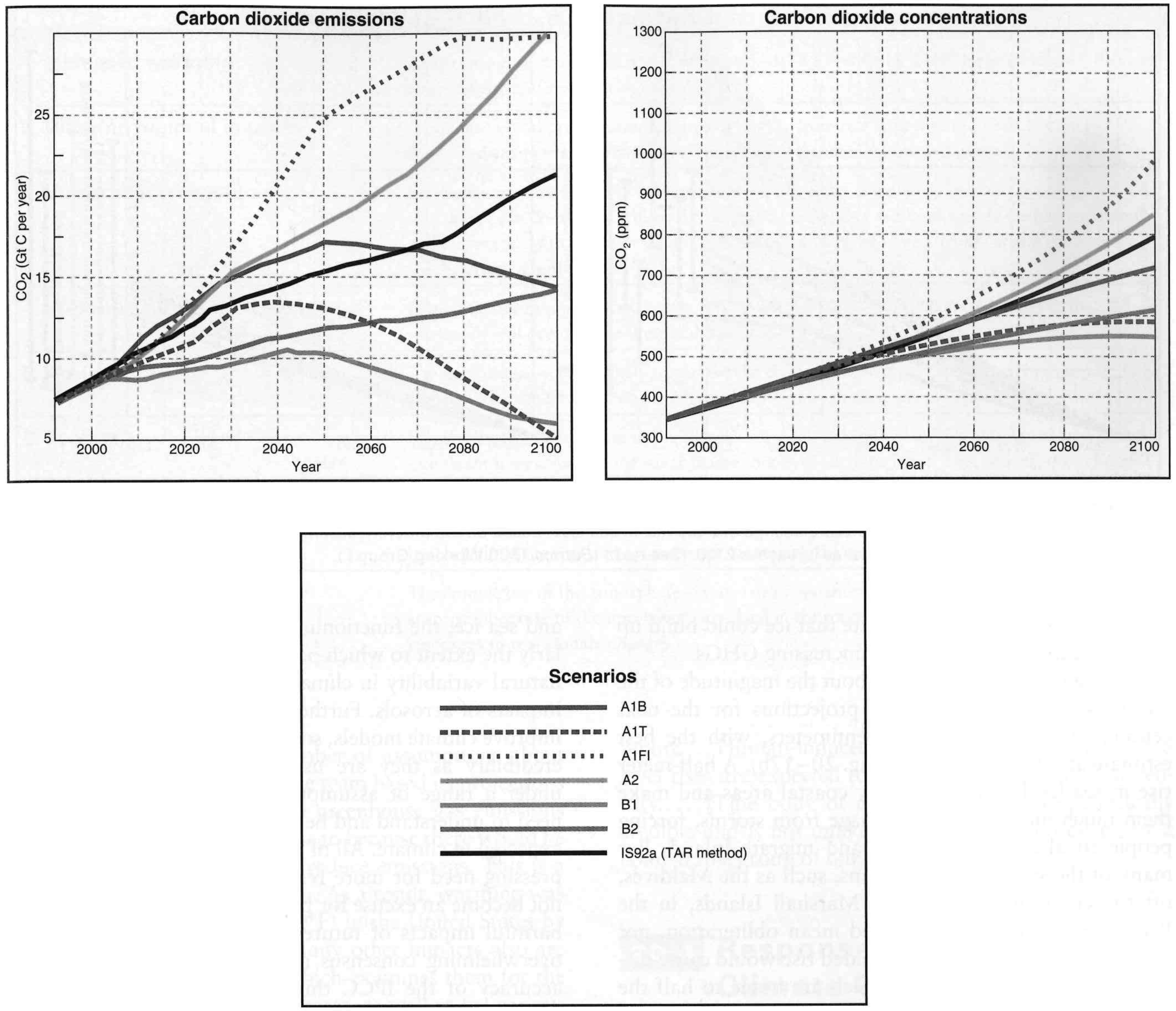


Figure 20–16 Twenty-first century carbon dioxide changes according to model scenarios. The projected carbon dioxide emissions and atmospheric concentrations are shown for seven computer model runs. Each is based on different assumptions. (See text.) (*Source:* IPCC Working Group I.)

For the agricultural community, the greatest difficulty in coping with climatic change is not knowing what to expect. Already, farmers lose an average of one in five crops because of unfavorable weather. As the climate shifts, the vagaries of weather will become more pronounced, and crop losses are likely to increase. Fortunately, farmers are capable of rapidly switching crops and land uses, so the impact may not be as bad as some observers think.

Benefits? Humans and ecosystems will be subjected to unprecedented changes in climate under most of the scenarios presented by the IPCC. Many regions will experience hotter summer weather, but many northern regions will also enjoy warmer winters and longer growing seasons. The increased CO_2 in the atmosphere will likely stimulate plant growth under some conditions and in some regions, but in many regions the increased heat will offset this benefit. Because of the rapid rate of changes that are anticipated, the net harm very likely will greatly outweigh the benefits.

Rising Sea Level. The warming at the poles due to rising temperatures could have an enormous effect when the ice melts, because so much water is stored in the world's remaining ice—enough to raise sea level by 75 m. The area of greatest concern is the Greenland ice sheet, where local warming is expected to be up to three times the global average. If this ice sheet melts completely, sea level could rise 7 meters! Another area of concern is the Antarctic, which holds most of the world's ice. West Antarctica's ice sheet is not greatly elevated above sea level; in fact, most of it rests on land that is below sea level. The Ross and Weddell Seas extend outward from this ice field, and the landward fringes of these seas are covered with thick floating shelves of ice. Currently, the rate of melting and of buildup seem to be about equal,

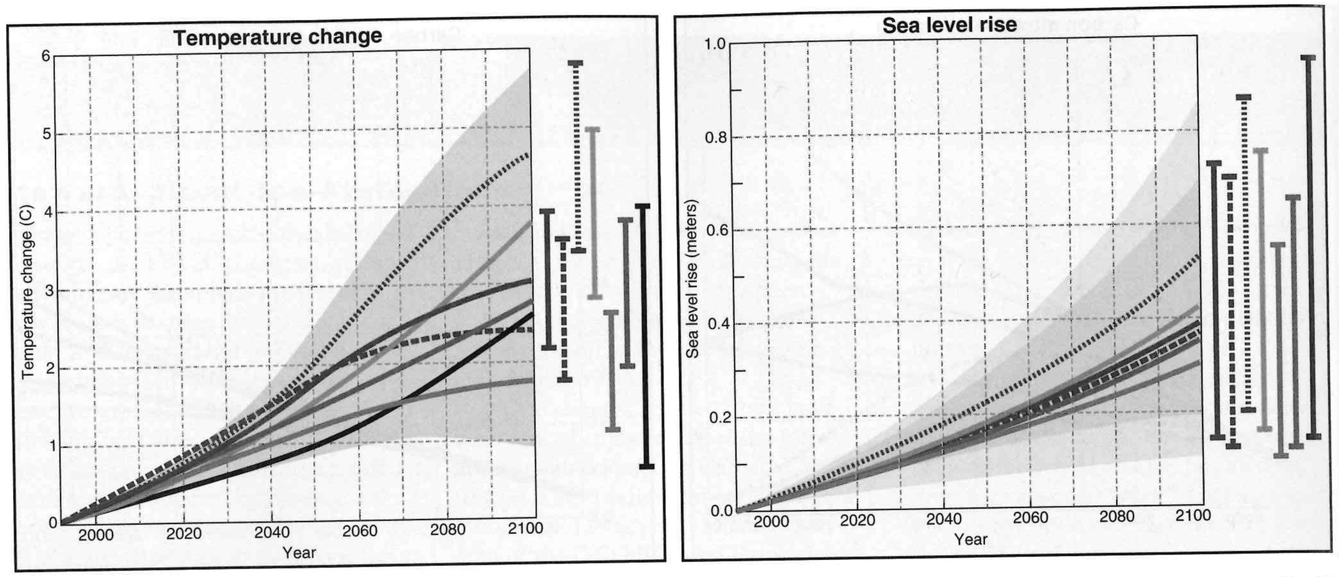


Figure 20–17 **Twenty-first century temperature change and sea-level rise.** The same model scenarios as in Figure 20–16 are used to project the range of temperature change and the rise in sea level based on the different assumptions. The vertical bars indicate the range of uncertainty for each model as it reaches 2100. (See text.) (*Source:* IPCC Working Group I.)

and many climate models indicate that ice could build up even more in the Antarctic with increasing GHGs.

