

AIR POLLUTION





CHAPTER

13

A severe air pollution episode at Kuala Lumpur, Malaysia, on August 10, 2005.
(Photo by Viviane Moos/CORBIS.)

Air pollution and meteorology are linked in two ways. One concerns the influence that weather conditions have on the dilution and dispersal of air pollutants. The second connection is the reverse and deals with the effect that air pollution has on weather and climate. The first of these associations is examined in this chapter. The second and equally important relationship is discussed in Chapter 14 and is the focus of several sections and special-interest boxes.*

In Chapter 4 the concept of atmospheric stability was introduced. You learned that the stability of air plays a significant role in controlling many aspects of daily weather. In this chapter you will see that atmospheric stability is closely related to urban air pollution. Air quality is not just a function of the quantity and types of pollutants emitted into the air, it is also closely linked to the atmosphere's ability to disperse these noxious substances. Dispersal, in turn, is related to the stability of the atmosphere.

Air pollution is a continuing threat to our health and welfare. An average adult male requires about 13.5 kilograms

(30 pounds) of air each day compared with about 1.2 kilograms (2.6 pounds) of food and 2 kilograms (4.4 pounds) of water. The cleanliness of air, therefore, should certainly be as important to us as the cleanliness of our food and water.

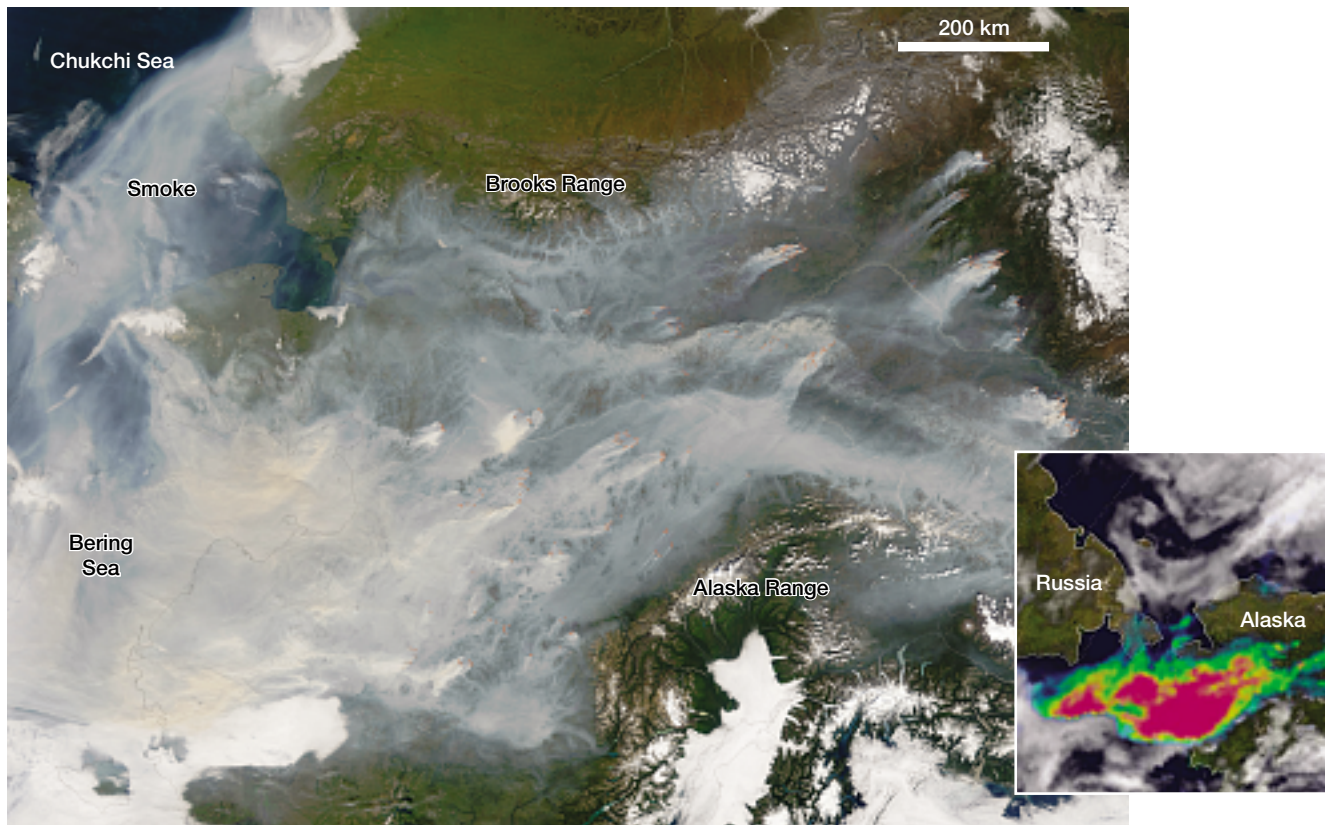
A Brief Historical Perspective

Air is never perfectly clean. Many natural sources of air pollution have always existed (Figure 13–1). Ash from volcanic eruptions, salt particles from breaking waves, pollen and spores released by plants, smoke from forest and brushfires, and windblown dust are all examples of “natural air pollution” (Figure 13–2). Ever since people have been on Earth, however, they have added to the frequency and intensity of some of these natural pollutants, especially the last two. For example, the dust storm in Figure 13–3 occurred when strong winds raised dry soil from plowed farm fields.

With the discovery of fire came an increased number of accidental as well as intentional burnings. Even today, in many parts of the world, fire is used to clear land for agricultural purposes (the so-called slash-and-burn method), filling the air with smoke and reducing visibility. When people clear the land of its natural vegetative cover for whatever purpose, soil is exposed and blown into the air. Yet when we consider the air in a modern-day industrial city, these

*See Box 3–4 “How Cities Influence Temperature” and Box 13–2 “Air Pollution Changes the Climate of Cities.” In addition, see the section on “Inadvertent Weather Modification: Urban-Induced Precipitation,” in Chapter 5 and the discussion of “Country Breeze” in Chapter 7.

