

# Air Pollution



Shown here is an aerial view of Dallas, Texas and the greater Kansas City metropolitan area are both participating in the new initiative called Sustainable Skylines, through the U.S. Environmental Protection Agency.

## LEARNING OBJECTIVES

The atmosphere has always been a sink—a place of deposition and storage—for gaseous and particulate wastes. When the amount of waste entering an area of the atmosphere exceeds the atmosphere’s ability to disperse or break down the pollutants, problems result. After reading this chapter, you should understand . . .

- The two major ways that pollution affects living things: by direct contact down here and by altering the atmosphere above us;
- Why air pollution from human activities, combined with meteorological conditions, may exceed the atmosphere’s natural ability to remove wastes;
- What the major categories and sources of air pollutants are;
- How “acid rain” is produced and how its environmental impacts might be minimized;
- Why air quality standards are important;
- Why the economics of air pollution is controversial and difficult;
- What the major indoor air pollutants are, where they come from, and why they cause some of our most serious environmental health problems;
- “Green buildings” and other major strategies for controlling and minimizing indoor air pollution;
- The “ozone hole” and the science of ozone depletion.

## CASE STUDY



# Sustainable Skylines: Dallas and Kansas City

Sustainable Skylines is an initiative that has been launched by the Environmental Protection Agency (EPA). Its objective is to achieve sustainable air quality by reducing the six major air pollutants, as well as other toxic air pollutants and greenhouse gases. Cities that participate in the program are encouraged to integrate energy, land use, transportation, and air quality planning in order to achieve measurable improvements within a three-year period. As of 2009, two cities participated—Dallas, Texas, and Kansas City, Kansas and Missouri (the greater Kansas City metropolitan area). The EPA hopes to have ten cities invested in the program by 2010. Among the projects included in a particular sustainable Skyline venture are the following:

- Reducing emissions from landscape equipment by improved irrigation of lawns and turf management, as well as retrofitting small off-road equipment to achieve reduced emissions of air pollutants.
- Reducing vehicle emissions by increasing public transportation and reducing the distances traveled in vehicles.
- Replacing existing taxis with “green taxis” that emit far less pollution.
- Encouraging “**green buildings**” with healthier interior environments and landscaping that benefit the local external environment.

- Reducing emissions from idling vehicles and retrofitting diesel engines to reduce emissions.
- Programs to encourage planting trees in the city to develop a tree canopy in as many areas as possible.

Each city that participates in the Sustainable Skylines Program will have its own local programs and policies, developed in collaboration with the city’s inhabitants and city leaders, along with public and private partners. For example, in Dallas, Texas, the description of activities has the goal of helping to reduce the urban “heat island” effect. Urban areas are often warmer than surrounding areas due to the abundance of equipment and lights, as well as surfaces that absorb heat. Cities with little vegetation also have less evaporative cooling. This is a particular problem in Dallas, which has a naturally warm climate much of the year. As a result, the goal of the Sustainable Skylines Program for Dallas is to increase the number of shaded surfaces and green vegetated surfaces of roofs and surrounding buildings in order to reduce the heat island effect and cool the city.

In the greater Kansas City area, the objectives are to encourage a variety of sustainable environmental projects with social benefits. They plan to address such issues as transportation, energy, land use, resource efficiency, green buildings, and air quality, with a focus on projects that will result in cleaner, healthier air for this large urban area.

## 21.1 Air Pollution in the Lower Atmosphere

### A Brief Overview

As the fastest-moving fluid medium in the environment, the atmosphere has always been one of the most convenient places to dispose of unwanted materials. The atmosphere has been a sink for waste disposal ever since we first used fire, and people have long recognized the existence of atmospheric pollutants, both natural and human-induced. Leonardo da Vinci wrote in 1550 that a blue haze formed from materials

emitted into the atmosphere by trees. What he had observed is a natural photochemical smog from hydrocarbons given off by living trees. This haze, whose cause is still not fully understood, gave rise to the name Smoky Mountains for the range in the southeastern United States.

The phenomenon of acid rain was first described in the 17th century, and by the 18th century it was known that plants in London were damaged by air pollution. Beginning with the Industrial Revolution in the 18th century, air pollution became more noticeable. The word *smog* was introduced by a physician at a public-health conference in 1905 to denote poor air quality resulting from a mixture of smoke and fog.

## Stationary and Mobile Sources of Air Pollution

The two major categories of air pollution sources are stationary sources and mobile sources. **Stationary sources** have a relatively fixed location and include point sources, fugitive sources, and area sources.

- *Point sources*, discussed in Chapter 10, emit pollutants from one or more controllable sites, such as power-plant smokestacks (Figure 21.1).
- *Fugitive sources* generate air pollutants from open areas exposed to wind. Examples include burning for agricultural purposes (Figure 21.2), as well as dirt roads, construction sites, farmlands, storage piles, surface mines, and other exposed areas.
- *Area sources*, also discussed in Chapter 10, are well-defined areas within which are several sources of air pollutants—for example, small urban communities, areas of intense industrialization within urban complexes, and agricultural areas sprayed with herbicides and pesticides.

**Mobile sources** of air pollutants include automobiles, trucks, buses, aircraft, ships, trains, and anything else that pollutes as it moves from place to place.<sup>2</sup>

## General Effects of Air Pollution

Air pollution affects many aspects of our environment, including its visual qualities, vegetation, animals, soils, water quality, natural and artificial structures, and human health. Air pollutants affect visual resources by discoloring the atmosphere and by reducing visual range and atmospheric clarity. We cannot see as far in polluted air, and



**FIGURE 21.1** This steel mill in Beijing, China, is a major source of air pollution.



**FIGURE 21.2** Burning sugarcane fields, Maui, Hawaii—an example of a fugitive source of air pollution.

what we do see has less color contrast. These effects were once limited to cities but now extend to some wide-open spaces of the United States. For example, near the Four Corners, where New Mexico, Arizona, Colorado, and Utah meet, emissions from two large fossil-fuel-burning power plants have altered visibility in a region where visibility used to be 80 km (50 mi) from a mountaintop on a clear day.<sup>1</sup> The power plants are two of the largest pollution sources in the U.S.

Air pollution's numerous effects on vegetation include damage to leaves, needles, and fruit; reduced or suppressed growth; increased susceptibility to diseases, pests, and adverse weather; and disruption of reproductive processes.<sup>1, 2</sup>

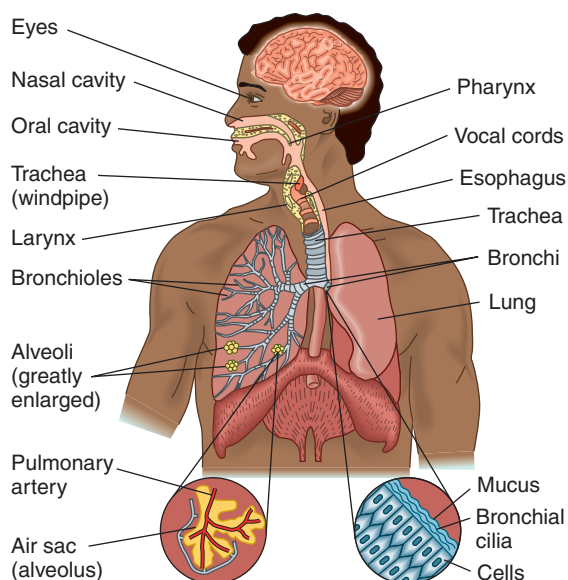
Air pollution is a significant factor in the human death rate in many large cities. For example, it has been estimated that in Athens, Greece, the number of deaths is several times higher on days when the air is heavily polluted; and in Hungary, where air pollution has been a serious problem in recent years, it may contribute to as many as 1 in 17 deaths. The United States is certainly not immune to health problems related to air pollution. The most polluted air in the nation is in the Los Angeles urban area, where millions of people are exposed to it. An estimated 175 million people live in areas of the United States where exposure to air pollution contributes to lung



disease, which causes more than 300,000 deaths per year. Air pollution in the United States is directly responsible for annual health costs of over \$50 billion. In China, whose large cities have serious air pollution problems, mostly from burning coal, the health cost is now about \$50 billion per year and may rise to about \$100 billion per year by 2020.

Air pollutants can affect our health in several ways, depending on the dose or concentration and other factors, including individual susceptibility (see the discussion of dose–response in Chapter 10). Some of the primary effects are cancer, birth defects, eye and respiratory system irritation, greater susceptibility to heart disease, and aggravation of chronic diseases, such as asthma and emphysema. People suffering from respiratory diseases are the most likely to be affected. Healthy people tend to acclimate to pollutants, but this is a physiological tolerance; as explained in Chapter 10, it doesn't mean that the pollutants are doing no harm (Figure 21.3).

It is worth noting here that many air pollutants have *synergistic effects*—that is, the combined effects are greater than the sum of the separate effects. For example, sulfate and nitrate may attach to small particles in the air, facilitating their inhalation deep into lung tissue. There, they may do greater damage than a combination of the two pollutants would be expected to, based on their separate effects. This phenomenon has obvious health consequences; consider joggers breathing deeply and inhaling



**FIGURE 21.3** Idealized diagram showing some of the parts of the human body (brain, cardiovascular system, and pulmonary system) that can be damaged by common air pollutants. The most severe health risks from normal exposures are related to particulates. Other substances of concern include carbon monoxide, photochemical oxidants, sulfur dioxide, and nitrogen oxides. Toxic chemicals and tobacco smoke also can cause chronic or acute health problems.

particulates as they run along the streets of a city. The effects of air pollutants on vertebrate animals in general include impairment of the respiratory system; damage to eyes, teeth, and bones; increased susceptibility to disease, parasites, and other stress-related environmental hazards; decreased availability of food sources (such as vegetation affected by air pollutants); and reduced ability for successful reproduction.<sup>2</sup>

Air-pollution deposits can also make soil and water toxic. In addition, soils may be leached of nutrients by pollutants that form acids. Air pollution's effects on man-made structures include discoloration, erosion, and decomposition of building materials (see the discussion of acid rain later in this chapter).

## The Major Air Pollutants

Nearly 200 air pollutants are recognized and assessed by the EPA and listed in the Clean Air Act. They can be classified as primary or secondary. **Primary pollutants** are emitted directly into the air. They include particulates, sulfur dioxide, carbon monoxide, nitrogen oxides, and hydrocarbons. **Secondary pollutants** are produced by reactions between primary pollutants and normal atmospheric compounds. For example, ozone forms over urban areas through reactions of primary pollutants, sunlight, and natural atmospheric gases. Thus, ozone is a secondary pollutant.

The major air pollutants occur either as particulate matter (PM) or in gaseous forms. Particulates are very small particles of solid or liquid substances and may be organic or inorganic. Gaseous pollutants include sulfur dioxide ( $\text{SO}_2$ ), nitrogen oxides ( $\text{NO}_x$ ), carbon monoxide (CO), ozone ( $\text{O}_3$ ) and volatile organic compounds (VOCs), such as hydrocarbons (compounds containing only carbon and hydrogen that include petroleum products), hydrogen sulfide ( $\text{H}_2\text{S}$ ), and hydrogen fluoride (HF).

The primary pollutants that account for nearly all air-pollution problems are carbon monoxide (58%), volatile organic compounds (11%), nitrogen oxides (15%), sulfur oxides (13%), and particulates (3%). In the United States today, about 140 million metric tons of these substances enter the atmosphere from human-related processes. If these pollutants were uniformly distributed in the atmosphere, the concentration would be only a few parts per million by weight. Unfortunately, pollutants are not uniformly distributed but tend to be produced, released, and concentrated locally or regionally—for example, in large cities.

In addition to pollutants from human sources, our atmosphere contains many pollutants of natural origin, such as sulfur dioxide from volcanic eruptions; hydrogen sulfide from geysers and hot springs, as well as from biological decay in bogs and marshes; ozone in the lower atmosphere as a result of unstable meteorological

conditions, such as violent thunderstorms; a variety of particles from wildfires and windstorms;<sup>1</sup> and natural hydrocarbon seeps, such as La Brea Tar Pits in Los Angeles.

The data in Table 21.1 suggest that, except for sulfur and nitrogen oxides, natural emissions of air pollutants exceed human-produced emissions. Nevertheless, it is the human component that is most abundant in urban areas and leads to the most severe problems for human health.

## Criteria Pollutants

The six most common pollutants are called **criteria pollutants** because the EPA has set specific limits on the levels of these six and they are responsible for most of our air-pollution problems. The six are sulfur dioxide, nitrogen oxides, carbon monoxide, ozone, particulates, and lead.

### Sulfur Dioxide

Sulfur dioxide (SO<sub>2</sub>) is a colorless and odorless gas normally present at Earth's surface in low concentrations. A significant feature of SO<sub>2</sub> is that once emitted into the atmosphere, it can be converted into fine particulate sulfate (SO<sub>4</sub>) and removed from the atmosphere by wet or dry deposition. The major anthropogenic (human) source of sulfur dioxide is the burning of fossil fuels, mostly coal in power plants (see Table 21.1). Another major source comprises a variety of industrial processes, ranging from petroleum refining to the production of paper, cement, and aluminum.<sup>1-4</sup>

Adverse effects of sulfur dioxide depend on the dose or the concentrations (see Chapter 10) and include injury or death to animals and plants, as well as corrosion of paint and metals. Crops, such as alfalfa, cotton, and barley, are especially susceptible. Sulfur dioxide can severely damage the lungs of people and other animals, especially in the sulfate form. It is also an important precursor to acid rain (see A Closer Look 21.1).<sup>1-4</sup>

U.S. emission rates of SO<sub>2</sub> from 1970 to 2007 are shown in Table 21.2. Emissions peaked at about 32 million tons in the early 1970s and since then have fallen 60%, to about 13 million tons, as a result of effective emission controls.

### Nitrogen Oxides

Although nitrogen oxides (NO<sub>x</sub>) occur in many forms in the atmosphere, they are emitted largely as nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>), and only these two forms are subject to emission regulations. The more important of the two is NO<sub>2</sub>, a yellow-brown to reddish-brown gas. A major concern with NO<sub>2</sub> is that it may be converted by complex reactions in the atmosphere to an ion, NO<sub>3</sub><sup>2-</sup>, within small water particulates, impairing visibility. As mentioned earlier, both NO and NO<sub>2</sub> are major contributors to smog, and NO<sub>2</sub> is also a major contributor to acid rain (see A Closer Look 21.1). Nitrogen oxides contribute to nutrient enrichment and eutrophication of water in ponds, lakes, rivers, and the ocean (see Chapter 19). Nearly all NO<sub>2</sub> is emitted

Table 21.1 MAJOR NATURAL AND HUMAN-PRODUCED COMPONENTS OF SELECTED AIR POLLUTANTS

AIR POLLUTANTS	EMISSIONS (% OF TOTAL)		MAJOR SOURCES OF HUMAN-PRODUCED COMPONENTS	PERCENT
	NATURAL	HUMAN-PRODUCED		
Particulates	85	15	Fugitive (mostly dust)	85
			Industrial processes	7
			Combustion of fuels (stationary sources)	8
Sulfur oxides (SO <sub>x</sub> )	50	50	Combustion of fuels (stationary sources, mostly coal)	84
			Industrial processes	9
Carbon monoxide (CO)	91	9	Transportation (automobiles)	54
Nitrogen dioxide (NO <sub>2</sub> )		Nearly all	Transportation (mostly automobiles)	37
			Combustion of fuels (stationary sources, mostly natural gas and coal)	38
Ozone (O <sub>3</sub> )	A secondary pollutant derived from reaction with sunlight NO <sub>2</sub> , and oxygen (O <sub>2</sub> )		Concentration present depends on reaction in lower atmosphere involving hydrocarbons and thus automobile exhaust	
Hydrocarbons (HC)	84	16	Transportation (automobiles)	27
			Industrial processes	7

Table 21.2 U.S. EMISSIONS OF CRITERIA POLLUTANTS FROM 1970–2007

	MILLIONS OF TONS PER YEAR							
	1970	1980	1985	1990	1995	2000	2005	2007
Carbon Monoxide (CO)	200	178	170	144	120	102	89	81
Lead	ND	0.074	0.023	0.005	0.004	0.002	0.003	0.002
Nitrogen Oxides (NO <sub>x</sub> )	~27	27	26	25	25	22	19	17
Volatile Organic Compounds (VOC)	~30	30	27	23	22	17	15	15
Particulate Matter (PM)								
PM <sub>10</sub>	ND	6	4	3	3	2	2	2
PM <sub>2.5</sub>		ND	ND	2	2	2	1	1
Sulfur Dioxide (SO <sub>2</sub> )	32	26	23	23	19	16	15	13
Totals	ND	267	250	220	191	161	141	129

Notes:

- In 1985 and 1996 EPA refined its methods for estimating emissions. Between 1970 and 1975, EPA revised its methods for estimating PM emissions.
- The estimates for 2002 are from 2002 NEI v2; the estimates for 2003 and beyond are preliminary and based on 2002 NEI v2.
- No data (ND)

Source: Environmental Protection Agency, 2008.  
Air Trends accessed June 10, 2008 @ www.epa.gov.

from anthropogenic sources. The two main sources are automobiles and power plants that burn fossil fuels.<sup>1, 2</sup>

Nitrogen oxides have various effects on people, including irritation of eyes, nose, throat, and lungs and increased susceptibility to viral infections, including influenza (which can cause bronchitis and pneumonia).<sup>1, 2</sup> Dissolved in water, nitrogen oxides form acids that can harm vegetation. But when the oxides are converted to nitrates, they can promote plant growth.

U.S. emission rates of NO<sub>x</sub> from 1970 to 2007 are shown in Table 21.2. Emissions are primarily from combustion of fuels in power plants and vehicles. They have been reduced by about 30% since 1980.

### Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas that, even at very low concentrations, is extremely toxic to humans and other animals. The high toxicity results from a physiological effect: Carbon monoxide and hemoglobin have a strong natural attraction for one another; if there is any carbon monoxide in the vicinity, the hemoglobin in our blood will take it up nearly 250 times faster than it will oxygen and carry mostly carbon monoxide, rather than oxygen, from the atmosphere to the internal organs. Effects range from dizziness and headaches to death. Many people have been accidentally asphyxiated by carbon monoxide from incomplete combustion of fuels in campers, tents,

and houses. Carbon monoxide is particularly hazardous to people with heart disease, anemia, or respiratory disease. It may also cause birth defects, including mental retardation and impaired fetal growth. Its effects tend to be worse at higher altitudes, where oxygen levels are lower. Detectors (similar to smoke detectors) are now commonly used to warn people if CO in a building reaches a dangerous level.