There is great uncertainty about the magnitude of the rise in sea level. IPCC model projections for the next century range from 9 to 88 centimeters, with the best estimate at 50 cm (1/2 meter) (Fig. 20–17b). A half-meter rise in sea level will flood many coastal areas and make them much more prone to damage from storms, forcing people to abandon properties and migrate inland. For many of the small oceanic nations, such as the Maldives, off the coast of India, or the Marshall Islands, in the Pacific, a rise in sea level would mean obliteration, not just alteration. The highest estimated rise would cause disasters in most coastal cities, which are home to half the world's population and its business and commerce.

7. Anthropogenic Climate Change Will Persist for Many Centuries. The estimated rise in sea level extends only through the next century, but the impact will certainly be greater beyond the year 2100. Are inland cities and communities ready to accommodate the billions of people that will be displaced? Are we ready to build dikes or modify all ports to accommodate the higher sea level? Once atmospheric greenhouse gas levels are stabilized, temperatures and sea levels will continue to rise for hundreds of years because of the slow response time of the oceans.

8. Further Action Is Required to Address Remaining Gaps in Information and Understanding. There are many uncertainties in our understanding of how global climate works—especially in how it will respond to the challenges of 21st-century additions of GHGs. There also is a great need for more research and observations on current climate variables, such as the occurrence and impacts of clouds; the extent of, and changes in, glaciers and sea ice; the functioning of the carbon cycle (particularly the extent to which oceans and land sequester CO_2); natural variability in climate; and the direct and indirect impacts of aerosols. Further research is needed as well to improve climate models, so that they may be given greater credibility as they are used to project future climates under a range of assumptions. Especially crucial is the need to understand and better assess the regional changes expected in climate. All of these uncertainties point to the pressing need for more research, but uncertainty should not become an excuse for putting off action to prevent the harmful impacts of future climate changes. There is an overwhelming consensus among scientists regarding the accuracy of the IPCC third assessment. In May 2001, 17 academies of science from various parts of the world issued a statement in support of the IPCC third assessment. Asserting that "business as usual is no longer a viable option," they stated, "The balance of the scientific evidence demands effective steps now to avert damaging changes to Earth's climate."

Other Assessments

U.S. National Assessment. In the Global Change Research Act of 1990, Congress mandated an assessment of the findings of research on global climate change and its implications for the 21st century in the United States. The assessment, titled *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, was the work of a team of climate experts from major U.S. universities and agencies and was released in November 2000, after extensive peer reviews and numerous drafts.

The assessment team employed several CGCMs in projecting changes, but based most of its work on two: one from the Canadian Climate Centre and the other from the Hadley Centre in the United Kingdom. Simulations run on the models can make any number of assumptions about future releases of GHGs, but the team based its projections on the assumption that world greenhouse gas emissions would rise at a rate of 1% per year, because there would be no significant interventions to reduce emissions. This is a "business-as-usual" assumption. As a result, warming was projected to rise 3–6°C (5–10°F) in the United States by the end of the 21st century. Many other impacts also are projected in the assessment, which examines them for the various regions of the United States, as well as for various sectors, such as agriculture, forests, human health, and water resources. The key findings of the assessment are presented in Table 20–3. They are consistent with similar scenarios projected by the IPCC. It is clear that the consequences of global climate change will eventually be experienced by everyone, everywhere in the United States, if "business as usual" is our response.

table 20-3 **Key Findings of the 2000 U.S. Climate Change Assessment**

1. Increased warming	Temperatures in the United States will rise 5–10°F (3–6°C) by 2100. Heat waves will become more intense and frequent in urban areas.
2. Differing regional impacts	Temperature and precipitation changes will vary from one region to the next. Instances of heavy and extreme precipitation will increase, and some regions will get drier.
3. Vulnerable ecosystems	Many ecosystems are highly vulnerable to the projected climate changes. Alpine meadows may disappear, coral reefs will be threatened by the higher sea level, and some barrier islands will disappear. Many of the valuable goods and services we expect from natural ecosystems will be affected and possibly lost.
4. Widespread water concerns	Droughts, floods, and water quality will be a concern in many regions. Changes in the snowpack will occur in the West and Alaska.
5. Agriculture	The agriculture sector is likely to survive the changes, and U.S. crop productivity may actually increase over the first half of the 21st century, although the gains will not be uniform.
6. Forests	Forest growth may increase in the first decades, but changes in species will occur, with some significant losses, such as the sugar maple forests of the Northeast. Fire, insects, drought, and diseases will likely start impairing forest growth in the long term.
7. Coastlines	Rising sea levels and increasing frequencies and intensities of storms will inundate many beaches along the east and south coasts, damaging the coastal infrastructure.
8. Surprises and uncertainty	The complexity of the atmosphere–land–ocean system will undoubtedly bring us some surprises, because of the uncertainty involved in the model's projections and in human responses to real climate changes.

U.S. National Research Council. Following the publication of the IPCC third assessment, President George W. Bush asked the National Academy of Sciences to review the scientific assessment, give its own judgment of the report's accuracy and estimates of future changes, and answer a list of questions originating with the administration. The National Academy appointed a special committee of the National Research Council to conduct this review, and the committee released its report in June 2001, entitled *Climate Change Science: An Analysis of Some Key Questions.* The report clearly endorsed the IPCC Working Group I (WG I) assessment, stating, "The committee generally agrees with the assessment of human-caused climate change presented in the IPCC Working Group I scientific report.... Human-induced warming and associated sea level rises are expected to continue through the 21st century.... [T]he body of the WG I report is scientifically credible and is not unlike what would be produced by a comparable group of only U.S. scientists.... "

20.4 Response to Climate Change

The world's industries and transportation networks are so locked into the use of fossil fuels that massive emissions of CO_2 and other GHGs seem sure to continue for the foreseeable future, bringing on significant climate change. One possible response to this situation is **adaptation.** That is, we must anticipate some harm to natural and human systems and should plan adaptive responses to lessen the vulnerability of people, their property, and the biosphere to coming changes.

Still, we can lessen the rate at which emissions are added to the atmosphere and, eventually, bring about a sustainable balance—although no one thinks that doing so will be easy. This is the **mitigation** response: Take action to reduce emissions.

Skeptics. Skeptics about global warming can be found in many sectors, from predictable sources such as the fossil-fuel industry, Rush Limbaugh, and many conservative think tanks, to members of the scientific community. They all stress the uncertainties of the global climate models and, in particular, emphasize that there is much that we do not know about the role of the oceans, the clouds, the biota, and the chemistry of the atmosphere. In the absence of "convincing evidence," many think that the threat of global warming may well be overplayed. Why take enormously costly steps, they ask, to prevent something that may have positive results or may even never happen?

Indeed, why respond at all? The FCCC has proposed **three principles** that speak to this question:

1. The first is the **precautionary principle,** as articulated in the 1992 Rio Declaration. The principle states, "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." Employing this principle is like taking out insurance: We are taking measures to avoid a highly costly, but uncertain, situation (albeit one that is appearing more and more likely). The risk of serious harmful consequences is real; the scientific consensus is strong, and the political response, as we will see, is becoming robust.
2. The second is the **polluter pays principle.** Polluters should pay for the damage their pollution causes. This principle has long been part of environmental legislation. CO_2 is where it is because the developed countries have burned so much fossil fuel since the beginning of the industrial era.
3. The third is the **equity principle.** Currently, the richest 1 billion people produce 55% of CO_2 emissions, while the poorest 1 billion produce only 3%. International equity and intergenerational equity are ethical principles that should compel the rich and privileged to care about those generations which follow—especially those in the poor countries who are even now experiencing the consequences of global climate change. If we are able to take action that will prevent both present and future harm, it would be wrong not to do so.

Response 1: Mitigation

A number of steps have been suggested to combat global climate change, with the goal of *stabilizing the greenhouse gas content of the atmosphere at levels and on a time scale that would prevent dangerous anthropogenic interference with the climate system and that are consistent with sustainable development.* (This is the stated objective of the Framework Convention on Climate Change—see below.) The various steps are presented in Table 20–4. All of these steps move societies in the direction of sustainability and have many benefits beyond their impacts on global climate change. For example, investing in more efficient use and production of energy reduces acid deposition, is economically sound, lowers the harmful health effects of air pollution, lowers our dependency on foreign oil and our vulnerability to terrorism—and reduces CO_2 emissions.