FIGURE 13-1 During the third week of August 2005, high pressure existed over Alaska. Large areas of high pressure are associated with conditions that inhibit the dispersal of pollutants. Unfortunately, the high pressure coincided with a period of significant forest-fire activity. For several days smoke piled up, leading to hazardous air-quality warnings. The inset image shows smoke measurements on August 15, 2005. Smoke concentrations are shown as an aerosol index that ranges from shades of blue (little or no smoke) to dull red (thick smoke). (NASA images)



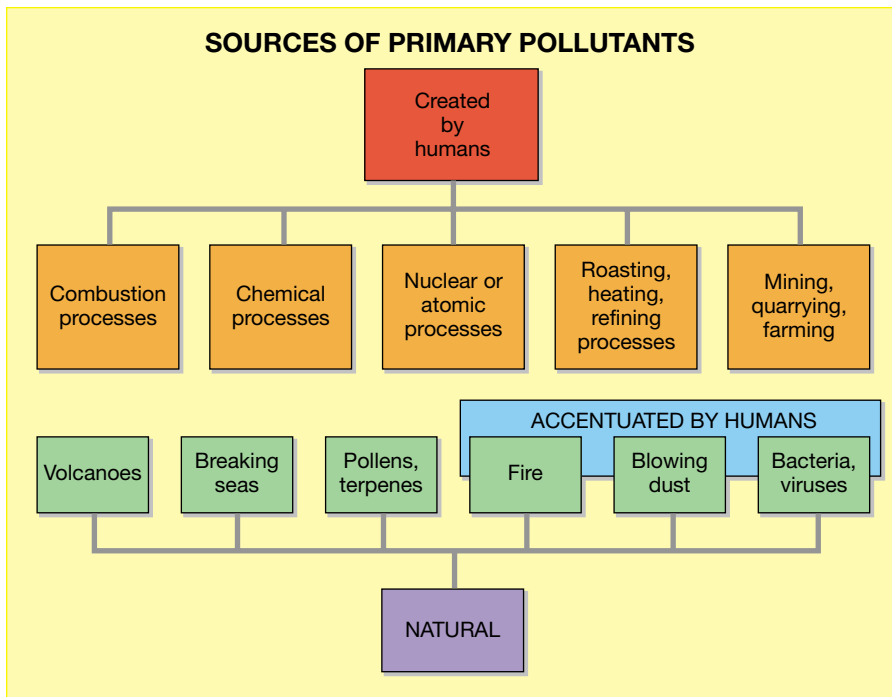


FIGURE 13-2 Sources of primary pollution. (After Reid A. Bryson and John E. Kutzbach, *Air Pollution, Commission on College Geography Resource Paper No. 6, Figure 2, p. 8.*)

human-accentuated forms of pollution, although significant, may seem minor by comparison.

Air Pollution: Not a New Problem

Although some types of air pollution are relatively recent creations, others have been around for centuries. Smoke pollution, for example, plagued London for centuries. Because of the odor and smoke produced by the burning of coal, King Edward I made the following proclamation in 1300: “Be it known to all within the sound of my voice, whosoever shall be found guilty of burning coal shall suffer the loss of his head.” Unfortunately, one Londoner did not heed the king’s warning and paid the extreme price for his misdeed. As far as is known, however, this is the only case of capital punishment resulting from an air-pollution violation!

The ban on burning coal led to the use of an alternative fuel—wood. The extensive wood burning soon dramatically reduced English forests, and coal consumption again increased despite royal disapproval. Thus, in 1661, when John Evelyn wrote *Fumifugium, or the Inconvenience of Aer and Smoak of London Dissipated, together with some Remedies Humbly Proposed*, the problem of foul air still plagued Londoners. In his book, Evelyn noted that a traveler, although many miles from London, “sooner smells than sees the city to which he repairs.” In fact, London continued to have severe air-pollution problems well into the twentieth century. It was only after a devastating smog disaster in 1952 that truly decisive action was taken to clean the air.

London, however, has not monopolized the air pollution scene. With the coming of the Industrial Revolution, many cities began to experience “big-time” air pollution. Instead of just simply accelerating natural sources, people found many new ways to pollute the air (Figure 13–2) and many new things with which to pollute it. In the mid- to late nineteenth

century, the population of many American and European cities swelled as people sought work in the growing numbers of new foundries and steel mills. As a result, the urban environment became increasingly fouled by the fumes of industry. In *Hard Times*, Charles Dickens vividly describes the scene in a late-nineteenth-century factory town:

It was a town of machinery and tall chimneys out of which interminable serpents of smoke trailed themselves forever and ever, and never got uncoiled. It had a black canal in it, and a river that ran purple with ill-smelling dye.

FIGURE 13-3 An example of natural air pollution that has been accentuated by human activities. This dust storm near Elkhart, Kansas, in May 1937 occurred because the soil was plowed and vulnerable to strong winds. It was because of storms like this that portions of the Great Plains were called the Dust Bowl in the 1930s. (Photo reproduced from the collection of the Library of Congress)



It is clear that poor air quality was not the only environmental pollution that plagued these places! However, it should be noted that the rapid rise in urban air pollution was not necessarily viewed with great alarm. Rather, chimneys belching forth smoke and soot were a symbol of growth and prosperity (Figure 13–4). The following quotation from an 1880 speech by the well-known lawyer and orator Robert Ingersoll, for example, is reported to have elicited great cheering and cries of “Good! Good!” from the audience: “I want the sky to be filled with the smoke of American industry and upon that cloud of smoke will rest forever the bow of perpetual promise. That is what I am for.” With the rapid growth of the world’s population and accelerated industrialization, the quantities of atmospheric pollutants increased drastically.