Approximately 90% of the carbon monoxide in the atmosphere comes from natural sources. The other 10% comes mainly from fires, automobiles, and other sources of incomplete burning of organic compounds, but these are easily concentrated locally, especially by enclosures, so this 10% causes most of the health problems. Emissions of CO peaked in the early 1970s at about 200 million metric tons and declined 60% to about 81 million metric tons by 2007 (Table 21.2). This significant reduction stemmed largely from cleaner-burning engines despite an increased number of vehicles.

### Ozone and Other Photochemical Oxidants

Photochemical oxidants are secondary pollutants arising from atmospheric interactions of nitrogen dioxide and sunlight. Ozone, of primary concern here, is a form of oxygen in which three atoms of oxygen occur together rather than the normal two. A number of other photochemical oxidants, known as PANs (peroxyacyl nitrates), occur with photochemical smog.

Ozone is relatively unstable and releases its third oxygen atom readily, so it oxidizes or burns things more readily and at lower concentrations than does normal oxygen. Released into the air or produced in the air, ozone may injure living things. However, since these include bacteria and other organisms, it is sometimes used for sterilizing purposes—for example, bubbling ozone gas through water is one way to purify water.

Ozone in the lower atmosphere is a secondary pollutant produced on bright, sunny days in areas where there is significant primary pollution. The major sources of ozone, as well as other oxidants, are automobiles and industrial processes that release nitrogen dioxide by burning fossil fuels. Because of the nature of its formation, ozone is difficult to regulate and thus is the pollutant whose health standard is most frequently exceeded in U.S. urban areas.<sup>5,6</sup>

The adverse environmental effects of ozone and other oxidants, like those of other pollutants, depend in part on the dose or concentration of exposure and include damage to plants and animals, as well as to materials, such as rubber, paint, and textiles. Ozone's effects on plants can be subtle. At very low concentrations, it can slow growth without visible injury. At higher concentrations, it kills leaf tissue and, if pollutant levels remain high, whole plants. The death of white pine trees along highways in New England is believed to be due in part to ozone pollution. In animals, including people, ozone causes various kinds of damage, especially to the eyes and respiratory system. Many millions of Americans are often exposed to ozone levels that damage cell walls in lungs and airways. Tissue reddens and swells, and cellular fluids seep into the lungs. Eventually, the lungs lose elasticity and are more susceptible to bacterial infection, and scars and lesions may form in the airways. Even young, healthy people may be unable to breathe normally, and on especially polluted days breathing may be shallow and painful. Ground-level ozone decreased by 9% from 1990 to 2007.<sup>1,2,6</sup>

While too much ozone causes problems down here, too little of it has become a problem in the stratosphere. Because of the effect of sunlight on normal oxygen, ozone forms a natural layer high in the stratosphere that protects us from harmful ultraviolet radiation from the sun. However, the emission of certain chemicals in the lower atmosphere has led to serious ozone depletion in the stratosphere. We will discuss the ozone-depletion story later in the chapter. Suffice it to say here that it is becoming an environmental success story at the global level.

### **Particulate Matter: $PM_{10}$ , $PM_{2.5}$ , and Ultrafine Particles**

Particulate matter (PM) is made up of tiny particles. The term *particulate matter* is used for varying mixtures of particles suspended in the air we breathe, but in regulations these are divided into three categories:  $PM_{10}$ ,

particles up to 10 micrometers ( $\mu\text{m}$ ) in diameter;  $PM_{2.5}$ , particles between 2.5 and 0.18 microns; and UP, **ultrafine particles** smaller than 0.18 micrometers in diameter, released into the air by vehicles on streets and freeways. For comparison, the diameter of a human hair is about 60 to 150  $\mu\text{m}$  (Figure 21.4).

Nearly all industrial processes, as well as the burning of fossil fuels, release particulates into the atmosphere. Farming, too, adds considerable particulate matter to the atmosphere, as do windstorms in areas with little vegetation and volcanic eruptions. Particles are everywhere, and high concentrations and/or specific types of particles pose a serious danger to human health, including aggravation of cardiovascular and respiratory diseases. Major particulates include asbestos (especially dangerous, discussed in detail in Chapter 10)<sup>2</sup> and small particles of heavy metals, such as arsenic, copper, lead, and zinc, which are usually emitted from smelters and other industrial facilities. Particulates can reduce visibility and affect climate (see Chapter 20).<sup>2</sup> Much particulate matter is easily visible as smoke, soot, or dust; other particulate matter is not easily visible.

Fine particles— $PM_{2.5}$  and smaller—are easily inhaled into the lungs, where they can be absorbed into the bloodstream or remain embedded for a long time. Among the most significant of these particles are sulfates and nitrates. As already explained, these are mostly secondary pollutants produced in the atmosphere by chemical reactions between normal atmospheric constituents and sulfur dioxide and nitrogen oxides. These reactions are important in the formation of sulfuric and nitric acids in the atmosphere and are further discussed when we consider acid rain.<sup>1,2</sup>

Ultrafine particles (UP), released into the air by motor vehicles, are so small that they cannot be easily filtered and can enter the bloodstream. Rich in organic compounds and other reactive chemicals, they may be the most hazardous components of air pollution, especially with respect to heart disease. They evidently can contribute to inflammation (cell and tissue damage by oxidation), reducing the protective quality of “good” cholesterol and leading to plaque buildup in the arteries that can result in heart attack and stroke. Those most at risk are the young, the elderly, and individuals living near a freeway, or exercising near heavy traffic, or spending a lot of time in traffic (sitting in slow-moving traffic can roughly triple your short-term risk of a heart attack). The risk to an individual is very small, but when millions of people are exposed to a small risk, large numbers are affected. The prudent approach is to limit your exposure. For example, avoid jogging or bike riding near heavy traffic for extended periods.<sup>3</sup>

Particulate matter is measured as *total suspended particulates* (TSPs). Values for TSPs tend to be much higher in large cities in developing countries, such as Mexico,



China, and India, than in developed countries, such as Japan and the United States.

Particulates affect human health, ecosystems, and the biosphere. In the United States, particulate air pollution is estimated to contribute to the death of 60,000 people annually.<sup>7</sup> Studies estimate that 2 to 9% of human mortality in cities is associated with particulate pollution, and that the mortality risk is about 15 to 25% higher in cities with the highest levels of fine particulate pollution.<sup>8</sup> Particulates are linked to both lung cancer and bronchitis (see Figure 21.4) and are especially hazardous to the elderly and to people who have respiratory problems, such as asthma. There is a direct relationship between particulate pollution and increased hospital admissions for respiratory distress.

Dust raised by road building and plowing not only makes breathing more difficult for animals (including humans) but also can be deposited on green plants, interfering with absorption of carbon dioxide and oxygen and release of water (transpiration). On a larger scale, particulates associated with large construction projects—such as housing developments, shopping centers, and industrial parks—may injure or kill plants and animals and damage surrounding areas, changing species composition, altering food chains, and thereby affecting ecosystems. The terrorist attacks that destroyed the Twin Towers in New York City on September 11, 2001, sent huge amounts of particles of all sizes into the air, causing serious health problems that continue even today in people who were exposed to it.

Modern industrial processes have greatly increased the total amount of suspended particulates in Earth's atmosphere. These particulates block sunlight and can cause **global dimming**, a gradual reduction in the solar

energy that reaches Earth's surface. Global dimming cools the atmosphere and has lessened the global warming that has been predicted. Its effects are most apparent in the midlatitudes of the Northern Hemisphere, especially over urban regions or where jet air traffic is more common. Jet plane exhaust emits particulates high in the atmosphere. That this could affect the climate was suggested in 2001, when civil air traffic was shut down for two days after the September 11 attacks in New York. During those two days, the daily temperature range over the United States was about 1°C higher than usual.<sup>9</sup> Of course, this may have been just a coincidence.

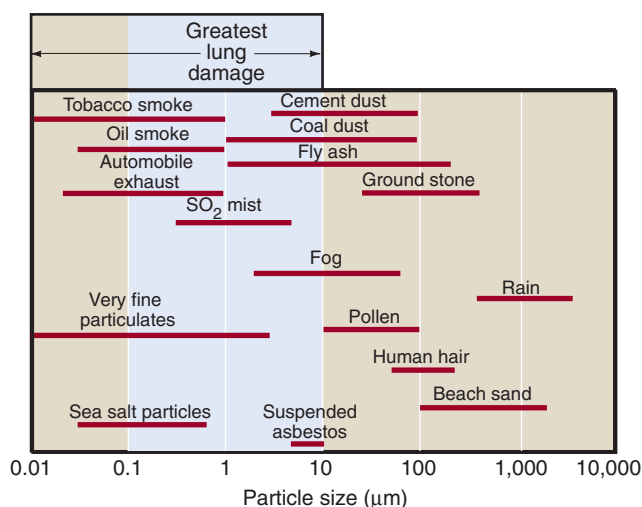
Table 21.2 shows that anthropogenic emissions of PM<sub>10</sub> in the United States from 1970 to 2007 declined by about two-thirds (66%).

### Lead

Lead (a heavy metal) is an important constituent of automobile batteries and many other industrial products. Leaded gasoline (still used in some countries) helps protect engines and promotes more effective fuel consumption. However, the lead is emitted into the air with the exhaust and has thereby been spread widely around the world, reaching high levels in soils and waters along roadways. Once released, lead can be transported through the air as particulates to be taken up by plants through the soil or deposited directly on their leaves. Thus, it enters terrestrial food chains. When lead is carried by streams and rivers, deposited in quiet waters, or transported to oceans or lakes, it is taken up by aquatic organisms and enters aquatic food chains. Lead is toxic to wildlife and people. It can damage the nervous system, impair learning, and reduce IQ and memory. In children it can also contribute to behavioral problems. (Recall that this is the subject of the Critical Thinking section in Chapter 10.) In adults it can contribute to cardiovascular and kidney disease, as well as anemia.<sup>1,2</sup>

Lead reaches Greenland as airborne particulates and in seawater and is stored in glacial ice. The concentration of lead in Greenland glaciers was essentially zero in A.D. 800 and reached measurable levels with the beginning of the Industrial Revolution in the mid-18th century. The lead content of the glacial ice increased steadily from 1750 until about 1950, when there was a sudden upsurge in the rate of lead accumulation, reflecting rapid growth in the use of leaded gasoline. The accumulation of lead in Greenland's ice illustrates that our use of heavy metals in the 20th century reached the point of affecting the entire biosphere.

Lead has now been removed from nearly all gasoline in the United States, Canada, and much of Europe. In the United States, lead emissions have declined about 98% since the early 1980s (Table 21.2). The reduction and eventual elimination of lead in gasoline are a good start in reducing levels of anthropogenic lead in the biosphere.



**FIGURE 21.4** Sizes of selected particulates. The shaded area shows the size range that produces the greatest lung damage. (Source: Modified from Fig. 7–8, p. 244 in *Chemistry, Man and Environmental Change: An Integrated Approach*, by J. Calvin Giddings. Copyright © 1973 by J. Calvin Giddings. Reprinted by permission of Harper Collins Publishers, Inc.)



# A CLOSER LOOK 21.1

## Acid Rain

**Acid rain** is precipitation in which the pH is below 5.6. The pH, a measure of acidity and alkalinity, is the negative logarithm of the concentration of the hydrogen ion ( $H^+$ ). Because the pH scale is logarithmic, a pH value of 3 is 10 times more acidic than a pH value of 4 and 100 times more acidic than a pH value of 5. Automobile battery acid has a pH value of 1. Many people are surprised to learn that all rainfall is slightly acidic; water reacts with atmospheric carbon dioxide to produce weak carbonic acid. Thus, pure rainfall has a pH of about 5.6, where 1 is highly acidic and 7 is neutral (see Figure 21.5). (Natural rainfall in tropical rain forests has been observed in some instances to have a pH of less than 5.6; this is probably related to acid precursors emitted by the trees.)

Acid rain includes both wet (rain, snow, fog) and dry (particulate) acidic depositions. The depositions occur near and downwind of areas where the burning of fossil fuels produces major emissions of sulfur dioxide ( $SO_2$ ) and nitrogen oxides ( $NO_x$ ). Although these oxides are the primary contributors to acid rain, other acids are also involved. An

example is hydrochloric acid emitted from coal-fired power plants.

Acid rain has likely been a problem at least since the beginning of the Industrial Revolution. In recent decades, however, it has gained more and more attention, and today it is a major, global environmental problem affecting all industrial countries. In the United States, nearly all of the eastern states are affected, as well as West Coast urban centers, such as Seattle, San Francisco, and Los Angeles. The problem is also of great concern in Canada, Germany, Scandinavia, and Great Britain. Developing countries that rely heavily on coal, such as China, are facing serious acid rain problems as well.

### Causes of Acid Rain

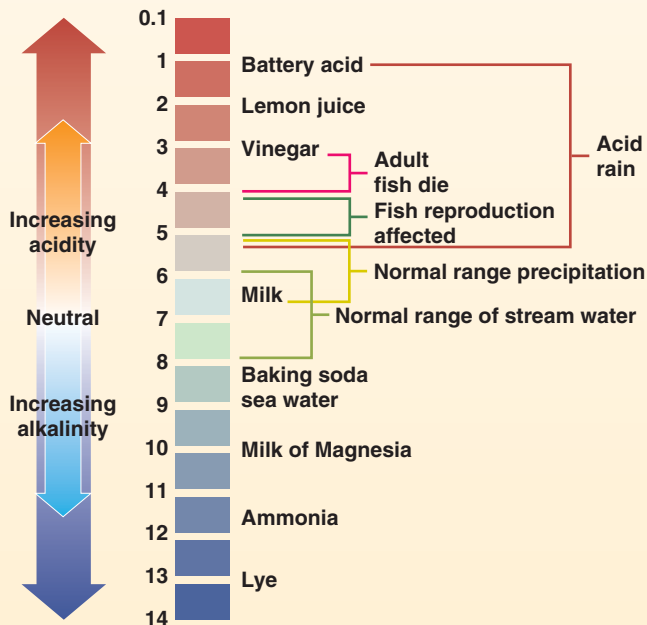
As we have said, sulfur dioxide and nitrogen oxides are the major contributors to acid rain. Amounts of these substances emitted into the environment in the United States are shown in Table 21.1. As shown earlier in Table 21.2, emissions of  $SO_2$  peaked in the 1970s and declined to about 13 million metric tons per year by 2007; and nitrogen oxides leveled off at about 25 million metric tons per year in the mid-1980s and had dropped to 17 million metric tons by 2007.

In the atmosphere, reactions with oxygen and water vapor transform  $SO_2$  and  $NO_x$  into sulfuric and nitric acids, which may travel long distances with prevailing winds and be deposited as acid precipitation—rainfall, snow, or fog (Figure 21.6). Sulfate and nitrate particles may also be deposited directly on the surface of the land as dry deposition and later be activated by moisture to become sulfuric and nitric acids.

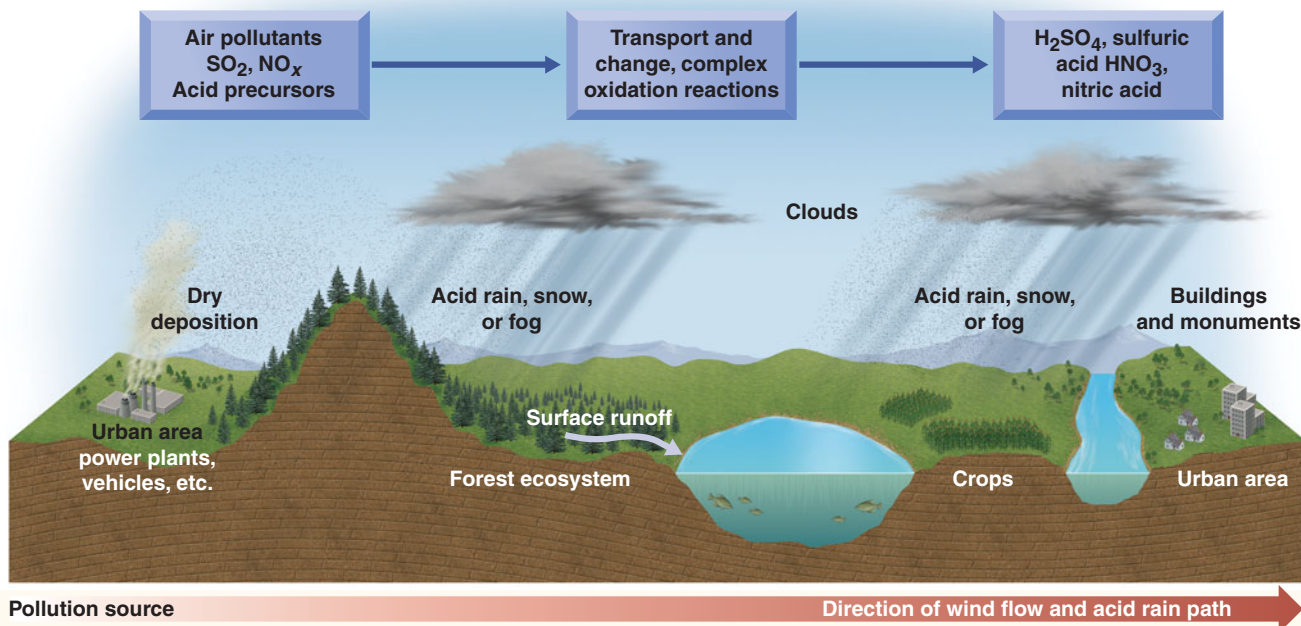
Again, sulfur dioxide is emitted primarily by stationary sources, such as power plants that burn fossil fuels, whereas nitrogen oxides are emitted by both stationary and mobile sources, such as automobiles. Approximately 80% of sulfur dioxide and 65% of nitrogen oxides in the United States come from states east of the Mississippi River.

### Sensitivity to Acid Rain

Geology, climate, vegetation, and soil help determine the effects of acid rain, because these differ widely in their “buffers”—chemicals that can neutralize acids. Sensitive areas are those in which the type of bedrock (such as granite) or soils (such as those consisting largely of sand) cannot buffer acid input. Limestone bedrock provides the best buffering because it is made up mainly of calcium carbonate ( $CaCO_3$ ), the mineral known as calcite. Calcium carbonate reacts with the hydrogen in the water and neutralizes the acid.



**FIGURE 21.5** The pH scale shows the levels of acidity in various fluids. The scale ranges from less than 1 to 14, with 7 being neutral: pHs lower than 7 are acidic; pHs greater than 7 are alkaline (basic). Acid rain can be very acidic and harmful to the environment. (Source: <http://ga.water.usgs.gov/edu/phdiagram.html>. Accessed August 12, 2005.)