What Has Been Done?

Framework Convention on Climate Change. One of the five documents signed by heads of state at the UNCED Earth Summit in Rio de Janeiro in 1992 was the **Framework Convention on Climate Change (FCCC).** This convention agreed to the goal of stabilizing greenhouse gas levels in the atmosphere, starting by reducing greenhouse gas emissions to 1990 levels by the year 2000 in all industrialized nations. Countries were to achieve the goal by voluntary means. Five years later, it was obvious that the voluntary approach was failing. All the developed countries except those of the European Union *increased* their greenhouse gas emissions by 7 to 9% in the ensuing five years. The developing countries increased theirs by 25%!

table 20-4 Options for Mitigation of Greenhouse Gas Emissions

Place a worldwide cap on GHG emissions; for CO_2, this can be accomplished by limiting the use of fossil fuels in industry and transportation. Rights to emit GHGs would be allocated to different countries and would be tradeable in a market-based system.
Invest in and deploy an increasing percentage of energy in the form of renewable-energy technologies: wind power, solar collectors, solar thermal energy, photovoltaics, hydrogen-powered vehicles, and geothermal energy, among others.
Remove fossil-fuel subsidies like depletion allowances, tax relief to consumers, support for oil and gas exploration, and the substantial costs of maintaining access to Middle Eastern oil.
Encourage the development of nuclear power, but only if issues concerning cost-effectiveness, reliability, spent fuel, and high-level waste are resolved.
Stop the loss of tropical forests and encourage the planting of trees and other vegetation over vast areas now suffering from deforestation.
Make energy conservation rules much more stringent. (Tighten building codes to require more insulation, use energy-efficient lighting, and so forth.)
Reduce the amount of fuels used in transportation by raising mileage standards, encouraging car pooling, stimulating mass transit in urban areas, and imposing increasingly stiff carbon taxes on fuels.
Sequester CO_2 emitted from burning fossil fuels by capturing it at the site of emission, converting it into liquid CO_2, and pumping it into the deep oceans, where the low temperatures and high pressure would preserve it as a solid mass.
Make a greater effort to slow the growth of the human population; a continually growing population will inevitably produce increasing amounts of greenhouse gas emissions.

Kyoto Protocol. Prompted by a coalition of island nations (whose very existence is threatened by global climate change), the third Conference of Parties to the FCCC met in Kyoto, Japan, in December 1997 to craft a binding agreement on reducing greenhouse gas emissions. In Kyoto, 38 industrial and former Eastern bloc nations agreed to reduce emissions of six GHGs to 5.2% *below* 1990 levels, to be achieved by 2012. The signatories to this agreement are called the *Annex I parties;* all others are *non-Annex I parties*—the developing countries. The percentages of the reductions varied (Table 20–5). At the conference, the developing countries refused to agree to *any* reductions, arguing that the developed countries had created the problem and that it was only fair that the developing countries continue on their path to development as the developed countries did, energized by fossil fuels.

Each participating country must *ratify* the accord, signifying that country's compliance with its terms. The accord requires that at least 55 countries ratify it, and Annex I ratifying countries must account for at least 55% of Annex I GHG emissions. At Bonn, Germany, in July 2001, and later in Marrakesh, Morocco, in October 2001, the signers of the Kyoto Protocol met to thrash out the details of the "rule book" for carrying out the requirements of the protocol. Following these meetings, ratification proceeded. Over 110 parties have ratified (many are non-Annex I parties), thus meeting the first requirement for the protocol. However, two countries—the United States and Australia—have pulled out of the agreement, and several Annex I parties have not yet committed themselves. The most important of the latter parties is Russia. With 17% of the Annex I 1990 carbon emissions, Russia's signature could put the Kyoto Protocol over the top. (Similarly, if the United States signed, its 36% share would push the accord way over the top.)

The targeted reductions of the Kyoto Protocol will *not* stabilize atmospheric concentrations of GHGs. The IPCC calculates that it would take immediate reductions in emissions of at least 60% worldwide to stabilize greenhouse gas concentrations at today's levels. Since this has no chance of happening, the concentration of greenhouse gases in the atmosphere will continue to rise. Nevertheless, Kyoto is an important first step toward the stabilization of the atmosphere. To achieve stabilization at 450 ppm will require an energy system that is revolutionary, because current carbon emissions at 6 ½ GtC/year will have to fall to 2 GtC by 2100 and then drop even further.

The signers of the Kyoto Protocol have a great deal of latitude in deciding how they will achieve their GHG reductions. The most desirable approach would be to select from a portfolio of policy options. The list of mitigation options presented in Table 20–4 includes several that are market based. One that is already underway is **carbon credit trading.** The World Bank has established the Prototype Carbon Fund, which provides developing countries and those in transition economies (Eastern Europe, the former Soviet Union) with the opportunity to initiate clean technologies—especially renewable energy—and their reductions in emissions are credited to the Fund's contributors (developed countries) in the form of credits. In 2002, a reduction of some 67 million tons of carbon emissions was accomplished in this way. Sample projects are a wind farm in Costa Rica and the reforestation of worn-out land in Romania.

table 20-5 Kyoto Emission Allowances and Eleven-Year Greenhouse Gas Emission Changes

Country	Kyoto Allowances (%) (1990–2008/12)	Observed Change (%) (1990–2001)	2001 Greenhouse Gas Emissions (10^6 Metric Tons of Carbon)
United States	−7	+15.7	1,510
European Union	−8	−0.2	829
United Kingdom	−12.5	−4.1	147
Germany	−21	−17.1	218
Australia	+8	+32.3	95
Canada	−6	+11.5	129
Japan	−6	+10.8	311
Russian Federation	0	−30.5	403
All Annex I countries	−5.2	−1.7	3,649*
Non-Annex I countries			2,621*

*1999 figures
(*Sources:* WorldWatch Institute, 2002; Carbon Dioxide Information Analysis Center.)

U.S. Policy. Early in March 2001, U.S. representatives signed a statement with the Group of Eight industrial countries that reaffirmed our commitment to uphold the Kyoto Protocol and expressed concern about the serious threat of global climate change. A week later, in a letter responding to a query from four senators about his administration's views on global climate change, President George W. Bush stated that he opposed the Kyoto Protocol for two reasons:

1. It exempts the developing countries and thus is unfair.
2. It would cause serious harm to the U.S. economy.

At the same time, the president retreated from his most significant and explicit campaign promise to protect the environment: to reduce CO_2 emissions as part of an overall strategy to regulate four air pollutants emitted by power plants. He also cited the "incomplete state of scientific knowledge of the causes of, and solutions to, global climate change. . . ." Later in March, EPA administrator Christine Whitman officially notified the world that the United States would withdraw from the Kyoto agreement.

Global Climate Change Initiative. The move away from the Kyoto Protocol does not mean that the United States is doing nothing about climate change. Instead, we are committed to going our own way. In February 2002, that way became clearer with the release of the administration's **Global Climate Change Initiative** (GCCI). The flagship policy of this initiative is an 18% cut in **emissions intensity** over the next 10 years. What is emissions intensity? It is *not* the same as emissions; it is the *ratio* of greenhouse gas emissions to economic output, the latter measured as gross domestic product (GDP). Emissions intensity in 2002 was 183 tons of CO_2 per million dollars of GDP, and the goal is to reduce it to 151 tons per million dollars of GDP.

Critics point out that the program is voluntary, and even if it works, it will simply continue a trend already in progress that has seen emissions intensity reduced by 16% from 1990 to 2000. While that happened, our total greenhouse gas emissions actually rose 14% (Fig. 20–18). Under the Bush plan, U.S. emissions in 2012 would be about 30% above the goal of returning emissions to their 1990 level, and since the Kyoto Protocol calls for a 7% reduction *below* 1990 levels, we are on a track of a 35% or more increase in greenhouse gas emissions, compared with our Kyoto-agreed goal!

Many of the programs of the GCCI, such as the Green Lights and Energy Star programs and the Climate Challenge and Natural Gas STAR programs, were already put in place during the Clinton administration. New initiatives include tax incentives for a number of climate-friendly energy technologies and increased funding for renewable-energy technologies and climate research. It is clear that the GCCI simply will not even come close to a reasonable reduction on the order of those being mandated by the Kyoto Protocol nations.