Students Sometimes Ask...

What is haze?

Haze is a reduction in visibility caused when light encounters atmospheric particulate matter and gases. Some light is absorbed by the particles and gases, and some is scattered away before it reaches an observer. More pollutants mean more absorption and scattering of light, which limits the distance we can see and can also degrade the color, clarity, and contrast of what we can see. Visibility impairment is one of the most obvious effects of air pollution. It not only occurs in urban areas but is a serious issue in many of our best-known national parks and wilderness areas. The same fine particles that are linked to serious health problems can also significantly affect our ability to see.

Some Historic Episodes

The first major air-pollution disaster to be studied in depth occurred in the Meuse valley of Belgium. Here for five days in December 1930, a blanket of smog hung in the valley, killing 63 people and causing 6000 to become ill. Since the 1930s, many air-pollution episodes have demonstrated the devastating effect that dirty air can have on life and property. In October 1948 Donora, Pennsylvania, had such an experience. The grime that settled from the air coated houses, streets, and sidewalks, so that pedestrians and autos actually left distinct footprints and tire tracks. Almost 6000 of the town’s 14,000 inhabitants became ill, and 20 died.

One of the most tragic air pollution episodes ever occurred in London in December 1952 (see Box 13–1). More than 4000 people died as a result of this five-day ordeal. The people who suffered most were those with respiratory and heart problems, primarily the elderly. Extreme air pollution darkened London again in 1953 and 1962 and affected New York City in 1953, 1963, and 1966. Since these events, the passage of legislation, the development of regulations and standards, and the advancement of control technology have reduced the frequency and severity of such episodes. Nevertheless, health authorities are equally concerned about the slow and subtle effects on our lungs and other organs of air-pollution levels that are much lower but that are present every day, year after year.

Sources and Types of Air Pollution

Air pollutants are airborne particles and gases that occur in concentrations that endanger the health and well-being of organisms or disrupt the orderly functioning of the

FIGURE 13-4 Stacks belching smoke and soot such as these were once a sign of economic prosperity. This is a view of a steel mill in East Chicago, Indiana, in the 1950s. (Photo by Art Shay/Life & Time Pictures/Getty Images)



TABLE 13-1 Air-pollution source categories

Category	Comments
Point sources	Includes factories and electric power plants
Mobil sources	Not only includes cars and trucks but also lawn mowers, airplanes, and anything else that moves and pollutes the air
Biogenic sources	This category includes all nonanthropogenic (not human-generated) sources. Examples include trees and other vegetation, microbial activity, oil and gas seeps, etc.
Area sources	Small and individual sources such as dry cleaners and degreasing operations.

environment. Pollutants can be grouped into two categories: primary and secondary. **Primary pollutants** are emitted directly from identifiable sources (Table 13–1). They pollute the air immediately upon being emitted. **Secondary pollutants**, in contrast, are produced in the atmosphere when certain chemical reactions take place among primary pollutants. The chemicals that make up smog are important examples. In some cases the impact of primary pollutants on human health and the environment is less severe than the effects of the secondary pollutants they form.

Primary Pollutants

Figure 13–5 depicts the major primary pollutants and the sources that produce them. When the various sources are examined, the significance of the transportation category is obvious. It accounts for nearly half of our pollution (by weight). In addition to highway vehicles, this category includes trains, ships, and airplanes. Still, the tens of millions of cars and trucks on U.S. roads are, without a doubt, the greatest contributors in this category (Figure 13–6). What follows is a brief survey and description of the major primary pollutants.

Particulate Matter. *Particulate matter* (PM) is the general term used for a mixture of solid particles and liquid droplets found in the air. Some particles are large or dark enough to be seen as soot or smoke. Others are so

small they can be detected only with an electron microscope. These particles, which come in a wide range of sizes (*fine* particles are less than 2.5 micrometers in diameter, and coarser-size particles are larger than 2.5 micrometers), originate from many different stationary and mobile sources as well as from natural sources. Fine particles (PM_{2.5}) result from fuel combustion from motor vehicles, power generation, and industrial facilities, as well as from residential fireplaces and wood stoves. Coarse particles (PM₁₀) are generally emitted from sources such as vehicles traveling on unpaved roads, materials handling, and crushing and grinding operations, as well as wind-blown dust. Some particles are emitted directly from their sources, such as smokestacks and cars. In other cases, gases such as sulfur dioxide interact with other compounds in the air to form fine particles.

Particulates are frequently the most obvious form of air pollution because they reduce visibility and leave deposits of dirt on the surfaces with which they come in contact. In addition, particulates may carry any or all of the other pollutants dissolved in or absorbed on their surfaces.