**FIGURE 21.6** Idealized diagram showing selected aspects of acid rain formation and paths.

Soils may lose their fertility when exposed to acid rain, either because nutrients are leached out by acid water or because the acid in the soil releases elements that are toxic to plants.

### Acid Rain's Effects on Forest Ecosystems

It has long been suspected that acid precipitation damages trees. Studies in Germany led scientists to cite acid rain and other air pollution as the cause of death for thousands of acres of evergreen trees in Bavaria. Similar studies in the Appalachian Mountains of Vermont (where many soils are naturally acidic) suggest that in some locations half the red spruce trees have died in recent years. Some high-elevation forests of the Appalachian Mountains, including the Great Smoky Mountains and Shenandoah National Park, have been impacted by acid rain, acid fog, and dry deposition of acid. Symptoms include slowed tree growth, leaves and needles that turn brown and fall off, and in extreme cases the death of trees. The acid rain does not directly kill trees; rather, it weakens them as essential nutrients are leached from soils or stripped from leaves by acid fog. Acidic rainfall also may release toxic chemicals, such as aluminum, that damage trees.<sup>10</sup>

### Acid Rain's Effects on Lake Ecosystems

Records from Scandinavian lakes show an increase in acidity accompanied by a decrease in fish. The increased acidity has been traced to acid rain caused by industrial processes in other countries, particularly Germany and Great Britain. Thousands of lakes, ponds, and streams in the eastern United States are sensitive to acidification, including the Adirondacks and Catskill Mountains of New York State and others in the

Midwest and in the mountains of the Western U.S. Little Echo Pond in Franklin, New York, is one of the most acidic lakes, with a measured pH of 4.2.<sup>10</sup>

Acid rain affects lake ecosystems in three ways. First, it damages aquatic species (fish, amphibians, and crayfish) directly by disrupting their life processes in ways that limit growth or cause death. For example, crayfish produce fewer eggs in acidic water, and the eggs produced often grow into malformed larvae.

Second, acid rain dissolves chemical elements necessary for life in the lake. Once in solution, the necessary elements leave the lake with water outflow. Thus, elements that once cycled in the lake are lost. Without these nutrients, algae do not grow, animals that feed on the algae have little to eat, and animals that feed on these animals also have less food.<sup>10, 11</sup>

Third, acid rain leaches metals, such as aluminum, lead, mercury, and calcium, from the soils and rocks in a drainage basin and discharges them into rivers and lakes. Elevated concentrations of aluminum are particularly damaging to fish because the metal can clog the gills and cause suffocation. The heavy metals may pose health hazards to people, too, because the metals may become concentrated in fish and then be passed on to people, mammals, and birds that eat the fish. Drinking water from acidic lakes may also have high concentrations of toxic metals.

Not all lakes are vulnerable to acidification. Acid is neutralized in waters with a high carbonate content (in the form of the ion  $\text{HCO}_3^-$ ). Therefore, lakes on limestone or other rocks rich in calcium or magnesium carbonates can readily buffer river and lake water against acids. Lakes with high

concentrations of such elements are called hard water lakes. Lakes on sand or igneous rocks, such as granite, tend to lack sufficient buffering to neutralize acids and are more susceptible to acidification.<sup>12</sup>

### Acid Rain's Effects on Human Society

Acid rain damages not only our forests and lakes but also many building materials, including steel, galvanized steel, paint, plastics, cement, masonry, and several types of rock, especially limestone, sandstone, and marble. Classical buildings on the Acropolis in Athens and in other cities show considerable decay (chemical weathering) that accelerated in the 20th century as a result of air pollution. The problem has grown to such an extent that buildings require restoration, and the protective coatings on statues and other monuments must be replaced quite frequently, at a cost of billions of dollars a year. Particularly important statues in Greece and other areas have been removed and placed in protective glass containers, leaving replicas standing in their former outdoor locations for tourists to view.<sup>11</sup>

Stone decays about twice as rapidly in cities as it does in less urban areas. The damage comes mainly from acid rain and humidity in the atmosphere, as well as from corrosive

groundwater.<sup>15</sup> This implies that measuring rates of stone decay will tell us something about changes in the acidity of rain and groundwater in different regions and ages. It is now possible, where the ages of stone buildings and other structures are known, to determine whether the acid rain problem has changed over time.

### Control of Acid Rain

We know what causes acid precipitation—the solution is what we are struggling with. One solution to lake acidification is rehabilitation by the periodic addition of lime, as has been done in New York State, Sweden, and Ontario. This solution is not satisfactory over a long period, however, because the continuing effort is expensive. A better approach is to target the components of acid rain, the emissions of sulfur dioxide and nitrogen oxides. As noted, sulfur dioxide emissions in the United States are down about 60% since 1970—a big improvement that is significantly reducing acid rain. Emissions were lowered by a market-based SO<sub>2</sub> cap-and-trade program of the U.S. Environmental Protection Agency's Acid Rain Program, by which utilities receive pollution allowances that they can trade or sell if they lower emissions from their power plants (see Chapter 7 for a discussion of cap and trade).<sup>14</sup>

## Air Toxics

Toxic air pollutants, or **air toxics**, are among those pollutants known or suspected to cause cancer and other serious health problems after either long-term or short-term exposure. The most serious exposure to air toxics occurs in California and New York, with Oregon, Washington, DC, and New Jersey making up the rest of the top five. States with the cleanest air include Montana, Wyoming, and South Dakota.

Air toxics include gases, metals, and organic chemicals that are emitted in relatively small volumes. They cause respiratory, neurological, reproductive, or immune diseases, and some may be carcinogenic. A 2006 EPA report estimated that the average risk of cancer from exposure to air toxics is about 1 in 21,000. The assessment concluded that benzene poses the most significant risk for cancer, accounting for 25% of the average individual cancer risk from all air toxics. Again, the effect on an individual's health depends on a number of factors, including duration and frequency of exposure, toxicity of the chemical, concentration of the pollutant the individual is exposed to, and method of exposure, as well as an individual's general health.<sup>15</sup>

Among the more than 150 known toxic air pollutants are hydrogen sulfide, hydrogen fluoride, various chlorine gases, benzene, methanol, and ammonia. In 2006 the EPA released an assessment of the national health risk from air toxics. It focused on exposure from breathing

the pollutants; it did not address other ways people are exposed to them.

Standards and regulations established for more than 150 air toxics are expected to reduce annual emissions from 1990 levels. Even though vehicle miles will likely increase significantly by 2020, emissions of gaseous air toxics (such as benzene) from vehicles on highways are projected to decline about 80% from 1990 levels. Following are several examples of air toxics.

#### *Hydrogen Sulfide*

Hydrogen sulfide (H<sub>2</sub>S) is a highly toxic corrosive gas, easily identified by its rotten-egg odor. Hydrogen sulfide is produced from natural sources, such as geysers, swamps, and bogs, and from human sources, such as petroleum refineries and metal smelters. The potential effects of hydrogen sulfide include functional damage to plants and health problems ranging from toxicity to death for humans and other animals.<sup>4</sup>

#### *Hydrogen Fluoride*

Hydrogen fluoride (HF) is a gas released by some industrial activities, such as aluminum production, coal gasification, and burning of coal in power plants. Hydrogen fluoride is extremely toxic; even a small concentration (as low as 1 ppb) may cause problems for plants and animals. It is potentially dangerous to grazing animals because some forage plants can become toxic when exposed to this gas.<sup>1</sup>

### *Mercury*

Mercury is a heavy metal released into the atmosphere by coal-burning power plants, other industrial processes, and mining. Natural processes—such as volcanic eruptions and evaporation from soil, wetlands, and oceans—also release mercury into the air. Its toxicity to people is well documented and includes neurological and development damage, as well as damage to the brain, liver, and kidneys. Mercury from the atmosphere may be deposited in rivers, ponds, lakes, and the ocean, where it accumulates through biomagnification and both wildlife and people are exposed to it.<sup>2</sup>

### *Volatile Organic Compounds*

Volatile organic compounds (VOCs) include a variety of organic compounds. Some of these compounds are used as solvents in industrial processes, such as dry cleaning, degreasing, and graphic arts. Hydrocarbons (compounds of hydrogen and carbon) comprise one group of VOCs. Thousands of hydrocarbons exist, including natural gas, or methane ( $\text{CH}_4$ ); butane ( $\text{C}_4\text{H}_{10}$ ); and propane ( $\text{C}_3\text{H}_8$ ). Analysis of urban air has identified many hydrocarbons, and their potential adverse effects are numerous. Some are toxic to plants and animals, and others may be converted to harmful compounds through complex chemical changes that occur in the atmosphere. Some react with sunlight to produce photochemical smog.

Globally, our activities produce only about 15% of hydrocarbon emissions. In the United States, however, nearly half the hydrocarbons entering the atmosphere are emitted from anthropogenic sources. The largest of these sources in the United States is automobiles. Anthropogenic sources are particularly abundant in urban regions. However, in some southeastern U.S. cities, such as Atlanta, Georgia, natural emissions (in Atlanta's case, apparently from trees) probably exceed those from automobiles and other human sources.<sup>3</sup>

Like emissions of sulfur dioxide and nitrogen oxide, VOCs peaked in the 1970s and have been reduced by 50% (Table 21.2) thanks to effective government-mandated emission controls for automobiles.

### *Methyl Isocyanate*

Some chemicals are so toxic that extreme care must be taken to ensure they do not enter the environment. This was demonstrated on December 3, 1984, when a toxic liquid from a pesticide plant leaked, vaporized, and formed a deadly cloud of gas that settled over a 64 km<sup>2</sup> area of Bhopal, India. The gas leak lasted less than an hour; yet more than 2,000 people were killed and more than 15,000 injured. The colorless gas that resulted from the leak was methyl isocyanate ( $\text{C}_2\text{H}_3\text{NO}$ ), which causes severe irritation (burns on contact) to eyes, nose, throat, and lungs. Breathing the gas in concentrations of only a few parts per million (ppm) causes violent coughing, swelling of the lungs, bleeding, and death. Less exposure can cause a variety of problems, including blindness.

Methyl isocyanate is an ingredient of a common pesticide known in the United States as Sevin, as well as two other insecticides used in India. An industrial plant in West Virginia also makes the chemical. Small leaks not leading to major accidents occurred there both before and after the catastrophe in Bhopal.

Clearly, chemicals that can cause widespread injury and death should not be stored near large population centers. In addition, chemical plants should have reliable accident-prevention equipment, as well as personnel trained to control and prevent problems.

### *Benzene*

Benzene ( $\text{C}_6\text{H}_6$ ) is a gasoline additive and an important industrial solvent. Generally, it is produced when carbon-rich materials, such as oil and gasoline, undergo incomplete combustion. It is also a component of cigarette smoke. Automobiles, trucks, airplanes, trains, and farm machinery are major sources of environmental benzene.<sup>15</sup>

### *Acrolein*

Acrolein ( $\text{CH}_2\text{CHCHO}$ ) is a volatile hydrocarbon that is extremely irritating to the eyes, nose, and respiratory system in general. It is produced by manufacturing processes that involve combustion of petroleum fuels and is a component of cigarette smoke.<sup>15</sup>

## Variability of Air Pollution

Pollution problems vary greatly among the different regions of the world and even within just the United States. For example, as noted earlier, in the Los Angeles basin and many U.S. cities, nitrogen oxides and hydrocarbons are particularly troublesome because they combine in the presence of sunlight to form photochemical smog. Most of the nitrogen oxides and hydrocarbons are emitted from automobiles and other mobile sources. In other U.S. regions, such as Ohio and the Great Lakes region, air quality also suffers from emissions of sulfur dioxide and particulates from industry and from coal-burning power plants, which are point sources.

Air pollution also varies with the time of year. For example, smog is usually a problem in the summer, when there is a lot of sunlight. Particulates are a problem in dry months, when wildfires are likely, and during months when the wind blows across the desert. For example, drought and heat in August of 2010 resulted in wildfires in Russia that produced a thick hazardous smoke and resulting very poor air quality in Moscow. The combination of heat and air pollution at the height of the pollution event killed about 700 people per day in Moscow.

Pollution from particulates is a problem in arid regions, where there is little vegetation and the wind easily picks up and transports fine dust. Las Vegas, Nevada, the fastest-growing urban area in the United States in the 1990s,



now has some of the most polluted air in the southwestern United States. The brown haze over Las Vegas is due mostly to the nearly 80,000 metric tons of  $\text{PM}_{10}$  that enter the air in that region from the desert environment. About 60% of the dust comes from new construction sites, dirt roads, and vacant land. The rest is natural windblown dust. Las Vegas also has a carbon monoxide problem from vehicles, but it is the particulates that are causing concern, possibly leading to future EPA sanctions and growth restrictions.

### Haze from Afar

Air pollution has become global and is not limited to urban areas. One example of this is Alaska's North Slope, a vast strip of land approximately 200 km (125 mi) wide that many consider to be one of the few unspoiled wilderness areas left on Earth. It seems logical to assume that air quality in the Arctic environments of Alaska would be pristine, except perhaps near areas where petroleum is being vigorously developed. However, ongoing studies suggest that the North Slope has an air-pollution problem that originates in Eastern Europe and Eurasia.

It is suspected that pollutants from burning fossil fuels in Eurasia are transported via the jet stream, at speeds that may exceed 400 km/hr (250 mi/hr), northeast over the North Pole to the North Slope of Alaska. There, they slow, stagnate, and produce a reddish-brown air mass known as "Arctic haze." The concentrations of air pollutants, including oxides of sulfur and nitrogen, are comparable to those of some eastern U.S. cities, such as Boston. Air quality problems in remote areas, such as Alaska, have significance as we try to understand air pollution at the global level.<sup>16</sup>

A curious global event occurred in the spring of 2001 when a white haze consisting of dust from Mongolia and industrial particulate pollutants arrived in North America. The haze affected one-fourth of the United States and could be seen from Canada to Mexico. In the United States, pollution levels from the haze alone were as high as two-thirds of federal health limits and caused respiratory problems. The haze demonstrates that pollution from Asia is carried by winds across the Pacific Ocean. Today we know from satellite observation that air pollutants transported by winds from East Asia to North America account for about 15% of the total pollutants originating from the United States and Canada.<sup>17</sup>

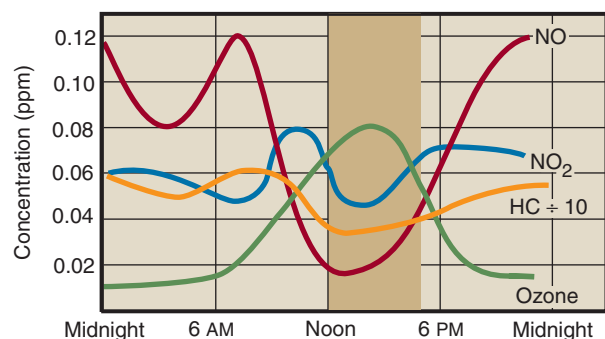
## Urban Air Pollution: Chemical and Atmospheric Processes

Now that we have introduced and discussed the various types of air pollutants. This preparation allows for a more detailed discussion of the processes and chemistry of urban **smog**.

There are two major types of urban smog: photochemical smog, sometimes called L.A.-type smog or brown air; and sulfurous smog, sometimes referred to as London-type smog, gray air, or industrial smog. **Sulfurous smog** is produced primarily by the burning of coal or oil at large power plants. Sulfur oxides and particulates combine under certain conditions to produce a concentrated sulfurous smog. **Photochemical smog** is directly related to automobile use.

Figure 21.7 shows a characteristic pattern in the way nitrogen oxides, hydrocarbons, and oxidants (mostly ozone) vary during a typically smoggy day in Southern California. Early in the morning, when commuter traffic begins to build up, concentrations of nitrogen oxide (NO) and hydrocarbons begin to increase. At the same time, nitrogen dioxide ( $\text{NO}_2$ ) may decrease because sunlight breaks it down to produce NO plus atomic oxygen ( $\text{NO} + \text{O}$ ). The atomic oxygen (O) is then free to combine with molecular oxygen ( $\text{O}_2$ ) to form ozone ( $\text{O}_3$ ). As a result, the concentration of ozone also increases after sunrise. Shortly thereafter, oxidized hydrocarbons react with NO to increase the concentration of  $\text{NO}_2$  by mid-morning. This causes the NO concentration to decrease and allows ozone to build up, producing a midday peak in ozone and a minimum in NO. As the smog develops, visibility may be greatly reduced as light is scattered by the pollutants. Figure 21.8 shows Los Angeles on a clear day, in sharp contrast to the way the city looks on a smoggy day.

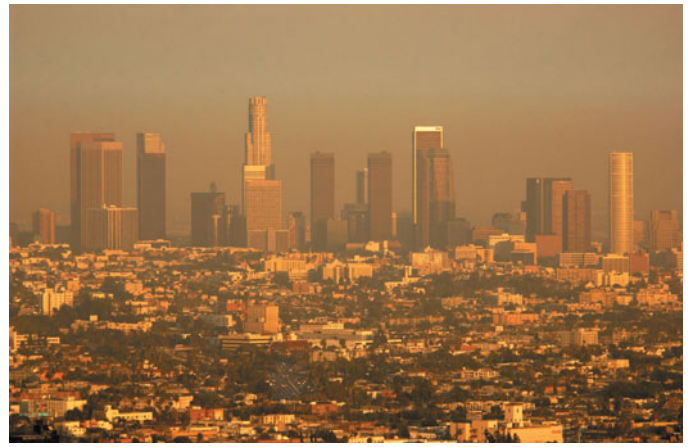
What are the chances that a deadly smog will occur somewhere in the world? Unfortunately, the answer is all too good, given the amount of air pollution in some large cities. Beijing, for example, might be a candidate; the city uses an immense amount of coal, and coughing is so pervasive that residents often refer to it as the "Beijing cough." Another likely candidate is Mexico City, which has one of the worst air-pollution problems anywhere in the world today.