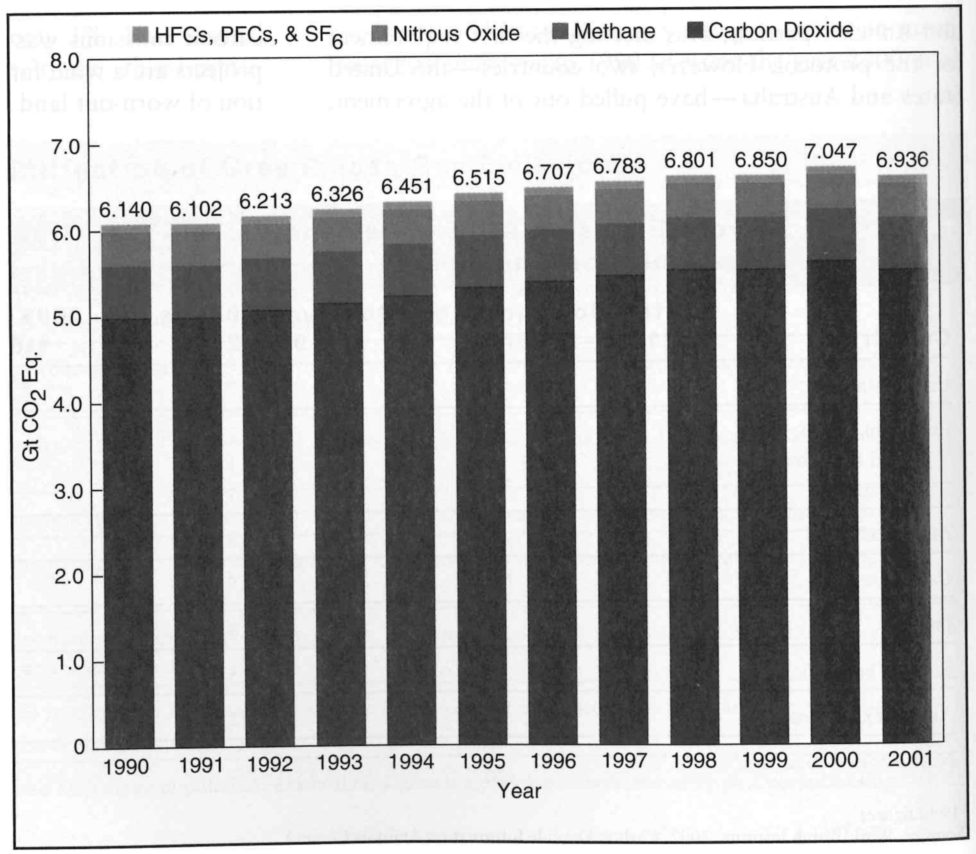


Figure 20–18 U.S. greenhouse gas emissions, 1990–2001. Four types of greenhouse gases are shown. Total emissions rose 14%, while greenhouse gas intensity fell 16%. Units in $GtCO_2$ equivalents. (*Source:* EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2001. April 15, 2003)

U.S. Climate Change Science Program (CCSP). In July 2003, the Bush administration released a report that provides guidelines for the government's Climate Change Science Program and puts a sharper image on the government's approach to climate research. The plan seeks to address a number of issues in climate science, such as the natural variability in climate, a quantitative approach to forces causing climate change, projections of future climate change, and the sensitivity and adaptability of human and natural ecosystems to climate change. Reports on key topics all have specific timetables, from two to four years. Critics of the plan see it as an excuse to stall action on global warming, holding that many of the questions which are addressed have already been well answered. Some scientists are cautiously optimistic that the CCSP is a serious effort to reduce the uncertainties in the scientific analysis of climate change so that improved policies will be forthcoming.

States and Corporations. It is encouraging that some U.S. states are taking unilateral action to address global climate change. Fourteen states are adopting renewable portfolio standards (see Chapter 14) and are mandating reporting of greenhouse gas emissions. In many states, bills have been introduced to build a framework for regulating CO_2, and 12 states have petitioned the U.S. Court of Appeals to force the EPA to regulate greenhouse gas emissions, using their authority under the Clean Air Act.

At a recent meeting of the World Economic Forum, the CEOs of the world's 1,000 largest corporations voted that climate change was the most urgent problem facing humanity. Some observers believe that this "bottom-up" approach to climate change action could provide the catalyst that will bring U.S. federal policy in line with that of the rest of the world.

Response 2: Adaptation

Climate change is already happening and will likely accelerate in the future, regardless of the mitigating steps taken. *Mitigation* is the response that is essential to reducing the magnitude of future climate change, but *adaptation* will also be needed, especially in view of the potential for the following consequences, some of which are already happening:

1. Crop yields are likely to be reduced in tropical and subtropical regions as warming and droughts become more severe. Some agriculture in the north temperate regions may be enhanced.
2. Water is likely to become more scarce in many regions already suffering from water scarcity, especially the subtropics.
3. Increased heat and moisture in many regions will likely lead to an increase in infectious disease and potentially lethal heat waves.
4. Increased intensity and frequency of storm events will bring severe flooding to many regions that already are prone to natural disasters. The rise in sea level will intensify the risks in coastal areas.

New Funds. In light of these risks, the IPCC stated, "The effects of climate change are expected to be greatest in developing countries in terms of loss of life and relative effects on investment and the economy." As a start, the FCCC 2001 Marrakesh meeting established two new funds to address this concern: a **Least Developed Countries Fund,** to advise countries on national adaptation strategies, and a **Special Climate Change Fund,** to provide additional financial assistance to developing countries affected by climate change. The emphasis of adaptation is on the developing countries, since it is assumed that the developed countries will be far more able to afford the costs of adaptation.

New Report. In 2003, the World Bank and a host of U.N. and other organizations released a report that addresses the preceding concerns. Called *Poverty and Climate Change: Reducing the Vulnerability of the Poor through Adaptation,* the report makes some telling points:

1. Climate change impacts will be superimposed on existing vulnerabilities—water availability, food security, health and disease, life in low-lying regions. The poor already suffer disproportionately from these risks.
2. The countries with the fewest resources will likely bear the greatest burden of climate change, with greater loss of life and economic impacts.
3. Ecosystem goods and services are likely to be disrupted by climate change. The poor depend especially on these for survival, so they will be most affected.
4. Even today, over 96% of disaster-related deaths take place in developing countries. Major weather events can set back development for decades.
5. Because poverty is so severe in these countries, adaptation must be treated in the context of reducing poverty and achieving the Millennium Development Goals. (See Table 6–2.) Practically every one of the goals is threatened by the anticipated impacts of climate change, and the report addresses these impacts in detail.

Strategies. Specific adaptation strategies will vary with the different circumstances, but, in general, the World Bank report suggests that "the best way to address climate change impacts on the poor is by integrating adaptation measures into sustainable development and poverty reduction strategies." Adaptations addressed in the report include improved governance, vulnerability assessments, access to accurate information on climate change, and the integration of impacts into economic processes. Those adaptations which have "no regrets" benefits—measures that would foster desirable social benefits, regardless of the intensity or existence of climate change impacts—are especially encouraged. *General poverty reduction* is one such measure. It is no surprise that the developing countries—especially the poorest ones—will need substantial assistance from the developed countries. The two new FCCC funds are a good start, but external support also needs to increase from the many development assistance channels, including NGO assistance and intergovernmental aid.

Conclusion. Global climate change is perhaps the greatest challenge facing human civilization in the 21st century. Both adaptation and mitigation are needed. The two are complementary responses to the many threats posed by increasing GHG emissions. Whatever the outcome, it is certain that we are conducting an enormous global experiment, and our children and their descendants will be living with the consequences.

Let us now turn our attention to ozone depletion, an atmospheric problem the public often confuses with global warming.

20.5 Depletion of the Ozone Layer

The stratospheric ozone layer protects Earth from harmful ultraviolet radiation. The depletion of this layer is another major atmospheric challenge that is due to human technology. Environmental scientists have traced the problem to a widely used group of chemicals: the CFCs. As with global warming, however, there were skeptics who were unconvinced that the problem was serious. However, scientists have achieved a strong consensus on the ozone depletion problem, reflected in the most recent report of the Scientific Assessment Panel of the Montreal Protocol: **Scientific Assessment of Ozone Depletion: 2002.** This section draws from that report and gives you an opportunity to examine the evidence.