Originally, total suspended particulate (TSP) was the indicator used to represent this category. It included all particles up to 45 micrometers in diameter. In 1987, the U.S. Environmental Protection Agency (EPA) set new standards that related only to particles smaller than 10 micrometers (identified as PM₁₀). Ten years later, in 1997, the EPA

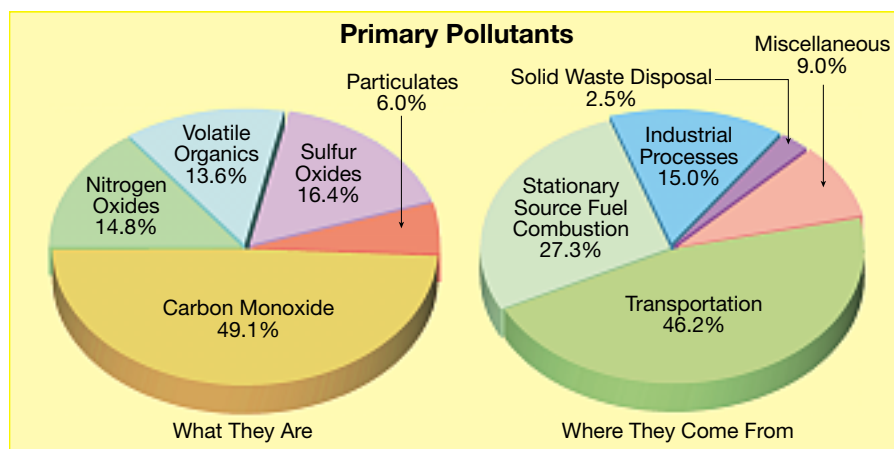


FIGURE 13-5 Major primary pollutants and their sources. Percentages are calculated on the basis of weight. (Data from the U.S. Environmental Protection Agency)



BOX 13-1

Atmospheric Hazard: The Great Smog of 1952

For centuries the fogs of Britain's major cities were polluted with smoke. London was especially well known for its poor air quality. In the early 1800s London's smoke-laden fog came to be known as a "London particular" (that is, a London characteristic). In 1853 Charles Dickens used the term in *Bleak House* and provided graphic descriptions of London's foul air in several of his novels.

One of London's most infamous air-pollution episodes occurred over a five-day span in December 1952. From December 5–9 acrid yellow smog shrouded the city, bringing premature death to thousands and inconvenience to millions (Figure 13–A). What conditions were responsible for this extraordinary event? As

in practically all major air-pollution episodes, it was a combination of emissions and meteorological circumstances.

The weather was unusually cold, and the people of London were burning large quantities of coal to warm their homes. The smoke that poured from these chimneys as well as from the chimneys of London's many factories was not dispersed but rather accumulated in a shallow zone of very stable air. The "lid" for this trap was a substantial temperature inversion associated with a high-pressure center that had become established over the southern British Isles.*

*The link between temperature inversions and air pollution episodes is explored in greater detail later in the chapter.

Fog developed during the day on Friday, December 5. It was not especially dense at first, and it had a smoky character. Beneath the well-developed temperature inversion, a very light wind stirred the saturated air to create a fog layer that was 100 to 200 meters thick. With nightfall came sufficient radiation cooling to produce an even denser fog. Of course, more and more smoke continued to collect in the saturated air. Visibility dropped to just a few meters in many areas. On Saturday, December 6, the weak winter Sun could not "burn away" the fog. The foul yellow mixture of smoke and fog got to be so thick that night that pedestrians could not find their way, even in familiar surroundings. The smog was so thick



FIGURE 13-A London's infamous Great Smog of 1952 persisted for five days and was responsible for thousands of deaths. (Photo by Getty Images, Inc.)

that people could not see their own feet!

Winds did not sweep away the foul air until Tuesday, December 9. In central London the visibility remained below 500 meters continuously for 114 hours and below 50 meters for 48 hours straight. At Heathrow Airport the visibility was less than 10 meters for 48 hours beginning on the morning of December 6.

The huge quantities of pollutants released into the atmosphere during the event were estimated to be as follows: 1000 tons of smoke particles, 2000 tons of carbon dioxide, 140 tons of hydrochloric acid, and 14 tons of fluorine compounds. Moreover, 370 tons of sulfur dioxide were converted into 800 tons of sulphuric acid.

This infamous episode of December 1952 came to be known as “The Great Smog.” Others called it “The

Big Smoke.” Even in a city where “pea soup” fogs were relatively common, this is a legendary event. No matter what name is used, this exceptional air-pollution episode is commonly viewed as the watershed event that gave rise to modern air-pollution control in Great Britain as well as elsewhere in Western Europe and North America.

Experts agree that “The Great Smog” killed about 4000 people in December 1952 alone (Figure 13-B). Furthermore, some researchers believe that an additional 8000 Londoners died in January and February 1953 due to the delayed effects of the smog or to lingering pollution. Other analyses disagree and blame the excess deaths on influenza. Yet others suggest that many of the deaths may have been the result of an interaction between the smog and the flu. Referring to these differences of

opinion, a recent article characterizes the situation this way:

The debate reveals how much is unknown even today about the effects of smog, which continues to menace big cities, especially in developing countries with weak air-pollution laws.**

The debate about the effects of London’s famous air-pollution episode of 1952 is more than just an academic exercise. Although London no longer experiences “great smogs,” foul air continues to plague big cities. The World Health Organization estimates that air pollution is responsible for about 600,000 deaths each year. “Some lessons of the Big Smoke still haven’t been learned.”***

**Richard Stone, “Counting the Cost of London’s Killer Smog,” *Science*, 13 December 2002, vol. 298, pp. 2106–7.

***Richard Stone, p. 2107.

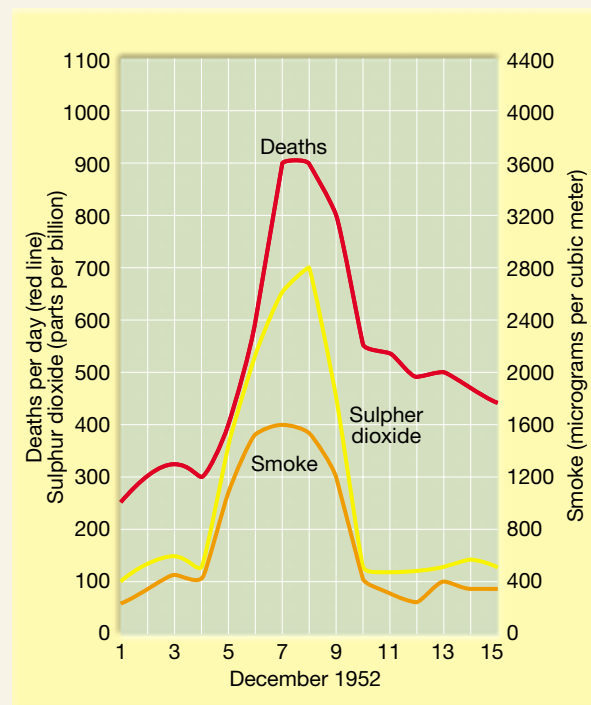


FIGURE 13-B Deaths and pollution during the Great Smog of 1952. Smoke and sulfur dioxide were monitored at various sites. The daily averages for 10 of these sites are shown here. (After British Meteorological Office, 1954)