**FIGURE 21.7** Development of photochemical smog over the Los Angeles area on a typical warm day.



(a)

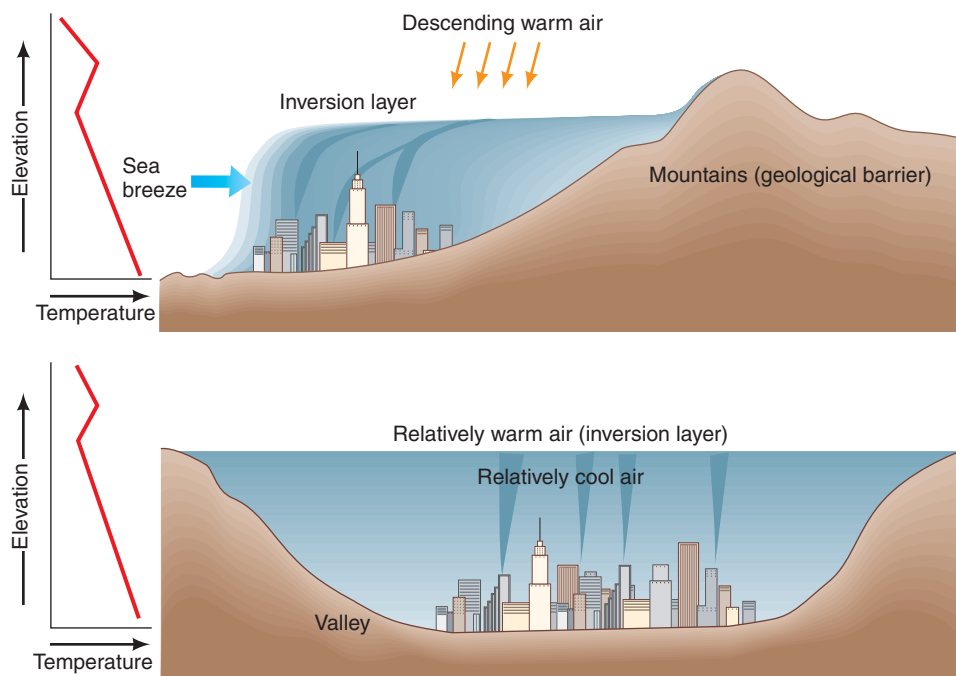


(b)

**FIGURE 21.8** The city of Los Angeles on (a) a clear day and (b) a smoggy day.

Wherever multiple sources emit air pollutants over a wide area, air pollution can develop. Whether it does or not depends on topography and meteorological conditions, which can determine whether air pollution is a nuisance or a major health problem. The primary adverse effects are damage to green plants and aggravation of chronic illnesses. Most of these effects are due to relatively low concentrations of pollutants over a long period. Periods of pollution generally do not directly cause numerous deaths. Serious pollution events (disasters) can develop over a period of days and lead to increases in illnesses and deaths.

In the lower atmosphere, restricted circulation associated with an atmospheric inversion may lead to pollution events. An **atmospheric inversion** occurs when warmer air lies above cooler air and there is little wind. The air stays still both vertically and horizontally, so any pollutant emissions stay there and build up. Figure 21.9 shows two types of atmospheric inversion that may contribute to air-pollution problems. In the upper diagram, which is somewhat analogous to the situation in the Los Angeles area, descending warm air forms a semipermanent inversion layer. Because the mountains act as a barrier to the pollution, polluted air moving in response to the sea breeze



**FIGURE 21.9** Two causes of the development of atmospheric inversion, which may aggravate air-pollution problems.



**FIGURE 21.10** Part of Southern California showing the Los Angeles basin (south coast air basin). (Source: Modified from S.J. Williamson, *Fundamentals of Air Pollution* [Reading, MA: Addison-Wesley, 1973].)

and other processes tends to move up canyons, where it is trapped. The air pollution that develops occurs primarily in summer and fall.

The lower part of Figure 21.9 shows a valley with relatively cool air overlain by warm air. This type of inversion can occur when cloud cover associated with a stagnant air mass develops over an urban area. Incoming solar radiation is blocked by the clouds, which reflect and absorb some of the solar energy and are warmed. On the ground or near Earth's surface, the air cools. If there is moisture in the air (humidity), then, as the air cools, the dew point (the temperature at which water vapor condenses) is reached, and fog may form. Because the air is cold, people burn more fuel to heat their homes and factories, so more pollutants are delivered into the atmosphere. As long as the stagnant conditions exist, the pollutants will build up. It was this mechanism that caused the deadly 1952 London smog that killed about 4,000 people over a one week period December 4 to 10.

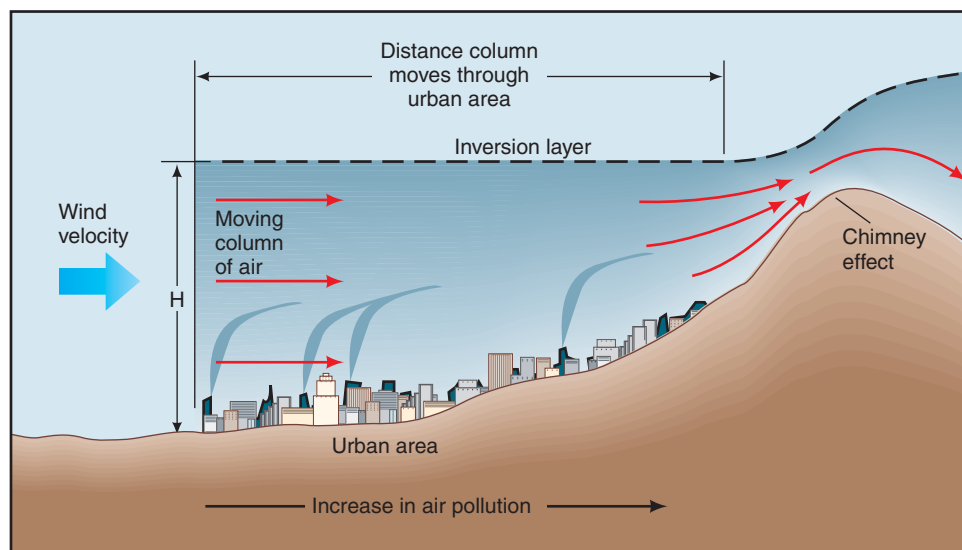
Cities in a valley or topographic bowl surrounded by mountains are more susceptible to smog problems than

are cities in open plains. Surrounding mountains and the occurrence of temperature inversions prevent pollutants from being dispersed by winds and weather systems. The production of air pollution is particularly well documented for Los Angeles, which has mountains surrounding part of the urban area and lies within a region where the air lingers, allowing pollutants to build up (Figure 21.10).

In sum, the potential for air pollution in urban areas is determined by the following:

- The rate of emission of pollutants per unit area.
- The distance that an air mass moves downwind through a city.
- The average speed of the wind.
- The elevation to which potential pollutants can be thoroughly mixed by naturally moving air in the lower atmosphere (Figure 21.11).<sup>18</sup>

The concentration of air pollutants is directly proportional to the first two factors: As either the emission rate or downwind travel distance through an urban area increases, so will the concentration of pollutants in the air. Again, the Los Angeles basin is a good example (see Figure 21.10). If there is a wind from the ocean, as is generally the case, coastal areas will experience much less air pollution than inland areas. Assuming a constant rate of emission of air pollutants, the air mass will collect more and more pollutants as it moves through the urban area; the inversion layer acts as a lid for the pollutants. However, near a geological barrier, such as a mountain, there may be a chimney effect in which the pollutants spill over the top of the mountain (see Figures 21.10 and 21.11). This has been noticed in the Los Angeles basin, where pollutants may climb several thousand meters, damaging mountain pines and other vegetation and spoiling the air of mountain valleys.



**FIGURE 21.11** The higher the wind velocity and the thicker the mixing layer (shown here as  $H$ ), the less air pollution. The greater the emission rate and the longer the downwind length of the city, the more air pollution. The chimney effect allows polluted air to move over a mountain and down into an adjacent valley.

City air pollution diminishes with increases in the third and fourth factors, which are meteorological: the wind velocity and the height of mixing. The stronger the wind and the higher the mixing layer, the lower the pollution.

## Future Trends for Urban Air Pollution

### *The United States*

What does the future hold for U.S. urban areas with respect to air pollution? The optimistic view is that urban air quality will continue to improve as it has in the past 40 years because we know so much about the sources of air pollution and have developed effective ways to reduce it (see Table 21.2). In recent years, as the U.S. population, gross domestic product, and energy consumption have increased, emissions of the major pollutants have decreased (Figure 21.12).<sup>2</sup>

Despite improvements, air pollution in the United States remains a serious problem in many parts of the country. The Los Angeles urban area, for example, still has the worst air quality in the United States. Southern California is coming to grips with the problem, and the people studying air pollution there understand that further pollution abatement will require massive efforts. There are encouraging signs of improvement. For example, from the 1950s to the present, the peak level of ozone (considered one of the best indicators of

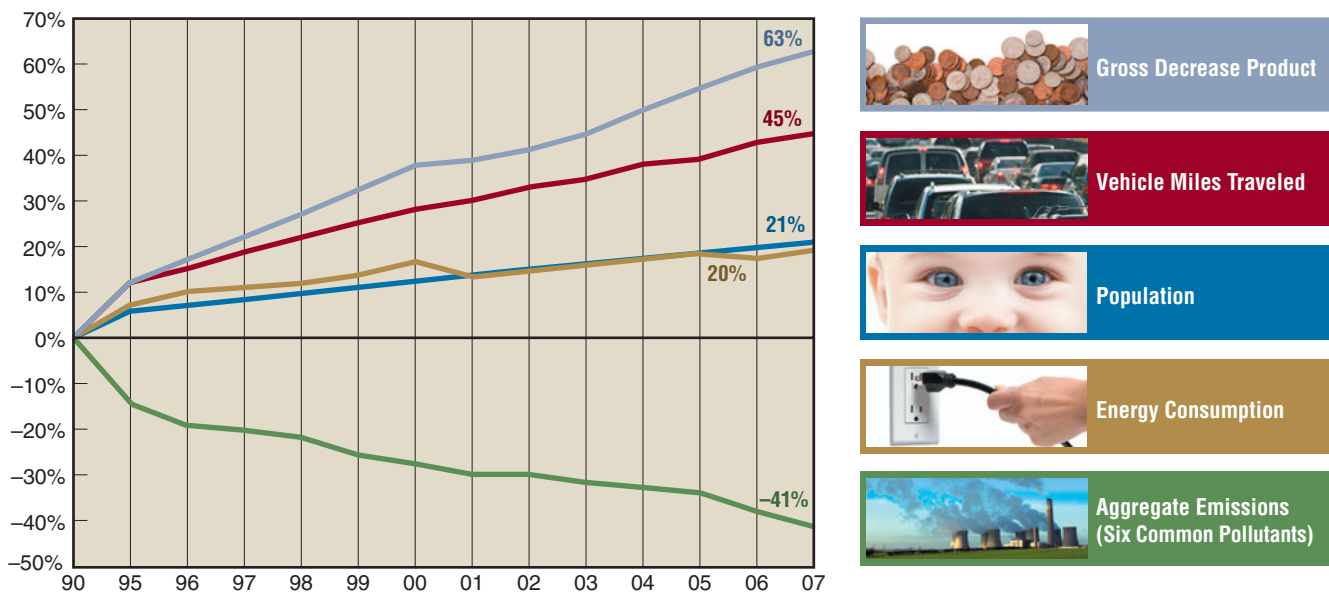
air pollution) has declined, even though the population nearly tripled and the number of motor vehicles quadrupled during this period. Nevertheless, exposure to ozone in Southern California remains the nation's worst. Even if all the aforementioned controls in urban areas are implemented, air quality will continue to be a significant problem in coming decades, particularly if the urban population continues to increase.

We have focused on air pollution in Southern California because its air quality is especially poor. However, most large and not-so-large U.S. cities have poor air quality for a significant part of the year. With the exception of the Pacific Northwest, no U.S. region is free from air pollution and its health effects.<sup>6</sup>

## Developing Countries

The pessimistic view is that population pressures and environmentally unsound policies and practices will dictate what happens in many developing parts of the world, and the result will be poorer air quality. They often don't have the financial base necessary to fight air pollution and are more concerned with finding ways to house and feed their growing populations.

Consider Mexico City. With a population of about 25 million, Mexico City is one of the four largest urban areas in the world. Cars, buses, industry, and power plants in the city emit hundreds of thousands of metric



**FIGURE 21.12** Change in United States population, gross domestic product, energy consumption, and aggregate emission of the six common air pollutants (ground-level ozone, particulates, lead, nitrogen dioxide, sulfur dioxide, and carbon monoxide) from 1990 to 2007. (Source: U.S. Environmental Protection Agency, 2008, air quality trends through 2007. [www.epa.gov](http://www.epa.gov).)



tons of pollutants into the atmosphere each year. The city is at an elevation of about 2,255 m (7,400 ft) in a natural basin surrounded by mountains, a perfect situation for a severe air pollution problem. It is becoming a rare day in Mexico City when the mountains can be seen. Headaches, irritated eyes, and sore throats are common when the pollution settles in, and physicians report a steady increase in respiratory diseases. They advise parents to take their children out of the city permanently. The people in Mexico City do not need to be told they have an air-pollution problem; it is all too apparent. However, developing a successful strategy to improve the quality of the air is difficult.<sup>19</sup>

## 21.2 Controlling Common Pollutants of the Lower Atmosphere

The most reasonable ways to control the most common air pollutants in our cities include reducing emissions, capturing them before they reach the atmosphere, and removing them from the atmosphere. From an environmental viewpoint, reducing emissions through energy efficiency and conservation (such as burning less fuel) is the preferred strategy, with clear advantages over all other approaches (see Chapters 14 to 16). Here, we discuss control of selected air pollutants.

### Particulates

Particulates emitted from fugitive, point, or area stationary sources are much easier to control than the very small particulates of primary or secondary origin released from mobile sources, such as automobiles. As we learn more about these very small particles, we will have to devise new methods to control them.

A variety of “settling chambers” or collectors are used to control emissions of coarse particulates from power plants and industrial sites (point or area sources) by providing a mechanism that causes particles in gases to settle out in a location where they can be collected for disposal in landfills. In recent decades, we have made great strides in controlling particulates, such as ash, from power plants and industry.

### Automobiles

Controlling such pollutants as carbon monoxide, nitrogen oxides, and hydrocarbons in urban areas is best achieved by pollution-control measures for automobiles. Control of these materials will also limit ozone formation in the lower atmosphere, since, as you have learned, ozone forms

through reactions with nitrogen oxides and hydrocarbons in the presence of sunlight.

Nitrogen oxides from automobile exhausts are controlled by recirculating exhaust gas and diluting the air-to-fuel mixture burned in the engine. Dilution lowers the temperature of combustion and decreases the oxygen concentration in the burning mixture so that it produces fewer nitrogen oxides. Unfortunately, the same process increases hydrocarbon emissions. Nevertheless, exhaust recirculation to reduce nitrogen oxide emissions has been common practice in the United States for more than 20 years.<sup>20</sup>

The exhaust system’s catalytic converter is the device most commonly used to reduce carbon monoxide and hydrocarbon emissions from automobiles. In the converter, oxygen from outside air is introduced, and exhaust gases from the engine are passed over a catalyst, typically platinum or palladium. Two important chemical reactions occur: Carbon monoxide is converted to carbon dioxide; and hydrocarbons are converted to carbon dioxide and water.

Other approaches to reducing air pollution from vehicles include reducing the number and types of cars on roads; developing cleaner fuels through use of fuel additives and reformulation; and requiring more fuel-efficient motor vehicles, such as those with electric engines and hybrid cars that have both an electric engine and an internal combustion engine.

### Sulfur Dioxide

Sulfur dioxide emissions have been reduced by using abatement measures before, during, or after combustion. Technology to clean up coal so that it will burn more cleanly is already available. Although removing the sulfur makes fuel more expensive, the expense must be balanced against the long-term consequences of burning high-sulfur coal. Switching from high-sulfur coal to low-sulfur coal seems an obvious way to reduce emissions of sulfur dioxide, and in some regions this will work. Unfortunately, however, most of the naturally low-sulfur coal in the United States is in the western part of the country, whereas most coal is burned in the East, so transportation is an issue and using low-sulfur coal is a solution only in cases where it is economically feasible.

Sulfur emissions can also be reduced by washing coal. When finely ground coal is washed with water, iron sulfide (mineral pyrite) settles out because of its relatively high density. But this is ineffective for removing organic sulfur bound up with carbonaceous material, and it is expensive.

Another option is *coal gasification*, which converts relatively high-sulfur coal to a gas in order to remove the sulfur.

The gas is quite clean and can be transported relatively easily, augmenting supplies of natural gas. True, it is still fairly expensive compared with gas from other sources, but its price may become more competitive in the future.

Desulfurization, or **scrubbing** (Figure 21.13), removes sulfur from stationary sources such as power plants. This technology was developed in the 1970s in the United States in response to passage of the Clean Air Act. However, the technology was not initially implemented in the United States; instead, regulators chose to allow plants to disperse pollutants through very tall smokestacks. This worsened the regional acid-rain problem.

Nearly all scrubbers (90%) used at coal-burning power plants in the United States are wet scrubbers that use a lot of water and produce a wet end product. Wet scrubbing is done after coal is burned. The  $\text{SO}_2$  rich gases are treated with a slurry (a watery mixture) of lime (calcium oxide,  $\text{CaO}$ ) or limestone (calcium carbonate,  $\text{CaCO}_3$ ). The sulfur oxides react with the calcium to form calcium sulfite, which is collected and then usually disposed of in a landfill.<sup>21</sup>

In West Virginia, a coal mine, power plant, and synthetic gypsum plant located close to each other joined forces in 2008 to produce electric energy, recover sulfur dioxide, and produce high-quality wallboard (sheetrock) for the construction industry. The power plant benefits by selling the raw gypsum (from scrubbers) rather than paying to dispose of it in a landfill. The wallboard plant is right next to the power plant and uses gypsum that does not have to be mined from earth.<sup>22</sup>

## Air Pollution Legislation and Standards

### *Clean Air Act Amendments of 1990*

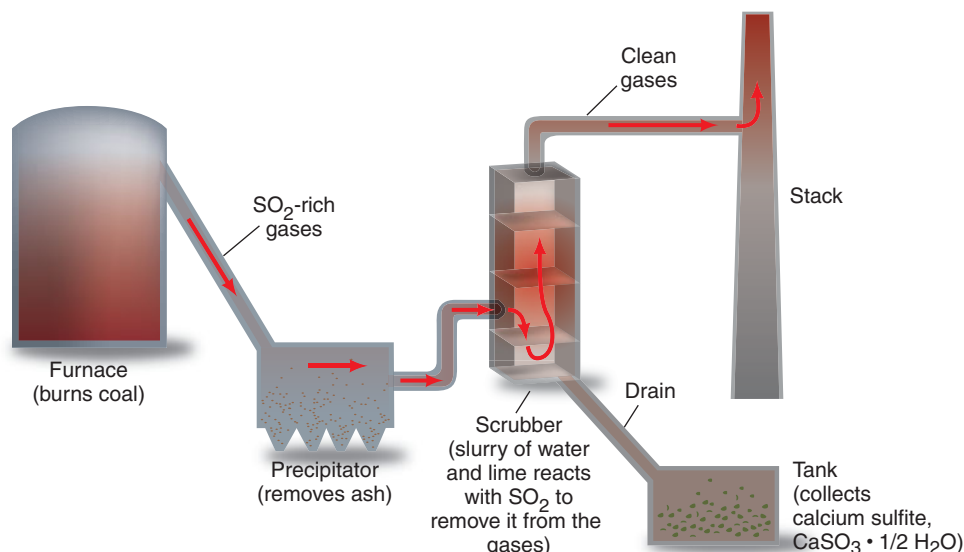
The Clean Air Act Amendments of 1990 are comprehensive regulations enacted by the U.S. Congress

that address the problems of acid rain, toxic emissions, ozone depletion, and automobile exhaust. In dealing with acid rain, the amendments establish limits on the maximum permissible emissions of sulfur dioxide from utility companies burning coal. The goal of the legislation—to reduce such emissions by about 50%, to 10 million tons a year, by 2000—was more than achieved (refer back to Table 21.2).