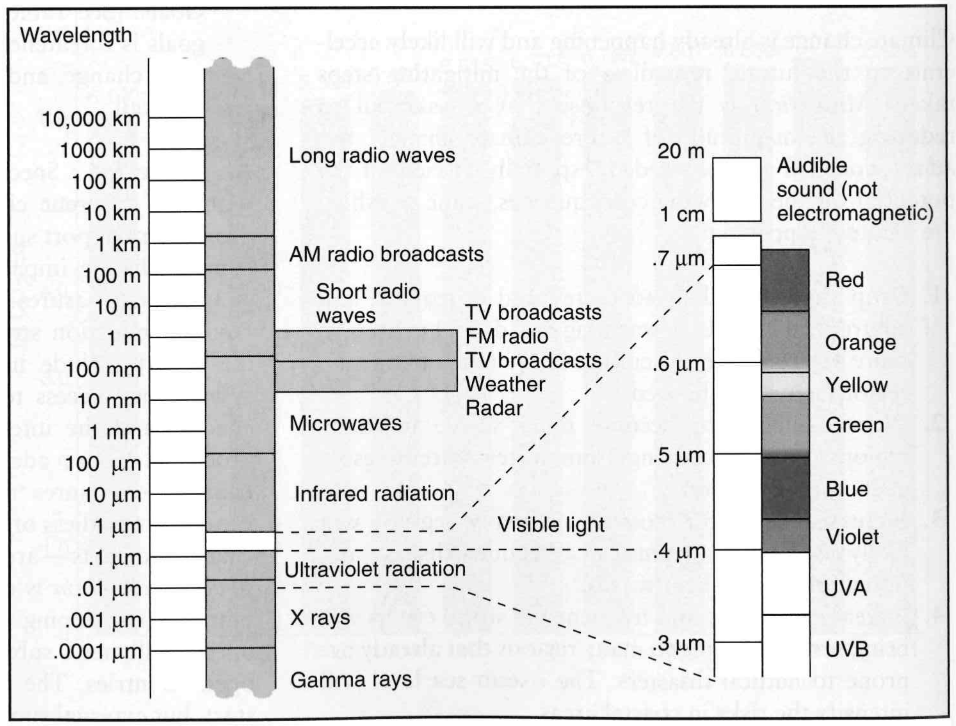
Radiation and Importance of the Shield

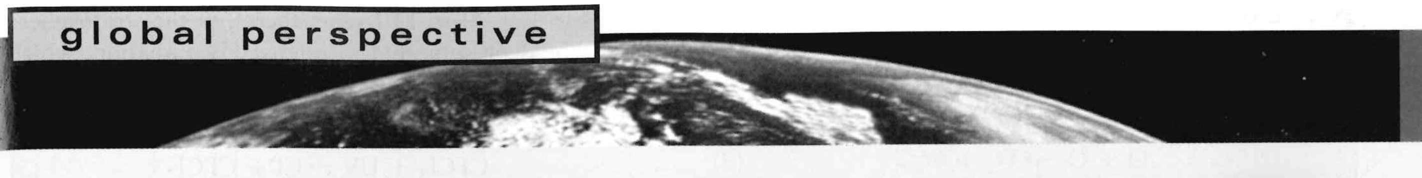
Solar radiation emits electromagnetic waves with a wide range of energies and wavelengths (Fig. 20–19). Visible light is that part of the electromagnetic spectrum which can be detected by the eye's photoreceptors. Ultraviolet (UV) wavelengths are slightly shorter than the wavelengths of violet light, which are the shortest wavelengths visible to the human eye. UVB radiation consists of wavelengths that range from 280 to 320 nanometers (0.28 to 0.32 μm), whereas UVA radiation is from 320 to 400 nanometers. Since energy is inversely related to wavelength, UVB is more energetic and therefore more dangerous, but UVA can also cause damage.

On penetrating the atmosphere and being absorbed by biological tissues, UV radiation damages protein and DNA molecules at the surfaces of all living things. (This damage is what occurs when you get a sunburn.) If the full amount of ultraviolet radiation falling on the stratosphere reached Earth's surface, it is doubtful that any life could survive. We are spared more damaging effects from UV rays because most UV radiation (over 99%) is absorbed by ozone in the stratosphere. For that reason, stratospheric ozone is commonly referred to as the **ozone shield** (Fig. 20–2).

However, even the small amount (less than 1%) of UVB radiation that does reach us is responsible for sunburns and more than 700,000 cases of skin cancer and precancerous ailments per year in North America, as well as for untold damage to plant crops and other life-forms. (See "Global Perspective" essay, p. 565.)

Figure 20–19 The electromagnetic spectrum. Ultraviolet, visible light, infrared, and many other forms of radiation are different wavelengths of the electromagnetic spectrum.





global perspective

Coping with UV Radiation

People living in Chile, Australia, and New Zealand are no strangers to the effects of the thinning ozone shield. UV alerts are given in those parts of the Southern Hemisphere during their spring months as lobes of ozone-depleted stratospheric air move outward from the Antarctic. At times, the ozone above those countries can be less than half its normal concentration, which means that greater intensities of UV radiation reach Earth's surface. It is now predicted that one out of every three Australians will develop serious and perhaps fatal skin cancer in his or her lifetime.

A thinning ozone layer has appeared above the Northern Hemisphere, too, and is getting serious attention. Concerned over the rising incidence of skin cancer and cataract surgery in the United States, the EPA, together with NOAA and the CDC, has initiated a new *UV index*. (See table below.) The index is in the form of daily forecasts of UV exposure, issued by the Weather Service for 58 cities. Satellite measurements of stratospheric ozone are combined with other weather patterns. The goal of the index is to remind people of the dangers of UV radiation and to prompt them to take appropriate action to avoid cancer, premature aging of the skin, eye damage, cataracts, and blindness. For at least the next two decades, the dangers will be quite noticeable, ranging from a greater incidence of sunburn to a likely epidemic of malignant melanoma.

Less obvious, but no less important, are the chronic effects of exposure to the Sun. The normal aging of skin is now known to be largely the result of damage from the Sun: coarse wrinkling, yellowing, and the development of irregular patches of heavily pigmented and unpigmented skin. This can happen even in the absence of episodes of sunburn. Further, a large proportion of the million cataract operations performed annually in the United States can be traced to UV exposure, another of the chronic effects of this kind of radiation.

The most serious impact of chronic exposure to the Sun is skin cancer, which occurs in some 700,000 new cases each year in the United States. Three types of skin cancer are traced to UV exposure: basal cell carcinoma (BCC), squamous cell carcinoma (SCC), and melanoma. Most of the skin cancers (75% to 90%) are BCCs, slow growing and therefore treatable. SCC accounts for about 20% of skin cancers and can also be cured if treated early. However, it metastasizes (spreads away from the source) more readily than BCC and thus is potentially fatal. Melanoma is the most deadly form of skin cancer, as it metastasizes easily. Melanoma is often traced to occasional sunburns during childhood or adolescence or to sunburns in people who normally stay out of the Sun.

What is an appropriate response to this disturbing information? First, know when UV intensity is greatest (three hours on either side of midday), and take precautions accordingly. Protect your eyes with sunglasses and a hat, and apply sunscreen with a protection factor (SPF) rating of 15 or higher during such times. Think twice before considering sunbathing or tanning beds, and never proceed without sunscreen that is strong enough to prevent sunburn. Always protect children with sunscreen. Their years of potential exposure are many, and their skin is easily burned. If you detect a patch of skin or a mole that is changing in size or color or that is red and fails to heal, consult a dermatologist for treatment.

UV Index (EPA)

Exposure Category	Index Value	Minutes to Burn for "Never Tans" (Most Susceptible)	Minutes to Burn for "Rarely Burns" (Least Susceptible)
Minimal	0–2	30	>120
Low	4	15	75
Moderate	6	10	50
High	8	7.5	35
Very high	10	6	30
Very high	15	<4	20

Formation and Breakdown of the Shield

Ozone is formed in the stratosphere when UV radiation acts on oxygen (O_2) molecules. The high-energy UV radiation first causes some molecular oxygen (O_2) to split apart into free oxygen (O) atoms, and these atoms then combine with molecular oxygen to form ozone via the following reactions:

$$O_2 + \text{UVB} \rightarrow O + O \quad (1)$$

$$O + O_2 \rightarrow O_3 \quad (2)$$

Not all of the molecular oxygen is converted to ozone, however, because free oxygen atoms may also combine with ozone molecules to form two oxygen molecules in the following reaction:

$$O + O_3 \rightarrow O_2 + O_2 \qquad (3)$$

Finally, when ozone absorbs UVB, it is converted back to free oxygen and molecular oxygen:

$$O_3 + UVB \rightarrow O + O_2 \qquad (4)$$

Thus, the amount of ozone in the stratosphere is dynamic. There is an equilibrium due to the continual cycle of reactions of formation [Eqs. (1) and (2)] and reactions of destruction [Eqs. (3) and (4)]. Because of seasonal changes in solar radiation, ozone concentration in the Northern Hemisphere is highest in summer and lowest in winter. Also, in general, ozone concentrations are highest at the equator and diminish as latitude increases—again, a function of higher overall amounts of solar radiation. However, the presence of other chemicals in the stratosphere can upset the normal ozone equilibrium and promote undesirable reactions there.