FIGURE 13-6 This crowded freeway in San Diego, California, reminds us that the transportation category is a major contributor to air pollution. Emissions from an individual vehicle are generally low, relative to the smokestack image many people associate with air pollution. But in numerous cities across the country, the personal automobile is the single greatest polluter, when emissions from millions of vehicles are added together. Driving a private car is probably a typical person's most polluting daily activity. (Photo by Jerry Schad/Photo Researchers, Inc.)

revised its standards for particulate matter again so that they were based on $PM_{2.5}$. This change was in response to a large amount of research that analyzed the health effects of particulates.

Inhalable particulate matter includes both fine and coarse particles. These particles can accumulate in the respiratory system and are associated with numerous health effects. Exposure to coarse particles is primarily associated with the aggravation of respiratory conditions, such as asthma. Fine particles are most closely associated with such health effects as increased hospital admissions and emergency room visits for heart and lung disease, increased respiratory symptoms and disease, decreased lung function, and even premature death. Sensitive groups that appear to be at greatest risk to such effects include the elderly, individuals with cardiopulmonary disease, such as asthma, and children. In addition to health problems, particulate matter is the major cause of reduced visibility in many parts of the United States. Airborne particles also can cause damage to paints and building materials (see Box 13-2).

Sulfur Dioxide. *Sulfur dioxide* (SO_2) is a colorless and corrosive gas that originates largely from the combustion of sulfur-containing fuels, primarily coal and oil. Impor-

tant sources include power plants, smelters, petroleum refineries, and pulp and paper mills. Once SO_2 is in the air, it is frequently transformed into sulfur trioxide (SO_3), which reacts with water vapor or water droplets to form sulfuric acid (H_2SO_4). Very tiny particles act as a medium on which the acidic sulfate ion (SO_4^{2-}) is carried over long distances in the atmosphere. When it is "washed out" of the air or deposited on surfaces, it contributes to a serious environmental problem known as *acid precipitation*. This issue is the subject of a later section.

High concentrations of SO_2 can result in temporary breathing impairment for asthmatic children and adults who are active outdoors. Short-term exposures of asthmatic individuals to elevated SO_2 levels while at moderate exertion may result in reduced lung function that may be accompanied by such symptoms as wheezing, chest tightness, or shortness of breath. Other effects that have been associated with longer-term exposures to high concentrations of SO_2 , in conjunction with high levels of particulate matter, include respiratory illness and aggravation of existing cardiovascular disease.

Students Sometimes Ask...

You mentioned the burning of coal as a significant source of SO_2 , but do we burn very much coal anymore?

Yes, indeed. According to the U.S. Geological Survey, about 52 percent of the electricity produced in the United States comes from coal combustion. In addition, coal is the fuel of choice for many heat-intensive processes such as producing steel, aluminum, concrete, and wallboard. Many countries are even more reliant on coal for their energy needs than the United States.

Nitrogen Oxides. *Nitrogen oxides* are gases that form during the high-temperature combustion of fuel when nitrogen in the fuel or the air reacts with oxygen. Power plants and motor vehicles are the primary sources. These gases also form naturally when certain bacteria oxidize nitrogen-containing compounds.

The initial product formed is nitric oxide (NO). When NO oxidizes further in the atmosphere, nitrogen dioxide (NO_2) forms. Commonly, the general term NO_x is used to describe these gases. Although NO_x forms naturally, its concentration in cities is 10 to 100 times higher than in rural areas. Nitrogen dioxide has a distinctive reddish, brown color that frequently tints polluted city air and reduces visibility. When concentrations are high, NO_2 can also contribute to lung and heart problems. When air is humid, NO_2 reacts with water vapor to form nitric acid (HNO_3). Like sulfuric acid, this corrosive substance also contributes to the acid-rain problem. Moreover, because nitrogen


BOX 13-2
Air Pollution Changes the Climate of Cities

In Box 3-4 you saw that air pollution in cities contributes to the heat island by inhibiting the loss of longwave radiation at night. In Chapter 5 you learned that pollutants may have a “cloud seeding” effect that increases precipitation in and downward of cities. These influences, however, are not the only ways in which pollutants influence urban climate.

The blanket of particulates over most large cities significantly reduces the amount of solar radiation reaching the surface. In some cities, the overall reduction in the receipt of solar energy is 15 percent or more, whereas short wavelength ultraviolet is decreased by up to 30 percent. This weakening of incoming solar energy is variable. Dur-

ing air pollution episodes, the decrease is much greater than for periods when air quality is good (Figure 13-C). Furthermore, particulates are most effective in reducing solar radiation near the ground when the Sun angle is low. This occurs because the length of the path through the polluted air increases as the Sun angle drops. Thus, for a given quantity of particulate matter, solar energy will be reduced by the largest percentage at high-latitude cities and during the winter.