An innovative aspect of the legislation is the incentives it offers to utility companies to reduce emissions of sulfur dioxide. As explained earlier here and discussed in detail in Chapter 7, the incentives are marketable permits (allowances) that allow companies to buy and sell the right to pollute<sup>23</sup> (see A Closer Look 21.1). The 1990 amendments also call for reducing emissions of nitrogen dioxides by approximately 2 million tons from the 1980 level. The actual reduction has been 10 million tons—an air-pollution success story!

### *Ambient Air Quality Standards*

Air quality standards are important because they are tied to emission standards that attempt to control the concentrations of various pollutants in the atmosphere. The many countries that have developed air quality standards include France, Japan, Israel, Italy, Canada, Germany, Norway, and the United States. National Ambient Air Quality Standards (NAAQS) for the United States, defined to comply with the Clean Air Act, are shown in Table 21.3. Tougher standards were set for ozone and  $\text{PM}_{2.5}$  in recent years to reduce adverse health effects on children and elderly people, who are most susceptible to air pollution. The new standards are saving the lives of thousands and improving the health of hundreds of thousands of children. The ozone standard was significantly strengthened in



**FIGURE 21.13** Scrubber used to remove sulfur oxides from the gases emitted by tall stacks.

2008. The change is expected to result in health benefits of more than \$15 billion per year.

### Air Quality Index

In the United States, the Air Quality Index (AQI) (Table 21.4) is used to describe air pollution on a given day. For example, air quality in urban areas is often reported as good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, or hazardous, corresponding to a color code of the Air Quality Index. The AQI is determined by measuring the concentration of five major pollutants: particulate matter, sulfur dioxide, carbon monoxide, ozone, and nitrogen dioxide. An AQI value greater than 100 is unhealthy. In most U.S. cities, AQI values range between 0 and 100. Values above 100 are generally recorded for a particular city only a few times a year, but some cities with serious air-pollution problems may exceed an AQI of 100 many times a year. In a typical year, AQI values above 200 (for all U.S. sites) are rare, and those above 300 are very rare. In large cities outside the United States with dense human populations and numerous uncontrolled sources of pollution, AQIs greater than 200 are frequent.

## The Cost of Controlling Outdoor Air Pollution

The cost of outdoor air pollution control varies widely from one industry to another. For example, the cost for incremental control in a fossil-fuel-burning utility is a few hundred dollars per additional ton of particulates removed. For an aluminum refinery, the cost to remove an additional ton of particulates may be as much as several thousand dollars. Some economists would argue that it is wise to raise the standards for utilities and relax them, or at least not raise them, for aluminum plants. This would lead to more cost-efficient pollution control while maintaining good air quality. However, the geographic distribution of various facilities will determine the trade-offs possible.<sup>23, 24</sup>

Economic analysis of air pollution is not simple. There are many variables, some of which are hard to quantify. We do know the following:

- With increasing air pollution controls, the capital cost for technology to control air pollution increases.
- As the controls for air pollution increase, the loss from pollution damages decreases.

**Table 21.3 U.S. NATIONAL AMBIENT AIR QUALITY STANDARDS (NAAQS)**

POLLUTANT	STANDARD VALUE <sup>a</sup>		STANDARD TYPE
Carbon monoxide (CO)			
8-hour average	9 ppm	(10 mg/m <sup>3</sup> )	Primary <sup>c</sup>
1-hour average	35 ppm	(40 mg/m <sup>3</sup> )	Primary
Nitrogen dioxide (NO <sub>2</sub> )			
Annual arithmetic mean	0.053 ppm	(100 µg/m <sup>3</sup> )	Primary and secondary <sup>d</sup>
Ozone (O <sub>3</sub> )			
8-hour average	0.075 ppm	(147 µg/m <sup>3</sup> )	Primary and secondary
Lead (Pb)			
Quarterly average	1.5 µg/m <sup>3</sup>		Primary and secondary
Particulate (PM 10) <i>Particles with diameters of 10 micrometers or less</i>			
Annual arithmetic mean	50 µg/m <sup>3</sup>		Primary and secondary
24-hour average	150 µg/m <sup>3</sup>		Primary and secondary
Particulate (PM 2.5) <sup>b</sup> <i>Particles with diameters of 2.5 micrometers or less</i>			
Annual arithmetic mean	15 µg/m <sup>3</sup>		Primary and secondary
24-hour average	65 µg/m <sup>3</sup>		Primary and secondary
Sulfur dioxide (SO <sub>2</sub> )			
Annual arithmetic mean	0.03 ppm	(80 µg/m <sup>3</sup> )	Primary
24-hour average	0.14 ppm	(365 µg/m <sup>3</sup> )	Primary
3-hour average	0.50 ppm	(1300 µg/m <sup>3</sup> )	Secondary

<sup>a</sup> Parenthetical value is an approximately equivalent concentration.

<sup>b</sup> The ozone 8-hour standard and the PM 2.5 standards are included for information only. A 1999 federal court ruling blocked implementation of these standards, which the EPA proposed in 1997. EPA has asked the U.S. Supreme Court to reconsider that decision. (Note: In March 2001, the Court ruled in favor of the EPA, and the new standards are expected to take effect within a few years.)

<sup>c</sup> Primary standards set limits to protect public health, including the health of sensitive populations such as asthmatics, children, and the elderly.

<sup>d</sup> Secondary standards set limits to protect public welfare, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

Source: U.S. Environmental Protection Agency.

Table 21.4 AIR QUALITY INDEX (AQI) AND HEALTH CONDITIONS

INDEX VALUES	DESCRIPTOR	CAUTIONARY STATEMENT	GENERAL ADVERSE HEALTH EFFECTS	ACTION LEVEL (AQI) <sup>a</sup>
0–50	Good	None	None	None
51–100	Moderate	Unusually sensitive people should consider limiting prolonged outdoor exertion.	Very few symptoms <sup>b</sup> for the most susceptible people <sup>c</sup>	None
101–150	Unhealthy for sensitive groups	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.	Mild aggravation of symptoms in susceptible people, few symptoms for healthy people	None
151–199	Unhealthy	Active children and adults, and people with respiratory disease, such as asthma, should avoid prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion.	Mild aggravation of symptoms in susceptible people, irritation symptoms for healthy people	None
200–300	Very unhealthy	Active children and adults, and people with respiratory disease, such as asthma, should avoid outdoor exertion; everyone else, especially children, should limit outdoor exertion.	Significant aggravation of symptoms in susceptible people, widespread symptoms in healthy people	Alert (200+)
Over 300	Hazardous	<i>Everyone</i> should avoid outdoor exertion.	300–400: Widespread symptoms in healthy people 400–500: Premature onset of some diseases Over 500: Premature death of ill and elderly people; healthy people experience symptoms that affect normal activity	Warning (300+) Emergency (400+)

<sup>a</sup> Triggers preventative action by state or local officials.

<sup>b</sup> Symptoms include eye, nose, and throat irritation; chest pain; breathing difficulty.

<sup>c</sup> Susceptible people are young, old, and ill people and people with lung or heart disease.

AQI 51–100 Health advisories for susceptible individuals.

AQI 101–150 Health advisories for all.

AQI 151–200 Health advisories for all.

AQI 200+ Health advisories for all; triggers an alert; activities that cause pollution might be restricted.

AQI 300 Health advisories to all; triggers a warning; probably would require power plant operations to be reduced and carpooling to be used.

AQI 400+ Health advisories for all; triggers an emergency; cessation of most industrial and commercial activities, including power plants; nearly all private use of vehicles prohibited.

Source: U.S. Environmental Protection Agency.

- The total cost of air pollution is the cost of pollution control plus the environmental damages of the pollution.

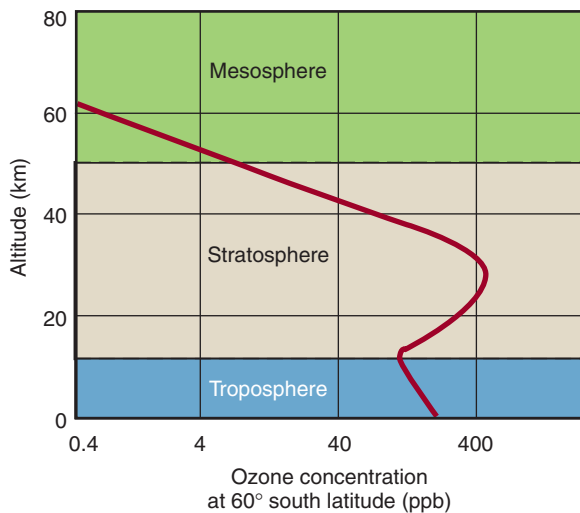
Although the cost of pollution-abatement technology is fairly well known, it is difficult to accurately determine

the loss from pollution damages, particularly when considering health problems and damage to vegetation, including food crops. For example, exposure to air pollution may cause or aggravate chronic respiratory diseases in people, at a very high cost. A recent study of the health



benefits of cleaning up the air quality in the Los Angeles basin estimated that the annual cost of air pollution in the basin is 1,600 lives and about \$10 billion.<sup>25</sup> Air pollution also leads to loss of revenue from people who choose not to visit some areas, such as Los Angeles and Mexico City, because of known air-pollution problems.<sup>26, 27</sup>

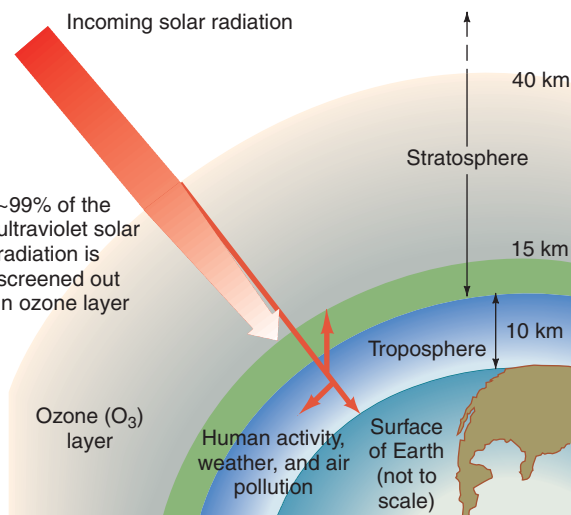
With our discussion of the more traditional outdoor air pollutants behind us, we turn now to ozone depletion in the stratosphere. This will be followed by a discussion of indoor air pollution, which has emerged as a serious environmental problem.



Stratosphere ozone (ozone layer):  
Contains 90% of atmospheric ozone;  
it is the primary UV radiation screen.

Troposphere ozone:  
Contains 10% of atmospheric ozone;  
it is smog ozone, toxic to humans,  
other animals, and vegetation.

(a)



(b)

**FIGURE 21.14** (a) Structure of the atmosphere and ozone concentration. (b) Reduction of the potentially most biologically damaging ultraviolet radiation by ozone in the stratosphere. (Source: Ozone concentrations modified from R.T. Watson, "Atmospheric Ozone," in J.G. Titus, ed., *Effects of Change in Stratospheric Ozone and Global Climate*, vol. 1, *Overview*, p. 70 (U.S. Environmental Protection Agency).

## 21.3 High-Altitude (Stratospheric) Ozone Depletion

The serious problem of ozone depletion in the stratosphere (about 9 to 25 km above Earth's surface) starts down here in the lower atmosphere.

About 21% of the air we breathe at sea level is *diatomic* oxygen ( $O_2$ ), which is two oxygen atoms bonded together. **Ozone ( $O_3$ )** is a *triatomic* form of oxygen in which three atoms of oxygen are bonded. Ozone is a strong oxidant and reacts chemically with many materials in the atmosphere.

In the lower atmosphere, as we have discussed, ozone is a pollutant produced by photochemical reactions involving sunlight, nitrogen oxides, hydrocarbons, and diatomic oxygen. In the stratosphere, however, ozone plays an entirely different role, protecting us from ultraviolet radiation.

### Ultraviolet Radiation and Ozone

The ozone layer in the stratosphere is often called the **ozone shield** because it absorbs most of the potentially hazardous ultraviolet radiation that enters Earth's atmosphere from the sun. Ultraviolet radiation has wavelengths between 0.1 and

0.4  $\mu\text{m}$  and is subdivided into ultraviolet A (UVA), ultraviolet B (UVB), and ultraviolet C (UVC). Ultraviolet radiation with a wavelength of less than about 0.3  $\mu\text{m}$  can be very hazardous to life. If much of this radiation reached Earth's surface, it would injure or kill most living things.<sup>28, 29</sup>

Ultraviolet C (UVC) has the shortest wavelength and is the most energetic of the three types. It has enough energy to break down diatomic oxygen ( $O_2$ ) in the stratosphere into two oxygen atoms, each of which may combine with an  $O_2$  molecule to create ozone. Ultraviolet C is strongly absorbed in the stratosphere, and negligible amounts reach Earth's surface.<sup>28, 29</sup>

Ultraviolet A (UVA) radiation has the longest wavelength and the least energy of the three types. UVA can cause some damage to living cells, is not affected by stratospheric ozone, and is transmitted to the surface of Earth.<sup>28</sup>

Ultraviolet B (UVB) radiation is energetic and strongly absorbed by stratospheric ozone. In fact, ozone is the only known gas that absorbs UVB. Thus, depletion of ozone in the stratosphere allows more UVB to reach the Earth. Because UVB radiation is known to be hazardous to living things,<sup>28-30</sup> this increase in UVB is the hazard we

are talking about when we discuss the problem of ozone depletion in the stratosphere.

The structure of the atmosphere and concentrations of ozone are shown in Figure 21.14. Approximately 90% of the ozone in the atmosphere is in the stratosphere, ranging from about 15 km to 40 km (9 to 25 mi) in altitude, with peak concentrations of about 400 ppb. The altitude of peak concentration varies from about 30 km (19 mi) near the equator to about 15 km (9 mi) in polar regions.<sup>28</sup>

Processes that produce ozone in the stratosphere are illustrated in Figure 21.15. The first step in ozone production is *photodissociation*—intense ultraviolet radiation (UVC) breaks an oxygen molecule ( $O_2$ ) into two oxygen atoms. These atoms then react with another oxygen molecule to form two ozone molecules. Ozone, once produced, may absorb UVC radiation, which breaks the ozone molecule into an oxygen molecule and an oxygen atom. This is followed by the recombination of the oxygen atom with another oxygen molecule to re-form into ozone. As part of this process, UVC radiation is converted to heat energy in the stratosphere. Natural conditions that prevail in the stratosphere result in a dynamic balance between the creation and destruction of ozone.

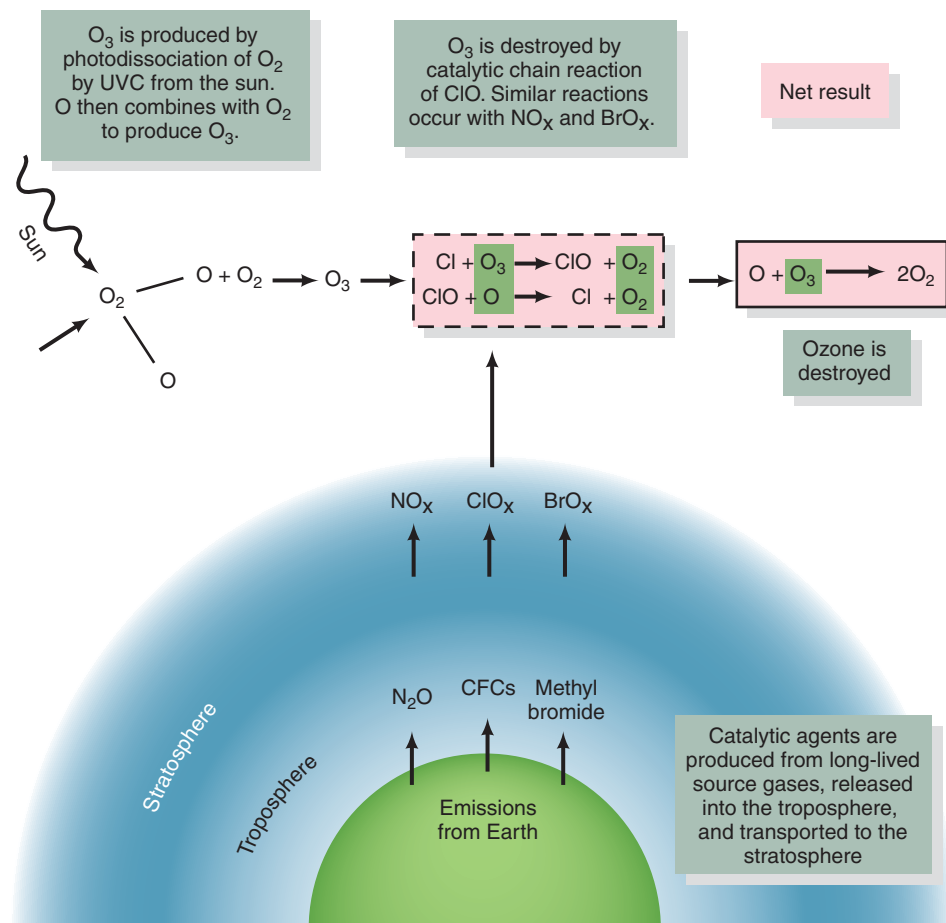
In sum, approximately 99% of all ultraviolet solar radiation (all UVC and most UVB) is absorbed or screened out in the ozone layer. The absorption of ultraviolet radiation

by ozone is a natural service function of the ozone shield and protects us from the potentially harmful effects of ultraviolet radiation.