Halogens in the Atmosphere. **Chlorofluorocarbons (CFCs)** are a type of halogenated hydrocarbon. (See Chapter 19.) CFCs are nonreactive, nonflammable, nontoxic organic molecules in which both chlorine and fluorine atoms have replaced some hydrogen atoms. At room temperature, CFCs are gases under normal (atmospheric) pressure, but they liquefy under modest pressure, giving off heat in the process and becoming cold. When they revaporize, they reabsorb the heat and become hot. These attributes led to the widespread use of CFCs (over a million tons per year in the 1980s) for the following applications:

- In refrigerators, air conditioners, and heat pumps as the heat-transfer fluid.
- In the production of plastic foams.
- By the electronics industry for cleaning computer parts, which must be meticulously purified.
- As the pressurizing agent in aerosol cans.

Rowland and Molina. All of the preceding uses led to the release of CFCs into the atmosphere, where they mixed with the normal atmospheric gases and eventually reached the stratosphere. In 1974, chemists Sherwood Rowland and Mario Molina published a classic paper[2] (for which they were awarded the Nobel prize in 1995) concluding that CFCs could damage the stratospheric ozone layer through the release of chlorine atoms and, as a result, would increase UV radiation and cause more skin cancer. Rowland and Molina reasoned that, although CFCs would be stable in the troposphere (they have been found to last 70 to 110 years there), in the stratosphere they would be subjected to intense UV radiation, which would break them apart, releasing free chlorine atoms via the following reaction:

$$CFCl_3 + UV \rightarrow Cl + CFCl_2 \qquad (5)$$

Ultimately, all of the chlorine of a CFC molecule would be released as a result of further photochemical breakdown. The free chlorine atoms would then attack stratospheric ozone to form chlorine monoxide (ClO) and molecular oxygen:

$$Cl + O_3 \rightarrow ClO + O_2 \qquad (6)$$

Furthermore, two molecules of chlorine monoxide may react to release more chlorine and an oxygen molecule:

$$ClO + ClO \rightarrow 2\,Cl + O_2 \qquad (7)$$

Reactions 6 and 7 are called the **chlorine catalytic cycle,** because chlorine is continuously regenerated as it reacts with ozone. Thus, chlorine acts as a **catalyst,** a chemical that promotes a chemical reaction without itself being used up in the reaction. Because every chlorine atom in the stratosphere can last from 40 to 100 years, it has the potential to break down 100,000 molecules of ozone. Thus, CFCs are judged to be damaging because they act as transport agents that continuously move chlorine atoms into the stratosphere. The damage can persist, because the chlorine atoms are removed from the stratosphere only very slowly. Figure 20–20 shows the basic processes of ozone formation and destruction, including recent refinements to our knowledge of those processes that will be explained shortly.

EPA Action. After studying the evidence, the EPA became convinced that CFCs were a threat and, in 1978, banned their use in aerosol cans in the United States. Manufacturers quickly switched to non-damaging substitutes, such as butane, and things were quiet for several years. CFCs continued to be used in applications other than aerosols, however, and skeptics demanded more convincing evidence of their harmfulness.

Atmospheric scientists reason that any substance carrying reactive halogens to the stratosphere has the potential to deplete ozone. These substances include halons, methyl chloroform, carbon tetrafluoride, and methyl bromide. Chemically similar to chlorine, bromine also attacks ozone and forms a monoxide (BrO) in a catalytic cycle. Because of its extensive use as a soil fumigant and pesticide, methyl bromide is thought to cause between 30 and 60% of current stratospheric ozone loss. (Bromine is 40 times as potent as chlorine in ozone destruction.)

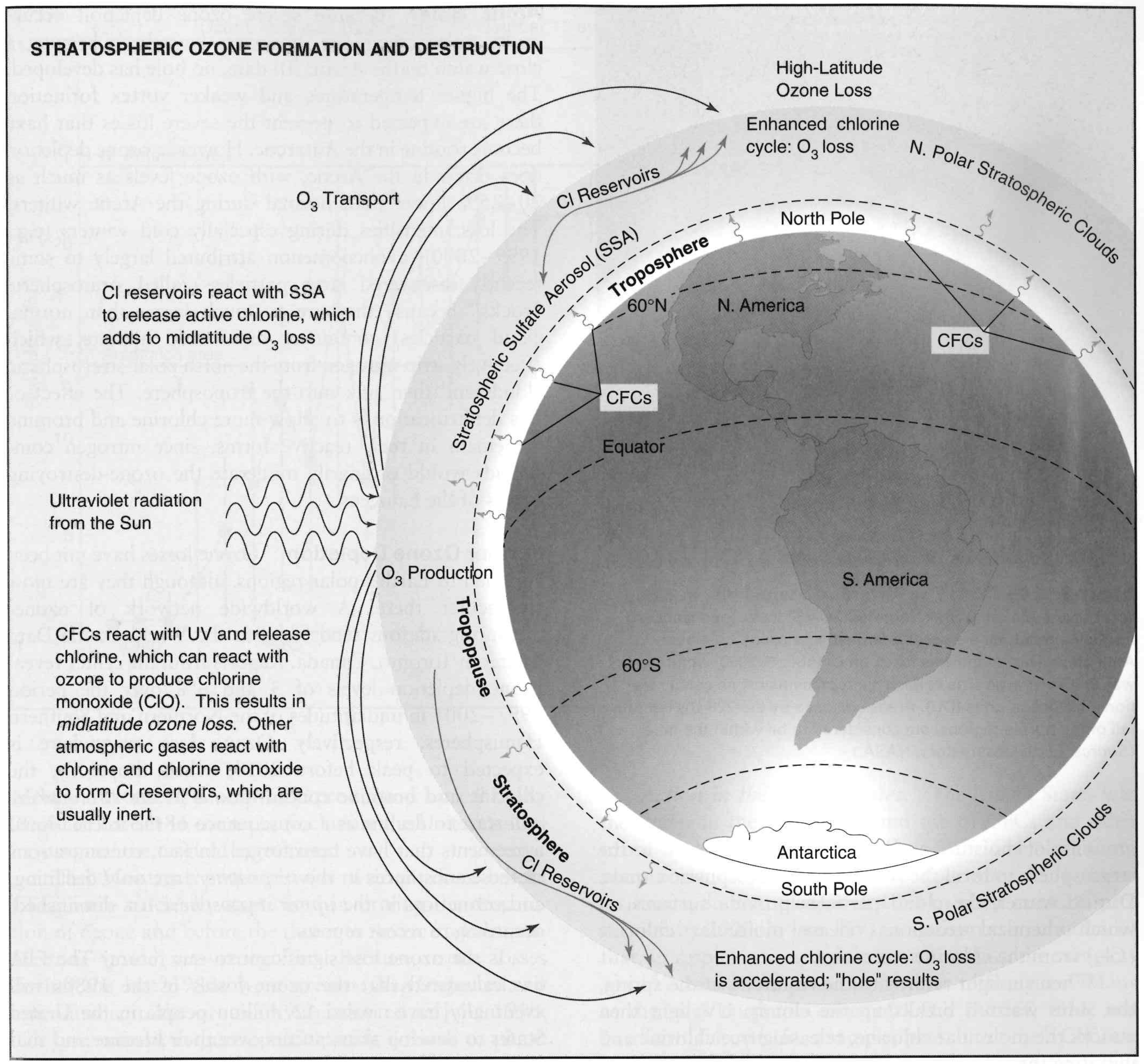


Figure 20–20 Stratospheric ozone formation and destruction. UV radiation stimulates ozone production at the lower latitudes, and ozone-rich air migrates to high latitudes. At the same time, CFCs and other compounds carry halogens into the stratosphere, where they are broken down by UV radiation, to release chlorine and bromine. Ozone is subject to high-latitude loss during winter, as the chlorine cycle is enhanced by the polar stratospheric clouds. Midlatitude losses occur as chlorine reservoirs are stimulated to release chlorine by reacting with stratospheric sulfate aerosol.