When compared to surrounding rural areas, the relative humidity in cities is generally from 2 to 8 percent lower. One reason is that cities are hotter. Remember from Chapter 4 that as air temperature increases,

capacity also rises and relative humidity drops. A second reason is that less water vapor is supplied to city air by evaporation from the surface. Evaporation is reduced in cities because rain water rapidly runs off, frequently into subsurface storm sewers.

Although relative humidity tends to be lower in cities, the occurrences of clouds and fogs are greater. What is the cause of this apparent paradox? A likely contributing factor is the large quantity of condensation nuclei produced by human activities in urban areas. When hygroscopic (water-seeking) nuclei are plentiful, water vapor readily condenses on them, even when the air is not quite saturated.



FIGURE 13-C An air-pollution episode at Shenyang, China. It is not difficult to understand why the amount of solar radiation reaching the surface is reduced in cities. (Photo by F. Hoffmann/The Image Works)

oxides are highly reactive gases, they play an important part in the formation of smog.

Volatile Organic Compounds. *Volatile organic compounds* (VOC for short), also called *hydrocarbons*, encompass a wide array of solid, liquid, and gaseous substances that are composed exclusively of hydrogen and carbon.

Large quantities occur naturally, with methane (CH_4) being the most abundant. Methane, however, does not interact chemically with other substances and has no negative health effects. In cities, the incomplete combustion of gasoline in motor vehicles is the principal source of reactive VOCs. Although some hydrocarbons from other sources are cancer-causing agents, most of the VOCs in city air do not

by themselves appear to pose significant environmental problems. However, as we shall see in a later discussion, when VOCs react with certain other pollutants (especially nitrogen oxides), noxious secondary pollutants result.

Carbon Monoxide. *Carbon monoxide* (CO) is a colorless, odorless, and poisonous gas produced by incomplete burning of carbon in fuels. It is the most abundant primary pollutant, with about two-thirds of the nationwide emissions coming from transportation sources, mainly highway vehicles.

Although CO is quickly removed from the atmosphere, it can nevertheless be dangerous. Carbon monoxide enters the bloodstream through the lungs and reduces oxygen delivery to the body's organs and tissues. Because it cannot be seen, smelled, or tasted, CO can have an effect on people without their realizing it. In small amounts, it causes drowsiness, slows reflexes, and impairs judgment. If concentrations are sufficiently high, CO can cause death. Carbon monoxide poses a serious health hazard where concentrations can reach high levels as in poorly ventilated tunnels and underground parking facilities.

Lead. *Lead* (Pb) is very dangerous because it accumulates in the blood, bones, and soft tissues. It can impair the functioning of many organs. Even at low doses, lead exposure is associated with damage to the nervous systems of young children.

In the past, automotive sources were the major contributor of lead emissions to the atmosphere because lead was added to gasoline as a way to prevent engine knock. Ever since the EPA-mandated phaseout of leaded gasoline, lead concentrations in the air of U.S. cities have shown a dramatic decline (Table 13–2). Occasional violations of the lead air-quality standard still occur near large industrial sources such as lead smelters.

Students Sometimes Ask...

What are toxic air pollutants?

They are chemicals in the air that are known or suspected to cause cancer or other serious health effects such as reproductive problems or birth defects. These substances are also commonly called “hazardous air pollutants” and “air toxics.” The U.S. Environmental Protection Agency regulates 188 toxic air pollutants. Examples include benzene, which is found in gasoline; perchlorethylene, which is emitted by some dry-cleaning facilities; and methylene chloride, which is used as a solvent and paint stripper.

Secondary Pollutants

Recall that secondary pollutants are not emitted directly into the air, but form in the atmosphere when reactions take place among primary pollutants. The sulfuric acid

TABLE 13-2 Air quality and emissions trends

Percent change in concentrations		
	1983–2002	1993–2002
NO ₂	–21	–11
O ₃ 1-hour	–22	–2
8-hour	–14	+4
SO ₂	–54	–39
PM ₁₀	—	–13
PM _{2.5}	—	–8
CO	–65	–42
Pb	–94	–57
Percent change in emissions		
	1983–2002	1993–2002
NO _x	–15	–12
VOC	–40	–25
SO ₂	–33	–31
PM ₁₀	–34	–22
PM _{2.5}	—	–17
CO	–41	–21
Pb	–93	–5

described earlier is one example of a secondary pollutant. After the primary pollutant, sulfur dioxide, is emitted into the atmosphere, it combines with oxygen to produce sulfur trioxide, which then combines with water to create this irritating and corrosive acid.

Air pollution in urban and industrial areas is often termed **smog**. The word was coined in 1905 by Harold A. Des Veaux, a London physician, and was created by combining the words “smoke” and “fog.” Des Veaux’s term was indeed an apt description of London’s principal air pollution threat, which was associated with the products of coal burning coupled with periods of high humidity.

Today, however, smog is used as a synonym for general air pollution and does not necessarily imply the smoke–fog combination. Therefore, when greater clarity is desired, we sometimes find the word “smog” preceded by such modifiers as “London-type,” “classical,” “Los Angeles-type,” or “photochemical.” The first two modifiers refer to the original meaning of the word, and the last two to air quality problems created by secondary pollutants.

Many reactions that produce secondary pollutants are triggered by strong sunlight and so are called **photochemical reactions**. One common example occurs when nitrogen oxides absorb solar radiation, initiating a chain of complex reactions. When certain volatile organic compounds are present, the result is the formation of a number of undesirable secondary products that are very reactive, irritating, and toxic. Collectively, this noxious mixture of gases and particles is called *photochemical smog*. One of the substances it usually contains is called PAN (peroxyacetyl nitrate), which damages vegetation and irritates the eyes.

The *major* component in photochemical smog is ozone. Recall from Chapter 1 that ozone is formed by natural processes in the stratosphere. However, when produced near Earth's surface, ozone is considered a pollutant.