## Measuring Stratospheric Ozone

Scientists first measured the concentration of atmospheric ozone in the 1920s from the ground, using an instrument known as a Dobson ultraviolet spectrometer. The Dobson unit (DU) is still commonly used to measure the ozone concentrations; 1 DU equals a concentration of 1 ppb  $O_3$ . Today, we have a record of ozone concentrations spanning about 50 years. Most of the measurement stations are in the midlatitudes, and the accuracy of the data varies with the levels of quality control.<sup>28</sup> Satellite measurements of atmospheric ozone concentrations began in 1970 and continue today.

Ground-based measurements first identified ozone depletion over the Antarctic. Members of the British Antarctic Survey began to measure ozone in 1957, and in 1985 they published the first data that suggested significant ozone depletion over Antarctica. The data are taken during October of each year—the Antarctic spring—and show that the concentration of ozone hovered around 300 DU from 1957 to about 1970, and then dropped sharply, to approximately 140 DU by 1986. Despite the variations, the direction of



**FIGURE 21.15** Processes of natural formation of ozone and destruction by CFCs,  $N_2O$ , and methyl bromide. (Source: Modified from NASA-GSFC, "Stratospheric Ozone," accessed August 22, 2000, at <http://see.gsfc.nasa.gov>.)

change, with minor exceptions, is clear: Ozone concentrations in the stratosphere during the Antarctic spring have been decreasing since the mid-1970s.<sup>31-34</sup> The depletion in ozone was dubbed the *ozone hole*. There is no actual hole in the ozone shield where all the ozone is depleted; rather, the term describes a relative depletion in the concentration of ozone that occurs during the Antarctic spring.

## Ozone Depletion and CFCs

The hypothesis that ozone in the stratosphere is being depleted by **chlorofluorocarbons (CFCs)** was first suggested in 1974 by Mario Molina and F. Sherwood Rowland.<sup>34</sup> This hypothesis, based mostly on physical and chemical properties of CFCs and knowledge about atmospheric conditions, was immediately controversial and vigorously debated by scientists, companies producing CFCs, and other interested parties.<sup>35-36</sup> The major features of the Molina and Rowland hypothesis are as follows:<sup>28, 29</sup>

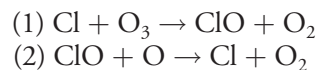
- CFCs emitted in the lower atmosphere by human activity are very stable and nonreactive in the lower atmosphere and therefore have a very long residence time (about 100 years). No significant sinks for CFCs are known, with the possible exception of soils, which evidently do remove an unknown amount of CFCs from the atmosphere at Earth's surface.<sup>36</sup>
- Because of their long residence time in the lower atmosphere, and because the lower atmosphere is very fluid, the CFCs eventually disperse, wander upward, and enter the stratosphere. Once they reach altitudes above most of the stratospheric ozone, they may be destroyed by the highly energetic solar ultraviolet radiation. This releases chlorine, a highly reactive atom.
- The reactive chlorine may then enter into reactions that deplete ozone in the stratosphere.
- Ozone depletion allows an increased amount of UVB radiation to reach Earth. Ultraviolet B is a cause of human skin cancers and is also believed to be harmful to the human immune system.

## Simplified Stratospheric Chlorine Chemistry

CFCs are considered responsible for most of the ozone depletion. Let us look more closely at how this occurs.

Earlier, we noted that there are no tropospheric sinks for CFCs. That is, the processes that remove most chemicals in the lower atmosphere—destruction by sunlight, rain-out, and oxidation—do not break down CFCs because CFCs are transparent to sunlight, are essentially insoluble, and are nonreactive in the oxygen-rich lower atmosphere.<sup>37</sup> Indeed, the fact that CFCs are nonreactive in the lower atmosphere was one reason they were attractive for use as propellants.

When CFCs wander to the upper part of the stratosphere, however, reactions do occur. Highly energetic ultraviolet radiation (UVC) splits up the CFC, releasing chlorine. When this happens, the following two reactions can take place:<sup>37</sup>



These two equations define a chemical cycle that can deplete ozone (Figure 21.15). In the first reaction, chlorine combines with ozone to produce chlorine monoxide, which, in the second reaction, combines with monatomic oxygen to produce chlorine again. The chlorine can then enter another reaction with ozone and cause additional ozone depletion. This series of reactions is what is known as a *catalytic chain reaction*. Because the chlorine is not removed but reappears as a product of the second reaction, the process may be repeated over and over again. It has been estimated that each chlorine atom may destroy approximately 100,000 molecules of ozone in one or two years before the chlorine is finally removed from the stratosphere through other chemical reactions and rain-out.<sup>37</sup> The significance of these reactions is apparent when we realize how many metric tons of CFCs have been emitted into the atmosphere.

It should be noted that what actually happens chemically in the stratosphere is considerably more complex than the two equations shown here. The atmosphere is essentially a chemical soup in which a variety of processes related to aerosols and clouds take place (some of these are addressed in the discussion of the ozone hole). Nevertheless, these equations show us the basic chemical chain reaction that occurs in the stratosphere to deplete ozone.

The catalytic chain reaction just described can be interrupted through storage of chlorine in other compounds in the stratosphere. Two possibilities are as follows:

1. Ultraviolet light breaks down CFCs to release chlorine, which combines with ozone to form chlorine monoxide (ClO), as already described. This is the first reaction discussed. The chlorine monoxide may then react with nitrogen dioxide (NO<sub>2</sub>) to form a chlorine nitrate (ClONO<sub>2</sub>). If this reaction occurs, ozone depletion is minimal. The chlorine nitrate, however, is only a temporary reservoir for chlorine. The compound may be destroyed, and the chlorine released again.
2. Chlorine released from CFCs combine with methane (CH<sub>4</sub>) to form hydrochloric acid (HCl). The hydrochloric acid may then diffuse downward. If it enters the troposphere, rain may remove it, thus removing the chlorine from the ozone-destroying chain reaction. This is the ultimate end for most chlorine atoms in the stratosphere. However, while the hydrochloric acid molecule is in the stratosphere, it may be destroyed by incoming solar radiation, releasing the chlorine for additional ozone depletion.

It has been estimated that the chlorine chain reaction that destroys ozone may be interrupted by the processes just described as many as 200 times while a chlorine atom is in the stratosphere.<sup>28, 38</sup>

It is important to remember that for the Southern Hemisphere and under natural conditions, the highest concentration of ozone is in the polar regions (about 60° south latitude) and the lowest near the equator. At first this may seem strange because ozone is produced in the stratosphere by solar energy, and there is more solar energy near the equator. But although much of the world's ozone is produced near the equator, the ozone in the stratosphere moves from the equator toward the poles with global air-circulation patterns.<sup>32</sup>

In part as a result of ozone depletion, concentrations of ozone have declined in both northern and southern temperate latitudes. While remaining relatively constant at the equator, ozone has been significantly reduced in the Antarctic since the 1970s. Massive destruction of ozone in the Antarctic constitutes the “ozone hole.”<sup>28</sup>

## The Antarctic Ozone Hole

Since the Antarctic ozone hole was first reported in 1985, it has captured the interest of many people around the world. Every year since then, ozone depletion has been observed in the Antarctic in October, the spring season there. Because the thickness of the ozone layer above the Antarctic in springtime has been declining since the mid-1970s, the geographic area covered by the ozone hole has grown from a million or so square kilometers in the late 1970s and early 1980s to about 29 million square kilometers by 1995—about the size of North America in 2000. It has since stabilized as the ozone concentration has ceased its steep decline.<sup>31, 39</sup>

## Polar Stratospheric Clouds

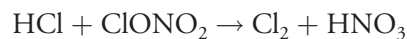
The minimum concentration of ozone in the Antarctic since 1980 has varied from about 50% to 70% of that in the 1970s. Polar stratospheric clouds over the Antarctic appear to be one of the causes of this variation. Observed for at least the past hundred years about 20 km (12 mi) above the polar regions, the clouds have an eerie beauty and an iridescent glow, reminiscent of mother-of-pearl.<sup>38</sup> They form during the polar winter (called the polar night because the tilt of Earth's axis limits sunlight). During the polar winter, the Antarctic air mass is isolated from the rest of the atmosphere and circulates about the pole in what is known as the Antarctic *polar vortex*. The vortex forms as the isolated air mass cools, condenses, and descends.<sup>31, 32</sup>

Clouds form in the vortex when the air mass reaches a temperature between 195 K and 190 K (−78° to −83°C; −108° to −117°F). At these very low temperatures, small sulfuric acid particles (approximately 0.1 μm) freeze and serve as seed particles for nitric acid (HNO<sub>3</sub>). These clouds are called Type I polar stratospheric clouds. If

temperatures drop below 190 K (−83°C; −117°F), water vapor condenses around some of the earlier-formed Type I cloud particles, forming Type II polar stratospheric clouds, which contain larger particles. Type II polar stratospheric clouds are the ones with the mother-of-pearl color.

During the formation of polar stratospheric clouds, nearly all the nitrogen oxides in the air mass are converted to the clouds as nitric acid particles, which grow heavy and descend below the stratosphere, leaving very little nitrogen oxide in the vicinity of the clouds.<sup>28, 38, 39</sup> This facilitates ozone-depleting reactions that may ultimately reduce stratospheric ozone in the polar vortex by as much as 1% to 2% per day in the early spring, when sunlight returns to the polar region (Figure 21.16).

An idealized diagram of the polar vortex that forms over Antarctica is shown in Figure 21.16*a*. The Ozone-depleting reactions within the vortex are illustrated in Figure 21.16*b*. As shown, in the dark Antarctic winter almost all available nitrogen oxides are tied up on the edges of particles in the polar stratospheric clouds or have settled out. Hydrochloric acid and chlorine nitrate (the two important sinks of chlorine) act on particles of polar stratospheric clouds to form dimolecular chlorine (Cl<sub>2</sub>) and nitric acid through the following reaction:<sup>40</sup>



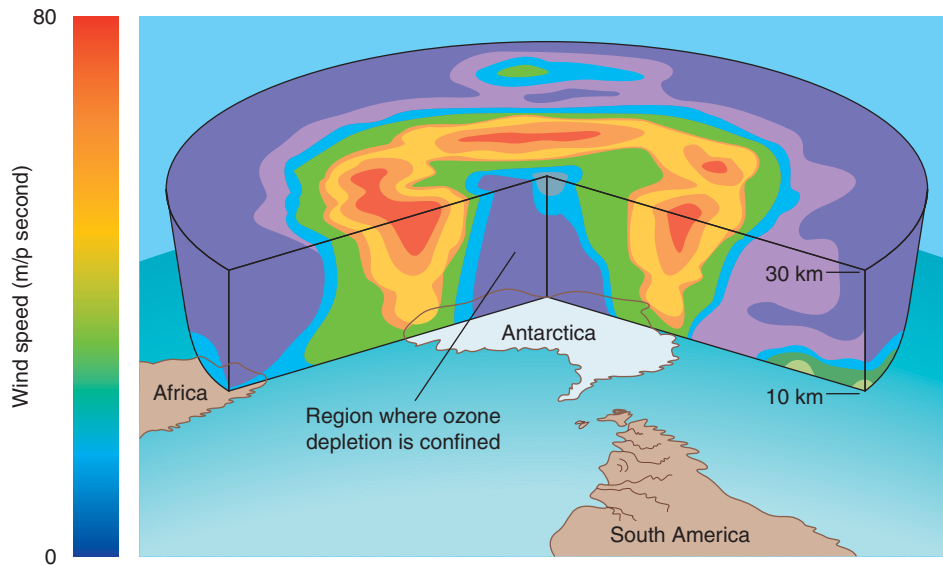
In the spring, when sunlight returns and breaks apart chlorine (Cl<sub>2</sub>), the ozone-depleting reactions discussed earlier occur. Nitrogen oxides are absent from the Antarctic stratosphere in the spring, so the chlorine cannot be sequestered to form chlorine nitrate, one of its major sinks, and remains free to destroy ozone. In the early Antarctic spring, these ozone-depleting reactions can be rapid, producing the 50% reduction in ozone observed in recent years. Ozone depletion in the Antarctic vortex ceases later in spring as the environment warms and the polar stratospheric clouds disappear, releasing nitrogen back into the atmosphere, where it can combine with chlorine and thus be removed from ozone-depleting reactions. Stratospheric ozone concentrations then increase as ozone-rich air masses again migrate to the polar region.

A weaker, shorter polar vortex forms over the North Pole area and can lead to ozone depletion of as much as 30–40%. When the vortex breaks up, it can send ozone-deficient air masses southward to drift over areas of Europe and North America.<sup>41</sup>

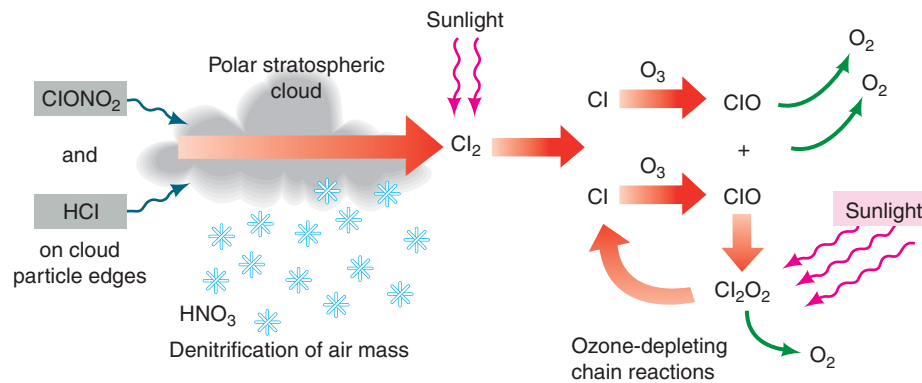
## Environmental Effects of Ozone Depletion

Ozone depletion damages some food chains on land and in the oceans and is dangerous to people, increasing the incidence of skin cancers and cataracts and suppressing immune systems.<sup>41, 42</sup> A 1% decrease





(a)



(b)

**FIGURE 21.16** (a) Idealized diagram of the Antarctic polar vortex and (b) the role of polar stratospheric clouds in the ozone-depletion chain reaction. (Source: Based on O.B. Toon and R.P. Turco, "Polar Stratospheric Clouds and Ozone Depletion," *Scientific American*, 264, no. 6 [1991]: 68–74.)

in ozone can cause a 1–2% increase in UVB radiation and a 2% increase in skin cancer.<sup>43</sup> Because skin cancers have increased globally, health-conscious people today are replacing tanning oils with sunblocks and hats, and newspapers in the United States now provide the **Ultraviolet (UV) Index** (Table 21.5). Developed by the National Weather Service and EPA, the index predicts UV intensity on a scale from 1 to 11+. Some news agencies also use the index to recommend the level of sunblock. It is speculated that the incidence of skin cancer due to ozone depletion will rise until about 2060 and then decline as the ozone shield recovers as a result of controls on CFC emissions.<sup>44, 45</sup>

You can lower your risk of skin cancer and other skin damage from UV exposure by taking a few simple precautions:

- Limit exposure to the sun between 10 A.M. and 4 P.M., the hours of intense solar radiation, and stay in the shade when possible.
- Use a sunscreen with an SPF of at least 30 (but remember that protection diminishes with increased exposure), or use clothing to cover up.
- Wear UV-protective sunglasses.
- Avoid tanning salons and sun lamps.
- Consult the UV Index before going out.

A simple guideline: If your shadow is longer than you are, such as in the evening or early morning, UV exposure is relatively low. If your shadow is shorter than you are, you are in the part of the day with highest UV exposure.

Table 21.5 ULTRAVIOLET (UV) INDEX FOR HUMAN EXPOSURE

EXPOSURE CATEGORY	UV INDEX	COMMENT
Low	< 2	Sunblock recommended for all exposure
Moderate	3 to 5	Sunburn can occur quickly
High	6 to 7	Potentially hazardous
Very high	8 to 10	Potentially very hazardous
Extreme	11	Potentially very hazardous

*Note:* At moderate exposure to UV, sunburn can occur quickly, at high exposure, fair-skinned people may burn in 10 minutes or less of exposure.

*Source:* Modified after U.S. Environmental Protection Agency 2004 (with the National Weather Service). Accessed June 16, 2004 at [www.epa.gov](http://www.epa.gov).

## The Future of Ozone Depletion

The signing of the Montreal Protocol in September 1987 was an important diplomatic achievement: 27 nations signed the agreement originally, and an additional 119 signed later. The protocol outlined a plan to eventually reduce global emissions of CFCs to 50% of 1986 emissions. It originally called for eliminating production of CFCs by 1999, but the period was shortened because of scientific evidence that stratospheric ozone was being depleted faster than predicted. An eventual phase-out of all CFC consumption is part of the Montreal Protocol. Stratospheric concentrations of CFCs are expected to return to pre-1980 levels by about 2050, and the rate of increase of CFC emissions has already been reduced.<sup>31, 46, 47</sup> Of primary importance is developing substitutes for CFCs that are both safe and effective. Hydrofluorocarbons (HFCs) are the long-term substitute for CFCs because they do not contain chlorine.

However, a troubling aspect of ozone depletion is that if the manufacture, use, and emission of all ozone-depleting chemicals were to stop today, the problem would not go away—because millions of metric tons of those chemicals are now in the lower atmosphere, working their way up to the stratosphere. Several CFCs have atmospheric lifetimes of 75–140 years. Thus, an estimated 35% of the CFC-12 molecules in the atmosphere will likely still be there in 2100, and approximately 15% in 2200.<sup>28</sup> In addition, some 10–15% of the CFC molecules manufactured in recent years have not yet been admitted to the atmosphere because they remain in foam insulation, air-conditioning units, and refrigerators.<sup>28</sup> Nevertheless, indicators suggest that growth in the concentrations of CFCs has been slowed and in some cases reversed, and recovery of ozone should be noticeable by 2020 or later.<sup>31</sup>

Today by necessity, we are adapting to ozone depletion by learning to live with higher levels of exposure to ultraviolet radiation. (For example using sunblock, wearing hats and avoiding direct mid day solar radiation.) In the long term, achieving a sustainable level of

stratospheric ozone will require management of man-made ozone-depleting chemicals.

## 21.4 Indoor Air Pollution

We have discussed air pollution in the lower atmosphere and the depletion of stratospheric ozone by chemical emissions that rise from the lower atmosphere to cause depletion of O<sub>3</sub> in the stratosphere that produces a hazard from exposure to ultraviolet radiation from the sun. We turn next to air pollution in our homes, schools, and other buildings that we spend time in.