The Ozone “Hole.” In the fall of 1985, British atmospheric scientists working in Antarctica reported a gaping “hole” (actually, a thinning of one area) in the stratospheric ozone layer over the South Pole (Fig. 20–21). There, in an area the size of the United States, ozone levels were 50% lower than normal. The hole would have been discovered earlier by NASA satellites monitoring ozone levels, except that computers were programmed to reject data showing a drop as large as 30% as due to instrument anomalies. Scientists had assumed that the loss of ozone, if it occurred, would be slow, gradual, and uniform over the whole planet. The ozone hole came as a surprise, and if it had occurred anywhere but over the South Pole, the UV damage would have been extensive. As it is, the limited time and area of ozone depletion there have not apparently brought on any catastrophic ecological events so far.

News of the ozone hole stimulated an enormous scientific research effort. A unique set of conditions was found to be responsible for the hole. In the summer, gases such as nitrogen dioxide and methane react with chlorine monoxide and chlorine to trap the chlorine, forming so-called **chlorine reservoirs** (Fig. 20–20), preventing much ozone depletion.

Polar Vortex. When the Antarctic winter arrives in June, it creates a vortex (like a whirlpool) in the stratosphere, which confines stratospheric gases within a ring of air circulating around the Antarctic. The extremely cold temperatures of the Antarctic winter cause the small

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[2] Molina, M. J. and Rowland, F. S. “Stratospheric Sink for Chlorofluoro-methanes: Chlorine-atom Catalyzed Distribution of Ozone.” *Nature* 249 (1974): 810–812.

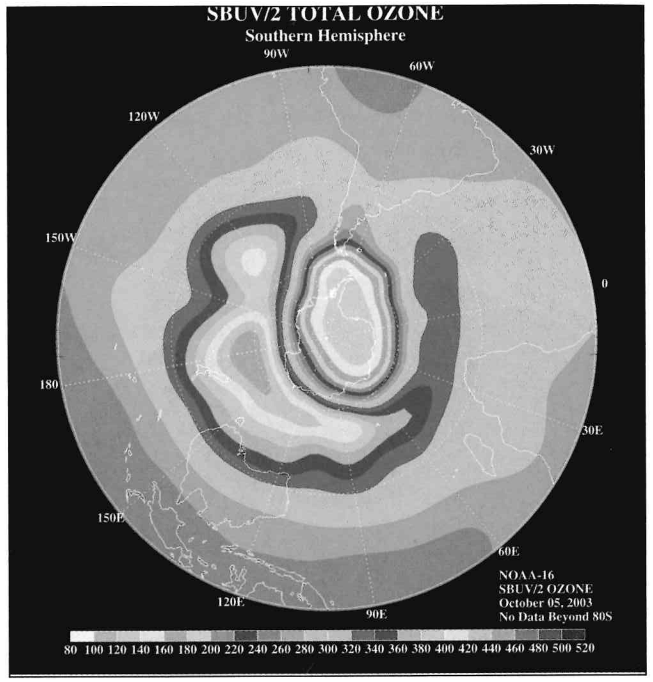

Figure 20–21 The Antarctic ozone hole. In 2003, Total Ozone Mapping Spectrometer (TOMS) instruments aboard a satellite recorded the second-largest-ever ozone hole over Antarctica. This image was taken on October 5, 2003, while the hole was still very large. The color scale represents ozone concentrations in Dobson units (DU). Areas enclosed by the 220-DU contour (all of the purple regions) are considered to be within the hole. (*Source:* Earth Observatory, NASA.)

amounts of moisture and other chemicals present in the stratosphere to form the south polar stratospheric clouds. During winter, the cloud particles provide surfaces on which chemical reactions release molecular chlorine (Cl_2) from the chlorine reservoirs.

When sunlight returns to the Antarctic in the spring, the Sun's warmth breaks up the clouds. UV light then attacks the molecular chlorine, releasing free chlorine and initiating the chlorine cycle, which rapidly destroys ozone. By November, the beginning of the Antarctic summer, the vortex breaks down and ozone-rich air returns to the area. However, by that time, ozone-poor air has spread all over the Southern Hemisphere. Shifting patches of ozone-depleted air have caused UV radiation increases of 20% above normal in Australia. Television stations there now report daily UV readings and warnings for Australians to stay out of the Sun. On the basis of current data, estimates indicate that in Queensland, where the ozone shield is thinnest, three out of four Australians are expected to develop skin cancer. The ozone hole intensified during the 1990s and has shown signs of leveling off between 9 and 10 million square miles, an area as large as North America. The 2003 hole reached 10.9 million square miles, however, the second largest on record. The 2002 hole was much smaller than usual (6 million square miles), a consequence of warmer-than-normal temperature patterns over Antarctica.

Arctic Hole? Because severe ozone depletion occurs under polar conditions, observers have been keeping a close watch on the Arctic. To date, no hole has developed. The higher temperatures and weaker vortex formation there are expected to prevent the severe losses that have become routine in the Antarctic. However, ozone depletion does occur in the Arctic, with ozone levels as much as 20–25% lower than normal during the Arctic winters. The loss intensifies during especially cold winters (e.g., 1999–2000), a phenomenon attributed largely to some recently discovered large particles (called stratospheric "rocks" because they are so much larger than normal cloud particles) containing nitric acid hydrate, which effectively strip nitrogen from the north polar stratospheric clouds and then sink into the troposphere. The effect of this denitrification is to allow more chlorine and bromine to remain in their reactive forms, since nitrogen compounds would ordinarily moderate the ozone-destroying effects of the halogens.

Further Ozone Depletion. Ozone losses have not been confined to Earth's polar regions, although they are most spectacular there. A worldwide network of ozone-measuring stations sends data to the World Ozone Data Center in Toronto, Canada. Reports from the center reveal ozone depletion levels of 3 and 6% over the period 1997–2001 in midlatitudes of the Northern and Southern Hemispheres, respectively. Ozone loss everywhere is expected to peak before 2010, when, hopefully, the chlorine and bromine concentrations in the *stratosphere* will start to decline as a consequence of the international agreements that have been forged. In fact, concentrations of these substances in the *troposphere* are now declining, and ozone loss in the *upper stratosphere* has diminished, according to recent reports.

Is the ozone loss significant to our future? The EPA has calculated that the ozone losses of the 1980s will eventually have caused 12 million people in the United States to develop skin cancers over their lifetime and that 93,000 of these cancers will be fatal. Americans are estimated to have developed more than 900,000 new cases of skin cancer a year in the 1990s. The ozone losses of that decade allowed more UVB radiation than ever to reach Earth. Studies have confirmed increased UVB levels, especially at higher latitudes.

Coming to Grips with Ozone Depletion

The dramatic growth of the hole in the ozone layer (Fig. 20–22) has galvanized a response around the world. In spite of the skepticism in the United States, scientists and politicians here and in other countries have achieved treaties designed to avert a UV disaster.

Montreal Protocol. In 1987, under the auspices of its environmental program, the United Nations convened a meeting in Montreal, Canada, to address ozone depletion. Member nations reached an agreement, known as the **Montreal Protocol,** to scale CFC production back 50% by 2000. To date, 184 countries (including the United States) have signed the original agreement.