The health and environmental effects of ozone are well documented. For example, according to the U.S. Environmental Protection Agency, health effects attributed to ozone exposure include significant decreases in lung function and increased respiratory symptoms such as chest pain and cough. Exposures to ozone can make people more susceptible to respiratory infection, result in lung inflammation, and aggravate preexisting respiratory diseases such as asthma. These effects generally occur while individuals are actively exercising, working, or playing outdoors. Children, active outdoors during the summer when ozone levels are at their highest, are most at risk of experiencing such effects. In addition, longer-term exposures to moderate levels of ozone present the possibility of irreversible changes in lung structure, which could lead to premature aging of the lungs.

Ozone also affects vegetation and ecosystems, leading to reductions in agricultural crop and commercial forest yields, reduced growth and survivability of tree seedlings, and increased plant susceptibility to disease, pests, and other environmental stresses such as harsh weather. In long-lived species, these effects may become evident only after many years or even decades, thus having the potential for long-term effects on forest ecosystems. Ground-level ozone damage to the foliage of trees and other plants can also decrease the aesthetic value of natural areas.

Because the reactions that create ozone are stimulated by strong sunlight, the formation of this pollutant is limited to daylight hours. Peaks occur in the afternoon following a series of hot, sunny, calm days. As we might expect, ozone levels are highest during the warmer summer months. The "ozone season" varies from one part of the country to another. Although May through October is typical, areas in the Sunbelt of the American South and Southwest may experience problems throughout the year. By contrast, northern states have shorter ozone seasons, such as May through September for North Dakota.

Trends in Air Quality

Although Table 13–2 shows us that considerable progress has been made in controlling air pollution, the quality of the air we breathe still remains a serious public health problem (see Box 13–3). Economic activity, population growth, meteorological conditions, and regulatory efforts to control emissions all influence the trends in air pollutant emissions. Up until the 1950s the greatest influences on emissions were related to the economy and population growth. Emissions grew as the economy and population increased. Emissions fell in periods of economic recession. For example, dramatic declines in emissions in the 1930s were due to the Great Depression (Figure 13–7). Emissions also increase as a result of shifts in the demand for various products. For instance, the tremendous upsurge in demand for gasoline following World War II increased emissions associated with petroleum refining and on-road vehicles.

In the 1950s the states issued air-pollution statutes generally targeted toward smoke and particulate emissions. It was not until the passage of the federal Clean Air Act as amended in 1970 that major strides were made in reducing air pollution. This legislation created the Environmental Protection Agency (EPA) and charged it with establishing air-quality and emissions standards.

The Clean Air Act of 1970 mandated the setting of standards for four of the primary pollutants—particulates, sulfur dioxide, carbon monoxide, and nitrogen oxides—as well as the secondary pollutant ozone. At the time, these five pollutants were recognized as being the most widespread and objectionable. Today, with the addition of lead, they are known as the *criteria pollutants* and are covered by the National Ambient Air Quality Standards (Table 13–3). The primary standard for each pollutant shown in Table 13–3 is based on the highest level that can be tolerated by humans without noticeable ill effects, minus a 10 to 50 percent margin for safety.

For some of the pollutants, both long-term and short-term levels are set. Short-term levels are designed to protect against acute effects, whereas the long-term standards were

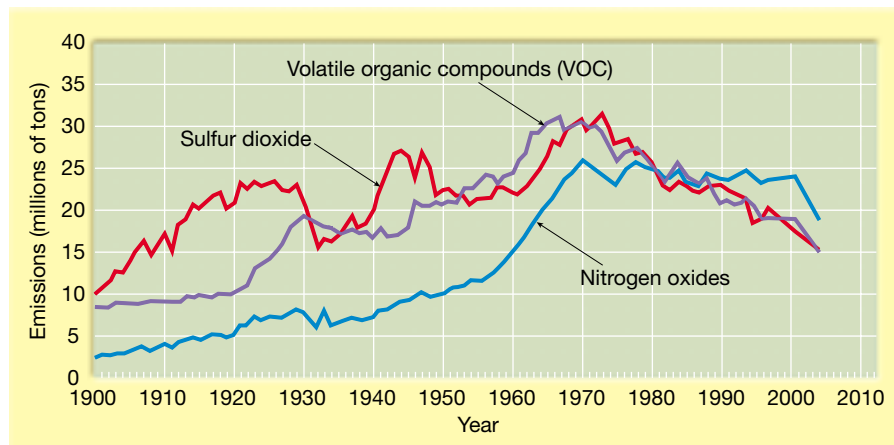


FIGURE 13-7 Trend in national emissions 1900–2004. Prior to the post-1970 period, economic activity and population growth were major factors influencing the emissions of air pollutants. Emissions grew as the economy and population increased and emissions declined during economic downturns. For example, dramatic declines in emissions in the 1930s were due to the Great Depression. Since 1970, much of the downward trend in emissions is due to the Clean Air Act. (After U.S. E.P.A., Office of Air Quality Planning and Standards)



BOX 13-3

Radon—An Example of Indoor Air Pollution

The primary focus of this chapter is urban and regional air pollution. However, the indoor environment should not be overlooked as a place where air pollution can be a significant problem. In fact, it is becoming increasingly clear that in some cases the air we breathe indoors may pose a greater health risk than the air we breathe outdoors. The health risks of indoor air pollution are magnified because people spend 70 to 90 percent or more of their time indoors. Indoor air pollution may be more of a problem today than it was in the past because the trend toward greater energy efficiency has tended to make houses and office buildings more airtight.

According to the U.S. Environmental Protection Agency (EPA), indoor air pollution can be a serious environmental cancer risk. One of the offending substances is the radioactive gas *radon*.