Indoor air pollution from fires for cooking and heating has affected human health for thousands of years. A detailed autopsy of a 4th-century Native American woman, frozen shortly after death, revealed that she suffered from **black lung disease** from breathing very polluted air over many years. The pollutants included hazardous particles from lamps that burned seal and whale blubber.<sup>48</sup> This same disease has long been recognized as a major health hazard for underground coal miners and has been called “coal miners’ disease.” As recently as the mid-1970s, black lung disease was estimated to be responsible for about 4,000 deaths each year in the United States.<sup>49</sup>

People today spend between 70% and 90% of their time in enclosed places—homes, workplaces, automobiles, restaurants, and so forth—but only recently have we begun to fully study the indoor environment and how pollution of that environment affects our health. The World Health Organization has estimated that as many as one in three people may be working in a building that causes them to become sick, and as many as 20% of public schools in the United States have problems related to indoor air quality. The EPA considers indoor air pollution one of the most significant environmental health hazards people face in the modern workplace.<sup>50</sup>

Hurricane Katrina in 2005 (see Chapter 22) left a great number of people homeless. In response, the Federal Emergency Management Agency (FEMA) provided thousands of trailers for people to live in. That sounded like a great idea until complaints started to come in about health problems of people living in the trailers. A study by the Centers for Disease Control and Prevention (CDC) confirmed that the mobile homes suffered from indoor air pollution by formaldehyde in their construction materials. Formaldehyde is a chemical widely used in the manufacture of building materials, as well as a number of other products. It is considered a probable human carcinogen (a substance that causes or promotes cancer). Common symptoms of exposure to formaldehyde include irritation of the skin, nose, throat, and eyes. People with asthma may be more sensitive to the chemical, and their symptoms may be worse. Since discovery of the high levels of formaldehyde in mobile homes in late 2007, plans have gone

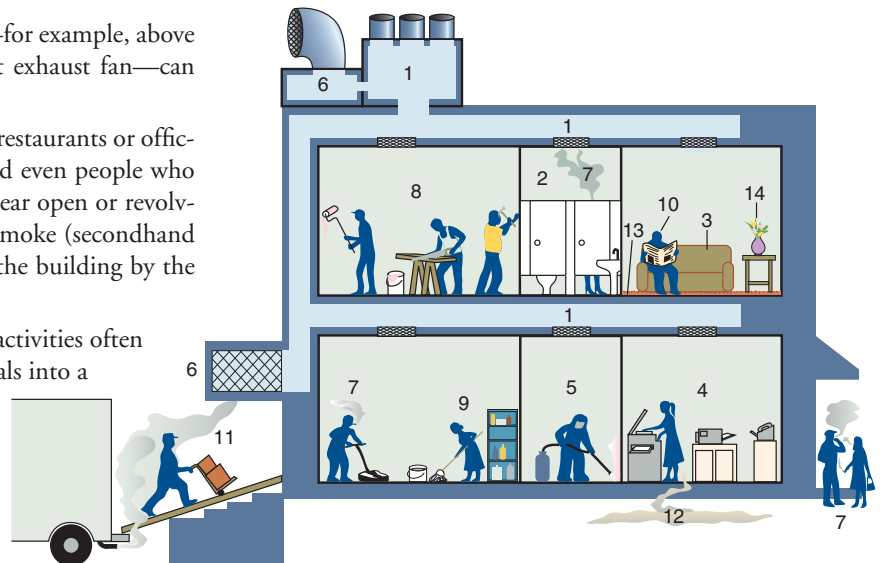
forward to remove the remaining people, particularly those experiencing symptoms of formaldehyde toxicity.<sup>51, 52</sup>

The history of formaldehyde in the mobile homes provided to Katrina victims is a sad legacy of the entire way our federal government responded to Hurricane Katrina and its aftermath. It is also important because it brings to the public consciousness the potential problems of indoor air pollution, which is often more significant than outdoor air pollution.

## Sources of Indoor Air Pollution

The sources of indoor air pollution are incredibly varied (Figure 21.17) and can arise from both human activities and natural processes. Two common pollutants are shown in Figure 21.18. Other common indoor air pollutants, together with guidelines for allowable exposure, are listed in Table 21.6.

1. Heating, ventilation, and air-conditioning systems may be sources of indoor air pollutants, including molds and bacteria, if filters and equipment are not maintained properly. Gas and oil furnaces release carbon monoxide, nitrogen dioxide, and particles.
2. Restrooms may have a variety of indoor air pollutants, including secondhand smoke, and also molds and fungi due to humid conditions.
3. Furniture and carpets often contain toxic chemicals (formaldehyde, organic solvents, asbestos) that may be released over time in buildings.
4. Coffee machines, fax machines, computers, and printers can release particles and chemicals, including ozone ( $O_3$ ), which is highly oxidizing.
5. Pesticides can contaminate buildings with cancer-causing chemicals.
6. Fresh-air intake that is poorly located—for example, above a loading dock or first-floor restaurant exhaust fan—can bring in air pollutants.
7. People who smoke indoors, perhaps in restaurants or offices, pollute the indoor environment, and even people who smoke outside buildings, particularly near open or revolving doors, may cause pollution as the smoke (secondhand smoke) is drawn into and up through the building by the chimney effect.
8. Remodeling, painting, and other such activities often bring a variety of chemicals and materials into a building. Fumes from such activities may enter the building's heating, ventilation, and air-conditioning system, causing widespread pollution.
9. A variety of cleaning products and solvents used in offices and other parts of buildings contain harmful chemicals whose fumes may circulate throughout a building.
10. People can increase carbon dioxide levels; they can emit bioeffluents and spread bacterial and viral contaminants.
11. Loading docks can be sources of organics from garbage containers, of particulates, and of carbon monoxide from vehicles.
12. Radon gas can seep into a building from soil; rising damp (water), which facilitates the growth of molds, can enter foundations and rise up walls.
13. Dust mites and molds can live in carpets and other indoor places.
14. Pollen can come from inside and outside sources.



**FIGURE 21.17** Some potential sources of indoor air pollution.

**Table 21.6 SOURCES, CONCENTRATIONS, OCCURRENCES, AND POSSIBLE HEALTH EFFECTS OF INDOOR AIR POLLUTANTS**

POLLUTANT	SOURCE	GUIDELINES (DOSE OR CONCENTRATIONS)	POSSIBLE HEALTH EFFECTS
Asbestos	Fireproofing; insulation, vinyl floor, and cement products; vehicle brake linings	0.2 fibers/mL for fibers larger than 5 $\mu\text{m}$	Skin irritation, lung cancer
Biological aerosols/ microorganisms	Infectious agents, bacteria in heating, ventilation, and air-conditioning systems; allergens	None available	Diseases, weakened immunity
Carbon dioxide	Motor vehicles, gas appliances, smoking	1,000 ppm	Dizziness, headaches, nausea
Carbon monoxide	Motor vehicles, kerosene and gas space heaters, gas and wood stoves, fireplaces; smoking	10,000 $\mu\text{g}/\text{m}^2$ for 8 hours; 40,000 $\mu\text{g}/\text{m}^3$ for 1 hour	Dizziness, headaches, nausea, death
Formaldehyde	Foam insulation; plywood, particleboard, ceiling tile, paneling, and other construction materials	120 $\mu\text{g}/\text{m}^3$	Skin irritant, carcinogen
Inhalable particulates	Smoking, fireplaces, dust, combustion sources (wildfires, burning trash, etc.)	55-110 $\mu\text{g}/\text{m}^3$ annual; 350 $\mu\text{g}/\text{m}^2$ for 1 hour	Respiratory and mucous irritant, carcinogen
Inorganic particulates			
Nitrates	Outdoor air	None available	
Sulfates	Outdoor air	4 $\mu\text{g}/\text{m}^3$ annual; 12 $\mu\text{g}/\text{m}^3$ for 24 hours	
Metal particulates			
Arsenic	Smoking, pesticides, rodent poisons	None available	Toxic, carcinogen
Cadmium	Smoking, fungicides	2 $\mu\text{g}/\text{m}^3$ for 24 hours	
Lead	Automobile exhaust	1.5 $\mu\text{g}/\text{m}^3$ for 3 months	
Mercury	Old fungicides; fossil fuel combustion	2 $\mu\text{g}/\text{m}^3$ for 24 hours	
Nitrogen dioxide	Gas and kerosene space heaters, gas stoves, vehicular exhaust	100 $\mu\text{g}/\text{m}^3$ annual	Respiratory and mucous irritant
Ozone	Photocopying machines, electrostatic air cleaners, outdoor air	235 $\mu\text{g}/\text{m}^3$ for 1 hour	Respiratory irritant causes fatigue
Pesticides and other semivolatile organics	Sprays and strips, outdoor air	5 $\mu\text{g}/\text{m}^3$ for chlordane	Possible carcinogens
Radon	Soil gas that enters buildings, construction materials, groundwater	4pCi/L	Lung cancer
Sulfur dioxide	Coal and oil combustion, kerosene space heaters, outside air	80 $\mu\text{g}/\text{m}^3$ annual; 365 $\mu\text{g}/\text{m}^3$ for 24 hours	Respiratory and mucous irritant
Volatile organics	Smoking, cooking, solvents, paints, varnishes, cleaning sprays, carpets, furniture, draperies, clothing	None available	Possible carcinogens

Source: N. L. Nagda, H. E. Rector, and M. D. Koontz, 1987; M. C. Baechler et al., 1991; E. J. Bardana Jr. and A. Montaro (eds.), 1997; M. Meeker, 1996; D. W. Moffatt, 1997.





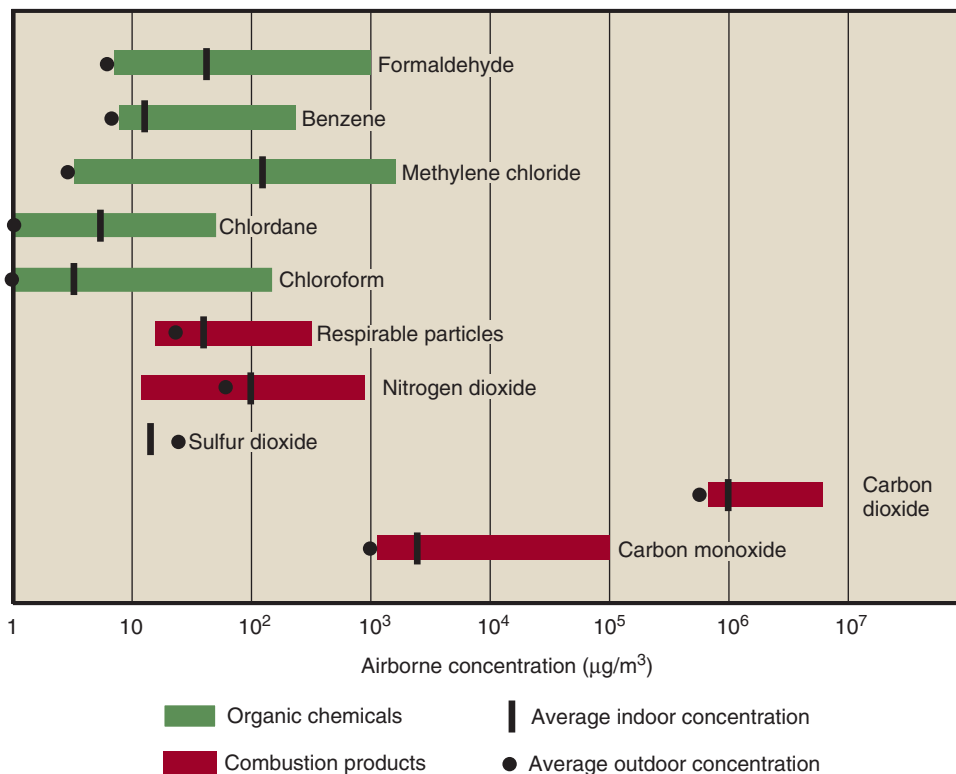
**FIGURE 21.18** (a) This dust mite (magnified about 140 times) is an eight-legged relative of spiders. It feeds on human skin in household dust and lives in materials such as fabrics on furniture. Dead dust mites and their excrement can cause allergic reactions and asthma attacks in some people. (b) Microscopic pollen grains that in large amounts may be visible as a brown or yellow powder. The pollen shown here is from dandelions and horse chestnuts.

Many products and processes used in our homes and workplaces are sources of pollution. Other air pollutants—such as carbon monoxide, particulates, nitrogen dioxide, radon, and carbon dioxide—may enter a building by infiltration, either through cracks and other openings in the foundations and walls or by way of ventilation systems, and are generally found in much higher concentrations indoors than outdoors (see Figure 21.19). The reason is somewhat ironic: The steps we have taken to make our homes and offices energy-efficient often trap pollutants inside. Two of the best ways to conserve energy in homes and other buildings are to increase insulation and decrease infiltration of outside air. But windows that don't open and extensive caulking and weather stripping, while reducing energy consumption, also reduce natural ventilation. With less natural ventilation, we must depend

more on the ventilation systems that are part of heating and air-conditioning systems.

### Pathways, Processes, and Driving Forces

Both natural and human processes create differential pressures that move air and contaminants from one area of a building to another. Areas of high pressure may develop on the windward side of a building, whereas pressure is lower on the leeward, or protected, side. As a result, air is drawn into a building from the windward side. Opening and closing doors produces pressure differentials that cause air to move within buildings. Wind, too, can affect the movement of air in a building, particularly if the structure is leaky.<sup>53</sup>



**FIGURE 21.19** Concentrations of common indoor air pollutants compared with outdoor concentrations plotted on a log scale, that is,  $10^2 = 100$ ;  $10^3 = 1,000$ ,  $10^4 = 10,000$ , etc. (Source: A.V. Nero Jr., "Controlling Indoor Air Pollution," *Scientific American*, 258, no. 5 [1998]: 42–48.)

A **chimney effect (or stack effect)** occurs when the indoor and outdoor temperatures differ. Warm air rises within a building. If the indoor air is warmer than the outdoor air, then as the warmer air rises to the building's upper levels, it is replaced in the lower levels by outdoor air drawn in through various openings—windows, doors, cracks in the foundations and walls. Because air is so fluid, the possible interactions between the driving forces and the building are complex, and the distribution of potential air contaminants and pollutants can be extensive. One outcome is that people in various parts of a building may complain about the air quality even if they are widely separated from each other and from potential sources of pollution.<sup>53</sup>

### ***Heating, Ventilation, and Air-Conditioning Systems***

Heating, ventilation, and air-conditioning systems are designed to provide a comfortable indoor environment. Their design depends on a number of variables, including the activity of people in the building, air temperature and humidity, and air quality. If the heating, ventilation, and air-conditioning system is designed correctly and functions properly, it will maintain a comfortable temperature and adequate ventilation (using outdoor air), and also remove common air pollutants via exhaust fans and filters.<sup>53</sup>

Regardless of the type of system used in a home or other building, its effectiveness depends on the proper design of the equipment for that building, proper installation, and correct maintenance and operating procedures. Indoor air pollution may result if any one of these factors concentrates pollutants from the many possible sources. Filters plugged or contaminated with fungi, bacteria, or other potentially infectious agents can cause serious problems. In addition, as we see later in this chapter, ventilation systems are not generally designed to reduce some types of indoor pollution.<sup>53, 54</sup>

### ***Environmental Tobacco Smoke***

**Environmental tobacco smoke (ETS)**, also known as *secondhand smoke*, comes from two sources: smoke exhaled by smokers and smoke emitted from burning tobacco in cigarettes, cigars, or pipes. People exposed to ETS are referred to as *passive smokers*.<sup>55</sup>

ETS is the most widely known hazardous indoor air pollutant. It is hazardous for the following reasons:<sup>55, 56</sup>

- Tobacco smoke contains several thousand chemicals, many of which are irritants. Examples include NO<sub>x</sub>, CO, hydrogen cyanide, and about 40 carcinogenic chemicals.
- Studies of nonsmoking workers exposed to ETS found that they have impaired airway functions comparable to that caused by smoking up to ten cigarettes a day. They suffer more illnesses, such as coughs, eye irritation, and colds, and lose more work time than those not exposed to ETS.
- In the United States, about 3,000 deaths from lung cancer and 40,000 deaths from heart disease a year are thought to be associated with ETS.

The number of smokers in the United States has declined, but there are still about 40 million. The rate is higher in the developing world, where health warnings are few or nonexistent. Smoking is extremely addictive because tobacco contains nicotine, a highly addictive substance. Nevertheless, education and social pressure have persuaded some thoughtful people to quit smoking and to encourage others to keep trying.

### ***Radon Gas***

It has become apparent over the past few decades that radon gas—colorless, odorless, and tasteless—may be a significant environmental health problem in the United States.<sup>57, 58</sup> **Radon** comes from natural processes, not from human activities. It is a naturally occurring radioactive gas that is a product of the radioactive-decay chain from uranium to stable lead. Radon-222, which has a half-life of 3.8 days, is emitted during the radioactive decay of radium-226. Radon decays with emission of an alpha particle to polonium-218, which has a half-life of approximately 3 minutes. (The discussion of radiation, radiation units, radiation doses, and health problems related to radiation in Chapter 17 will help you understand the following discussion.)

**Geology and radon gas.** The concentration of radon gas that reaches the surface of the Earth and thus can enter our dwellings is related to the concentration of radon in the rocks and soil, as well as the efficiency of the transfer processes from the rocks or soil to the surface. Some regions in the United States contain bedrock with an above-average natural concentration of uranium. A large area that includes parts of Pennsylvania, New Jersey, and New York—an area known as the Reading Prong—has many homes with elevated radon concentrations.<sup>57</sup> Such areas have also been identified in a number of other states, including Florida, Illinois, New Mexico, South Dakota, North Dakota, Washington, and California.

**How dangerous is radon gas?** Many people today are worried about radon in their homes because studies indicate that exposure to elevated concentrations increases the risk of lung cancer, and that the risk increases with the level and duration of exposure and also certain habits, such as smoking.<sup>58</sup> Radon, combined with smoking, is thought to produce a synergistic effect that is particularly hazardous. One estimate is that the combination of exposure to radon gas and tobacco smoke is 10 to 20 times more hazardous than exposure to either pollutant by itself.<sup>58</sup>

The Environmental Protection Agency (EPA) estimates that 14,000 lung cancer deaths per year in the United States are related to exposure to radon and its daughter products (products that result from its radioactive decay), primarily polonium-218. (The estimate actually ranges from 7,000 to 30,000.) By comparison, approximately 140,000 people die of lung cancer in the United States each year. If these estimates are correct—and they are controversial—approximately 10% of the lung cancer deaths in the United States can be attributed to radon. Exposure to radon has also been linked to other forms of cancer, such as melanoma (a deadly skin cancer) and leukemia, but, again, such linkages are highly controversial.<sup>59, 60</sup> The link between radon and cancer is mostly based on studies of uranium miners, a group of people exposed to high concentrations of radon in mines.