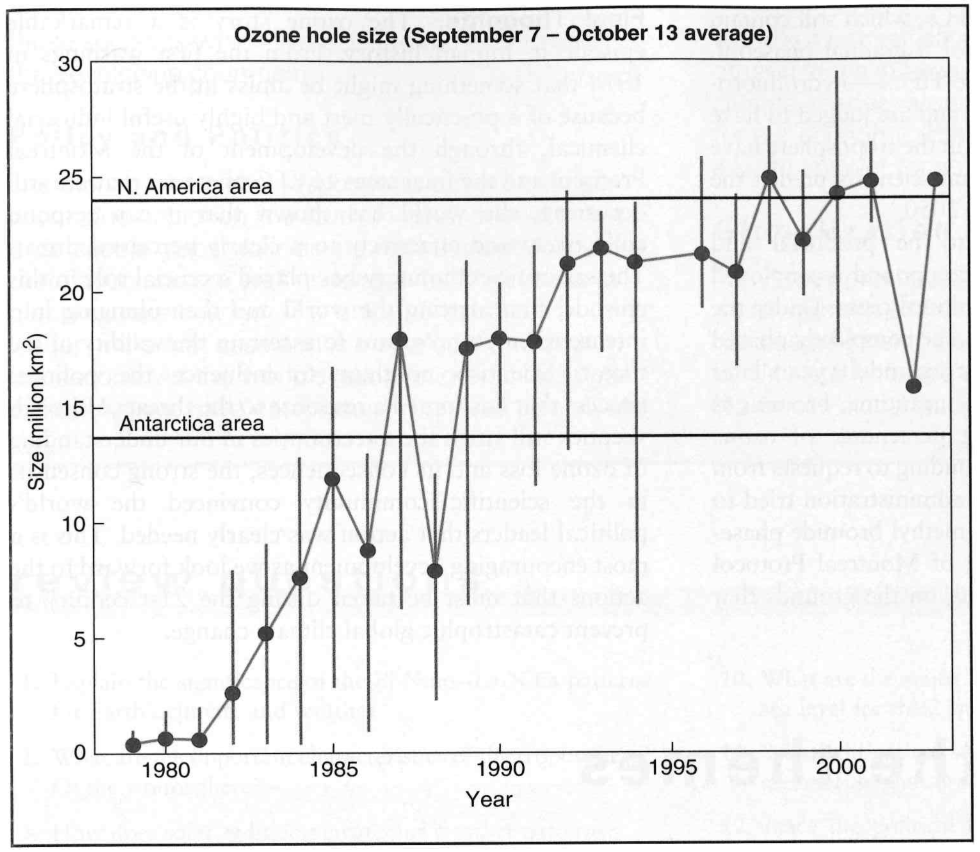

Figure 20–22 Ozone hole size. The size of the ozone hole is plotted from 1979 to 2003, showing the time of origin of the hole to its leveling off in the last few years. Note that the hole was as great as all of N. America for four different years. (*Source:* NASA.)

The Montreal protocol was written even before CFCs were so clearly implicated in driving the destruction of ozone and before the threat to Arctic and temperate-zone ozone was recognized. Because ozone losses during the late 1980s were greater than expected, an amendment to the protocol was adopted in June 1990. The amendment requires participating nations to phase out the major chemicals destroying the ozone layer by 2000 in developed countries and by 2010 in developing countries. In the face of evidence that ozone depletion was accelerating even more, another amendment to the protocol was adopted in November 1992, moving the *target date for the complete phaseout of CFCs to January 1, 1996.* Timetables for phasing out all of the suspected ozone-depleting halogens were shortened at the 1992 meeting.

Quantities of CFCs are still being manufactured to satisfy legitimate demand in the developing countries. These legal CFCs, however, are being sidetracked into black-market trade because of hefty taxes on the legal sales in developing countries. Some of the black-market CFCs are smuggled into developed countries. By 2003, the U.S. Justice Department had charged 114 individuals and numerous businesses with smuggling CFCs into the United States, leading to hefty fines, significant jail time, and the recovery of tons of the banned chemicals.

Action in the United States. The United States was the leader in the production and use of CFCs and other ozone-depleting chemicals, with du Pont Chemical Company being the major producer. Following 15 years of resistance, du Pont pledged in 1988 to phase out CFC production by 2000. In late 1991, a spokesperson announced that, in response to new data on ozone loss, the company would accelerate its phaseout by three to five years. Many of the large corporate users of CFCs (AT&T, IBM, and Northern Telecom, for example) phased out their CFC use by 1994. Also, du Pont spoke in opposition to three bills introduced into the 104th Congress in September 1995. The bills were designed to terminate U.S. participation in, and compliance with, the CFC-banning protocols.

The Clean Air Act of 1990 also addresses this problem, in Title VI, "Protecting Stratospheric Ozone." Title VI is a comprehensive program that restricts the production, use, emissions, and disposal of an entire family of chemicals identified as ozone depleting. For example, the program calls for a phaseout schedule for the hydrochlorofluorocarbons (HCFCs), a family of chemicals being used as less damaging substitutes for CFCs until nonchlorine substitutes are available. Halons—used in chemical fire extinguishers—were banned in 1994. The act also regulates the servicing of refrigeration and air-conditioning units.

January 1, 1996, has come and gone, and in most of the industrialized countries CFCs are no longer being produced or used. Substitutes for CFCs are readily available and, in some cases, are even less expensive than the CFCs. The most commonly used substitutes are HCFCs, which still contain some chlorine and are scheduled for a gradual phaseout. The most *promising* substitutes are HFCs—hydrofluorocarbons, which contain no chlorine and are judged to have no ozone-depleting potential. CFCs in the troposphere have peaked and are slowly declining, and scientists predict the ozone shield will recover entirely by 2050.

Methyl bromide continues to be produced and released into the atmosphere; the compound is employed as a soil fumigant to control agricultural pests. Under the Montreal Protocol, it is scheduled to be completely phased out by 2005 in the developed countries and 10 years later in the developing countries. In the meantime, bromine is likely to contribute an increasing percentage of ozone depletion relative to chlorine. Responding to requests from the agricultural industry, the Bush administration tried to get an exemption to the scheduled methyl bromide phaseout at a November 2003 meeting of Montreal Protocol nations. The exemption was denied, on the grounds that suitable substitutes were available.

Final Thoughts. The ozone story is a remarkable episode in human history. From the first warnings in 1974 that something might be amiss in the stratosphere because of a practically inert and highly useful industrial chemical, through the development of the Montreal Protocol and the final steps of CFC phaseout that are still occurring, the world has shown that it can respond collectively and effectively to a clearly perceived threat. The scientific community has played a crucial role in this episode, first alerting the world and then plunging into intense research programs to ascertain the validity of the threat. Scientists continue to influence the political process that has forged a response to the threat. Although skeptics still stress the uncertainties in our understanding of ozone loss and its consequences, the strong consensus in the scientific community convinced the world's political leaders that action was clearly needed. This is a most encouraging development as we look forward to the actions that must be taken during the 21st century to prevent catastrophic global climate change.

revisiting the themes

Sustainability

Earth is in the midst of an unsustainable rise in atmospheric greenhouse gas levels, the result of our intense use of fossil fuels. In short, we completely depend on a technology that is threatening our future. All projections of future fossil-fuel use and greenhouse gases point to global consequences that are serious, but not inevitable. The United States and other developed countries will not escape these consequences, but the gravest of them affects the developing countries. A sustainable pathway is still open to us, and it involves a combination of steps we can take to mitigate the emissions and bring the atmospheric concentration of greenhouse gases to a stable, even declining, level. The ozone story represents such a sustainable pathway. Levels of ozone-destroying chemicals are now stabilizing and will soon decline, and it is very likely that the ozone layer will be "healthy" by midcentury.

Stewardship

Stewardly care for Earth is not really an option. We *must* act, and several principles have been cited as arguments for effective action to prevent dangerous climate change: the precautionary principle, the polluter pays principle, and the equity principle. If we care about our neighbors and our descendants, we will take action both to mitigate the production of greenhouse gases and to enable especially the poorer countries to adapt to coming unavoidable climate changes, even if taking such action is costly. The "Ethics" essay points to the work of a caring steward: Sir John Houghton. The ozone story, again, is a model for effective, stewardly action in the face of a major threat to people yet unborn.

Sound Science

Much of this chapter is about sound science, since our knowledge of climate change and ozone depletion depends on the solid work of thousands of scientists. It is largely the scientists who are calling attention to the perils of climate change. They were the first to discover the risks involved, and they are now the chief advocates of effective action. Nevertheless, more good science needs to be done, because there are still many unanswered questions and uncertainties. We know enough now to act, however, and the model of ozone depletion stands as proof that we can act even before every loose end is tied up.

Ecosystem Capital

Ecosystems depend on climate, and if we change the climate too rapidly, many ecosystems are likely to suffer serious disruptions and will no longer provide the essential goods and services societies now depend on. We allow these ecosystems to change at our own peril. In the end, ecosystems will redevelop and many species will adapt or move to new locations, but there may well be major losses in biodiversity, and the ecosystem adaptations will not happen overnight. The short-term impacts will be especially hard on