If the estimated risks from radon are anywhere close to the actual risk, then the hazard is a large one. The U.S. Surgeon General has stated that “indoor radon gas is a national health problem.” The risks posed by radon are thought to be hundreds of times higher than risks from outdoor pollutants in air and water. Such pollutants are generally regulated to reduce the risk of premature death and disease to less than 0.001%. Risks from some indoor pollutants, such as organic chemicals, may be as high as 0.1%.<sup>61</sup> These risks still are very small compared with the risk for radon. For example, people who live in homes for about 20 years with an average concentration of radon of about 25 pCi/L are estimated to have a 1 to 2% chance of contracting lung cancer.<sup>58, 61</sup>

#### *How does radon enter homes and other buildings?*

Radon enters homes and other buildings in three main ways: (1) It migrates up from soil and rock into basements and lower floors; (2) dissolved in groundwater, it is pumped into wells and then into homes; and (3) radon-contaminated materials, such as building blocks, are used in construction. It is difficult to estimate how many homes in the United States may have elevated concentrations of radon. The EPA estimates that about 7% have elevated radon levels and recommends that all homes and schools be tested. The test is simple and inexpensive.

## Symptoms of Indoor Air Pollution

People living or working in particular indoor environments may react to pollutants in different ways: Some are particularly susceptible to indoor air pollution; some report different symptoms from the same pollutant; and some report symptoms that turn out not to stem from air pollution.

A wide variety of symptoms can result from exposure to indoor air pollutants (see Table 21.7). Some chemical pollutants can cause nosebleeds, chronic sinus infections, headaches, and irritation of the skin or eyes, nose, and throat. More-serious problems include loss of balance and memory, chronic fatigue, difficulty in speaking, and allergic reactions, including asthma.

#### *Sick Buildings*

An entire building can be considered “sick” because of environmental problems. There are two types of “sick” buildings:

- Buildings with identifiable problems, such as toxic molds or bacteria known to cause disease. The diseases are known as *building-related illnesses* (BRI).
- Buildings with **sick building syndrome (SBS)**, where the symptoms people report cannot be traced to any known cause.

A sick building’s indoor environment appears to be unhealthy in that a number of people in the building report adverse health effects that they believe are related to the amount of time they spend in the building. Their complaints may range from funny odors to more-serious symptoms, such as headaches, dizziness, nausea, and so forth. In addition, an unusual number of people in the building may feel sick, or may have contracted a serious disease, such as cancer.<sup>62-64</sup>

In many cases, it is difficult to establish what may be causing the sick building syndrome. It has sometimes been found to be related to poor management and low worker morale, rather than to toxins in the building. When the occupants of a building report adverse health effects and a study does not detect the cause, a number of other things may be happening:<sup>53</sup>

## 21.5 Controlling Indoor Air Pollution

As much as \$250 billion per year might be saved by decreasing illnesses and increasing productivity through improving the work environment.<sup>50</sup> A good starting point would be environmental legislation requiring certain indoor air quality standards. At a minimum, these should include increasing the inflow of fresh air through ventilation. In Europe, systems of filters and pumps in many office buildings circulate air three times as frequently as is typical in the United States. Many building codes in Europe require that workers have access to fresh air (windows) and natural light. Unfortunately, no similar codes

Table 21.7 SOME SYMPTOMS OF INDOOR AIR POLLUTION

SYMPTOMS	ETS <sup>a</sup>	COMBUSTION PRODUCTS <sup>b</sup>	BIOLOGIC POLLUTANTS <sup>c</sup>	VOCS <sup>d</sup>	HEAVY METALS <sup>e</sup>	SBS <sup>f</sup>
<b>Respiratory</b>						
Inflammation of mucous membranes of the nose, nasal congestion	Yes	Yes	Yes	Yes	No	Yes
Nosebleed	No	No	No	Yes	No	Yes
Cough	Yes	Yes	Yes	Yes	No	Yes
Wheezing, worsening asthma	Yes	Yes	No	Yes	No	Yes
Labored breathing	Yes	No	Yes	No	No	Yes
Severe lung disease	Yes	Yes	Yes	No	No	Yes
<b>Other</b>						
Irritation of mucous membranes of eyes	Yes	Yes	Yes	Yes	No	Yes
Headache or dizziness	Yes	Yes	Yes	Yes	Yes	Yes
Lethargy, fatigue, malaise	No	Yes	Yes	Yes	Yes	Yes
Nausea, vomiting, anorexia	No	Yes	Yes	Yes	Yes	No
Cognitive impairment, personality change	No	Yes	No	Yes	Yes	Yes
Rashes	No	No	Yes	Yes	Yes	No
Fever, chills	No	No	Yes	No	Yes	No
Abnormal heartbeat	Yes	Yes	No	No	Yes	No
Retinal hemorrhage	No	Yes	No	No	No	No
Muscle pain, cramps	No	No	No	Yes	No	Yes
Hearing loss	No	No	No	Yes	No	No
<sup>a</sup> Environmental tobacco smoke.						
<sup>b</sup> Combustion products include particles, NO <sub>x</sub> , CO, and CO <sub>2</sub> .						
<sup>c</sup> Biologic pollutants include molds, dust mites, pollen, bacteria, and viruses.						
<sup>d</sup> Volatile organic compounds, including formaldehyde and solvents.						
<sup>e</sup> Heavy metals include lead and mercury.						
<sup>f</sup> Sick building syndrome.						
Source: Modified from American Lung Association, Environmental Protection Agency, and American Medical Association, "Indoor Air Pollution—An introduction for Health Professionals," 523-217/81322 (Washington, D.C.: GPO, 1994).						

exist for U.S. workers, and many buildings use central air-conditioning with windows permanently sealed.<sup>50</sup>

You might think that heating, ventilating, and air-conditioning systems, operating properly and well maintained, will ensure good indoor air quality, but in fact these systems are not designed to maintain all aspects of air quality. For example, commonly used ventilation systems do not generally reduce radon gas. Other strategies include source removal, source modification, and air cleaning.<sup>62</sup>

Education also plays an important role in developing strategies to reduce indoor air pollution; it enables people to make informed decisions about exposure to chemicals, such as paints and solvents, and about strategies to avoid potentially hazardous conditions in the home and workplace.<sup>62</sup> At one level, this may involve deciding not to install unvented or poorly vented appliances. A surprising (and tragic) number of people are killed each year by carbon monoxide poisoning due to



poor ventilation in homes, campers, and tents. Educated people are also more aware of their legal rights with respect to product liability and safety.

## Making Homes and Other Buildings Radon Resistant

Protecting new homes from potential radon problems is straightforward and relatively inexpensive. It is also easy to upgrade an older home to reduce radon. The techniques vary according to the type of foundation the structure has. The basic strategy is to prevent radon from entering a home (usually sealing entry points) and ensure that radon is removed from the site (this generally involves designing a ventilation system).<sup>65, 66</sup>

## Designing Buildings to Minimize Indoor Air Pollution

There is a movement under way in the United States and the world to create buildings specifically designed to provide a healthful indoor environment for their occupants. The basic objectives of the design are to minimize indoor air pollutants; ensure that fresh air is supplied and circulated; manage moisture to avoid problems such as mold; reduce energy use; use materials whose origin is environmentally benign and can be recycled, as much as possible; create as pleasing a working environment as possible; use vegetation planted on roofs and wherever else possible to take up carbon dioxide, release oxygen, and add to the general pleasantness of the working environment.



## CRITICAL THINKING ISSUE

### Should Carbon Dioxide Be Regulated along with Other Major Air Pollutants?

The six common pollutants, sometimes called the *criteria pollutants*, are ozone, particulate matter, lead, nitrogen dioxide, carbon monoxide, and sulfur dioxide. These pollutants have a long history with the EPA, and major efforts have been made to reduce them in the lower atmosphere over the United States. This effort has been largely successful—all of them have been significantly reduced since 1990.

In 2009, the EPA suggested that we add carbon dioxide to this list. Two years earlier, the U.S. Supreme Court had ordered the EPA to make a scientific review of carbon dioxide as an air pollutant that could possibly endanger public health and welfare. Following that review, the EPA announced that greenhouse gases pose a threat to public health and welfare. This proclamation makes it possible that greenhouse gases, especially carbon dioxide, will be regulated by the Clean Air Act, which regulates most other serious air pollutants. The EPA's conclusion that greenhouse gases harm or endanger public health and welfare is based primarily on the role these gases play in climate change. The analysis states that the impacts include, but are not limited to, increased drought that will impact agricultural productivity; more intense rainfall, leading to a greater flood hazard; and increased frequency of heat waves that affect human health.

The next step in adding carbon dioxide and other greenhouse gasses, such as methane, to the list of pollutants regulated by the EPA will be a series of public hearings and feedback from a variety of people and agencies. Some people oppose listing

carbon dioxide as an air pollutant because, first of all, it is a nutrient and stimulates plant growth; and, second, it does not directly affect human health in most cases (the exception being carbon dioxide emitted by volcanic eruption and other volcanic activity, which can be extremely toxic).

#### Critical Thinking Questions

After going over the information concerning global climate change and the role of carbon dioxide in causing change, consider the following questions:

1. Do you think carbon dioxide, along with other greenhouse gases, should be controlled under the Clean Air Act? Why? Why not?
2. Assuming carbon dioxide and other greenhouse gases are to be controlled under the Clean Air Act, what sorts of programs might be used for such control? For example, the control of sulfur dioxide was primarily through a cap-and-trade program where the total amount of emissions were set, and companies bought and sold shares of allowed pollution up to the cap.
3. If the United States can curtail emissions of carbon dioxide under the Clean Air Act, how effective will this be in, say, reducing the global concentration of carbon dioxide to about 350 parts per million given what other countries are likely to do in the future with respect to emissions and given that the concentration today is about 390 parts per million?

## SUMMARY

- There are two main kinds of air pollutants: primary and secondary. Primary pollutants are emitted directly into the air: particulates, sulfur dioxide, carbon monoxide, nitrogen oxides, and hydrocarbons. Secondary pollutants are produced through reactions between primary pollutants and other atmospheric compounds. Ozone is a secondary pollutant that forms over urban areas through photochemical reactions between primary pollutants and natural atmospheric gases.
- There are also two kinds of sources: stationary and mobile. Stationary sources have a relatively fixed position and include point sources, area sources, and fugitive sources.
- Meteorological conditions—in particular, restricted circulation in the lower atmosphere due to temperature inversion—greatly determine whether or not polluted air is a problem in an urban area.
- Pollution-control methods are tailored to specific pollution sources and types and vary from settling chambers for particulates to scrubbers that remove sulfur before it enters the atmosphere.
- Emissions of air pollutants in the United States are decreasing, but in large urban areas of developing countries it remains a serious problem.
- The concentration of atmospheric ozone has been measured for more than 70 years. Concentrations in the stratosphere have declined since the mid-1970s, allowing more ultraviolet radiation to reach the lower atmosphere, where it can damage living things.
- In 1974, Mario Molina and F. Sherwood Rowland hypothesized that stratospheric ozone might be depleted by emissions of chlorofluorocarbons (CFCs) into the lower atmosphere. Major features of the hypothesis are that CFCs are very stable and have a long residence time in the atmosphere. Eventually they reach the stratosphere, where they may be destroyed by solar ultraviolet radiation, releasing chlorine. The chlorine may then enter into a catalytic chain reaction that depletes ozone in the stratosphere.
- Banning chemicals that deplete stratospheric ozone is a step in the right direction. However, millions of tons of these are now in the lower atmosphere and working their way up, so even if all production, use, and emission of these chemicals stopped today, the problem would continue for a long time. The good news is that concentrations of CFCs in the atmosphere have apparently peaked and are now static or in slow decline.
- Possible sources of indoor air pollution are construction materials, furnishings, types of equipment used for heating and cooling, as well as natural processes that allow gases to seep into buildings.
- Indoor concentrations of air pollutants are generally greater than outdoor concentrations of the same pollutants.
- Ventilation is commonly used to control indoor air pollution, but tighter construction impedes ventilation, and many popular ventilation systems do not reduce certain types of indoor air pollutants.
- The most common natural process that affects interior air quality is the “chimney” or “stack effect” that occurs when the indoor and outdoor environments differ in temperature.
- People react to indoor air pollution in different ways, and so reported symptoms may vary.
- In some cases, reported symptoms have nothing to do with air pollution.
- Controlling indoor air pollution involves several strategies, including ventilation, source removal, source modification, and air-cleaning equipment, as well as education.

## REEXAMINING THEMES AND ISSUES



### Human Population

Population growth will exacerbate air pollution problems. As the number of people increases, so does the use of resources, many of which are related to emissions of air pollutants. This may be partially offset in developed countries, where the per capita emissions of air pollutants have been reduced in recent years.



### Sustainability

Ensuring that future generations inherit a quality environment is an important objective of sustainability. Thus, it is vital that we develop technology that minimizes air pollution.



## Global Perspective

Atmospheric processes and atmospheric pollution occur on regional and global scales. Pollutants emitted into the atmosphere at a particular site may join the global circulation pattern and spread throughout the world, and pollutants emitted from urban or agricultural areas may be dispersed to pristine areas far removed from human activities. Therefore, an understanding of global atmospheric processes is critical to finding solutions to many air pollution problems, including acid deposition.



## Urban World

Cities and urban corridors are sites of intense human activity, and many of these activities contribute to air pollution. Some large cities have such severe air pollution problems that the health and lives of people are being affected.



## People and Nature

Although we think of nature as unspoiled, in reality nature can be toxic. This is especially true with regard to air pollution—for example, the vast majority of particulates and carbon monoxide are generated by volcanic eruption and wildfire. Even hydrocarbons have local sources, such as seeps, which, in areas such as offshore Goleta, California, emit a significant amount of hydrocarbons that contribute to smog.



## Science and Values

The science and technology necessary to reduce air pollution are well known; what we do with these tools involves a value judgment. It is clear that people value a high-quality environment, and clean air is at the top of the list. The developed countries have an obligation to take a leadership role in finding ways to use resources while minimizing air pollution. Of particular importance is finding methods and technologies that will allow for reducing air pollution while stimulating economies. What is considered waste in one part of the urban-industrial complex may be used as resources in another part. This idea is at the heart of what is sometimes called industrial ecology. The discovery, understanding, and management of ozone-depleting chemicals is an environmental success, reflecting the value of the environment.

## KEY TERMS

acid rain	469	global dimming	468	secondary pollutants	464
air toxics	471	green building	462	sick building syndrome (SBS)	491
atmospheric inversion	474	mobile sources	463	smog	473
black lung disease	486	ozone (O <sub>3</sub> )	481	stationary sources	463
chimney effect (or stack effect)	490	ozone shield	481	sulfurous smog	473
chlorofluorocarbons (CFCs)	483	photochemical smog	473	Ultraviolet (UV) Index	485
criteria pollutants	465	primary pollutants	464	ultrafine particles	467
environmental tobacco smoke (ETS)	490	radon	490		
		scrubbing	478		

## STUDY QUESTIONS

1. Since the amount of pollution emitted into the air is a very small fraction of the total material in the atmosphere, why do we have air-pollution problems?
2. What are the differences between primary and secondary pollutants?
3. Carefully examine Figure 21.11, which shows a column of air moving through an urban area, and Figure 21.7, which shows relative concentrations of pollutants that develop on a typical warm day in Los Angeles. What linkages between the information in these two figures might be important in trying to identify and learn more about potential air pollution in an area?
4. Why is acid deposition a major environmental problem, and how can it be minimized?
5. Why will air-pollution abatement strategies in developed countries probably be much different in terms of methods, process, and results than air-pollution abatement strategies in developing countries?
6. In a highly technological society, is it possible to have 100% clean air? Is it likely?
7. Study Figure 21.14 carefully and discuss how the information in parts (a) and (b) are linked and related to the chapter in general. Apply Critical Thinking skills.
8. Discuss the processes responsible for stratospheric ozone depletion. Which are most significant? Where? Why?
9. What are some of the common sources of indoor air pollutants where you live, work, or attend classes?
10. Develop a research plan to complete an audit of the indoor air quality in your local library. How might that research plan differ from a similar audit for the science buildings on your campus?
11. What do you think about the concept of sick building syndrome? If you were working for a large corporation and a number of employees said they were getting sick and listed a series of symptoms and problems, how would you react? What could you do? Play the role of the administrator and develop a plan to look at the potential problem.
12. Suppose that next year our understanding of ozone depletion is changed by the discovery that concentrations of stratospheric ozone have natural cycles and that lower concentrations in recent years have resulted not from our activities but from natural processes. How would you put all the information in this chapter into perspective? Would you think science had let you down?

## FURTHER READING

- Boubel, R.W., D.L. Fox, D.B. Turner, and A.C. Stern, *Fundamentals of Air Pollution*, 4th ed.** (New York: Academic, 2008). A thorough book covering the sources, mechanisms, effects, and control of air pollution.
- Brenner, D.J., *Radon: Risk and Remedy*** (New York: Freeman, 1989). A wonderful book about the hazard of radon gas. It covers everything from the history of the problem to what was happening in 1989, as well as solutions.
- Christie, M., *The Ozone Layer: A Philosophy of Science Perspective*** (Cambridge: Cambridge University Press, 2000). A complete look at the history of the ozone hole, from the first discovery of its existence to more recent studies of the hole over Antarctica.
- Hamill, P., and O.B. Toon.** "Polar Stratospheric Clouds and the Ozone Hole," *Physics Today* 44, no. 12 (1991): 34–42. A good review of the ozone problem and important chemical and physical processes related to ozone depletion.
- Reid, S., *Ozone and Climate Change: A Beginner's Guide*** (Amsterdam: Gordon & Breach Science Publishers, 2000). A look at the science behind the ozone hole and future predictions, written for a general audience to make the science understandable.
- Rowland, F.S.** "Stratospheric Ozone Depletion by Chlorofluorocarbons." *AMBIO* 19, no. 6–7 (1990): 281–292. An excellent summary of stratospheric ozone depletion, it discusses some of the major issues.
- Wang, L., "Paving out Pollution," *Scientific American*, February 2002, p. 20.** Discussion of an innovative approach to reducing air pollution.