Radioactivity is the spontaneous emission of atomic particles and/or electromagnetic waves from unstable atomic nuclei. In a sample of uranium-238, unstable nuclei decay and produce a variety of radioactive progeny or “daughter” products as well as ener-

getic forms of radiation (Table 13–A). One of its radioactive decay products is radon—a colorless, odorless, invisible gas.

Radon gained public attention in 1984 when a worker in a Pennsylvania nuclear power plant set off radiation alarms not when he left work, but when he first arrived. His clothing and hair were contaminated with radon decay products. Investigation revealed that the basement of his home had a radon level 2800 times the average level in indoor air.

Originating in the radioactive decay of traces of uranium and thorium found in almost all soils, radon isotopes (Rn-222 and Rn-220) are continually renewed in an ongoing, natural process. Geologists estimate that the top six feet of soil from an average acre of land contains about 50 pounds of uranium (about 2 to 3 parts per million); some types of rocks contain more. Radon is continually generated by the gradual decay of this uranium. Because uranium has a half-life of about 4.5 billion years, radon will be with us forever.

Once radon is produced in the soil, it diffuses throughout the tiny

spaces between soil particles. Some radon ultimately reaches the soil surface, where it dissipates into the air. Radon enters buildings and homes through holes and cracks in basement floors and walls. Radon’s density is greater than air, so it tends to remain in basements during its short decay cycle.

Radon itself decays, having a half-life of only about four days. Its decay products (except lead-206) are all radioactive solids that adhere to dust particles, many of which we inhale. During prolonged exposure to a radon-contaminated environment, some decay will occur while the gas is in the lungs, thereby placing the radioactive radon progeny in direct contact with delicate lung tissue. Steadily accumulating evidence indicates that radon is a significant cause of lung cancer—second only to smoking. The EPA estimates that radon causes about 14,000 deaths per year in the United States.

A house with a radon level of 4.0 picocuries per liter of air has about eight to nine atoms of radon decaying every minute in every liter of air. The EPA suggests indoor radon levels be kept below this level. EPA risk estimates are conservative; they are based on an assumption that one would spend 75 percent of a 70-year time span (about 52 years) in the contaminated space, which most people would not.

Although you cannot see radon, it is not hard to determine if a radon problem exists in your home. Many kinds of inexpensive, do-it-yourself radon test kits are available through the mail and in hardware stores and other retail outlets. If a problem exists, there are relatively simple solutions available. A trained radon-reduction contractor can assist in picking an appropriate treatment method.

TABLE 13–A Decay products of uranium-238

Some decay products of uranium-238	Half-Life*
Uranium-238	4.5 billion years
Radium-226	1600 years
Radon-222	3.82 days
Polonium-218	3.1 minutes
Lead-214	26.8 minutes
Bismuth-214	19.7 minutes
Polonium-214	1.6×10^{-4} second
Lead-210	20.4 years
Bismuth-210	5.0 days
Polonium-210	138 days
Lead-206	stable

*Half-life is a common way of expressing the rate of radioactive disintegration. It is the time required for one half of the atoms of a radioactive substance to decay.

TABLE 13-3 National ambient air-quality standards.

Pollutant	Standard value	
Carbon monoxide (CO)		
8-hour average	9 ppm [°]	(10 mg/m ³) [†]
1-hour average	35 ppm	(40 mg/m ³)
Nitrogen dioxide (NO₂)		
Annual arithmetic mean	0.053 ppm	(100 µg/m ³) ^{°°}
Ozone (O₃)		
1-hour average	0.12 ppm	(235 µg/m ³)
8-hour average	0.08 ppm	(157 µg/m ³)
Lead (Pb)		
Quarterly average		1.5 µg/m ³
Particulate <10 micrometers (PM₁₀)		
Annual arithmetic mean		50 µg/m ³
24-hour average		150 µg/m ³
Particulate <2.5 micrometers (PM_{2.5})		
Annual arithmetic mean		15 µg/m ³
24-hour average		65 µg/m ³
Sulfur dioxide (SO₂)		
Annual arithmetic mean	0.03 ppm	(80 µg/m ³)
24-hour average	0.14 ppm	(365 µg/m ³)
3-hour average	0.50 ppm	(1300 µg/m ³)

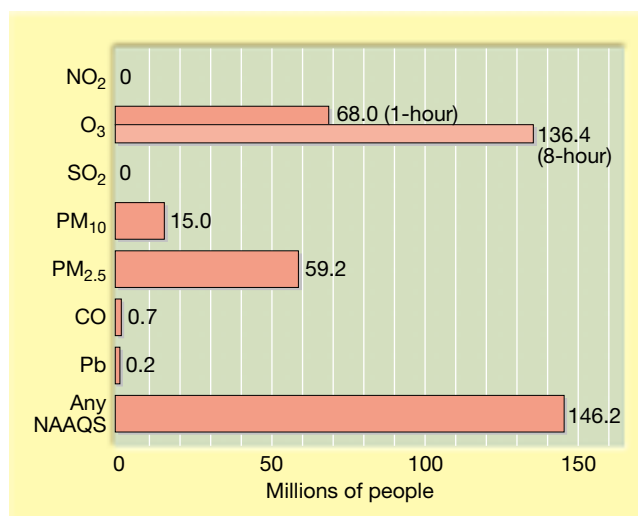
[°]ppm, parts per million.
[†]mg/m³, milligrams per cubic meter of air. A milligram is one-thousandth of a gram.
^{°°}µg/m³ micrograms per cubic meter. A microgram is one-millionth of a gram.
Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards.

established to guard against chronic effects. *Acute* refers to pollutant levels that may be life-threatening within a period of hours or days. *Chronic* pollutant levels cause gradual deterioration of a variety of physiological functions over a span of years. It should be pointed out that standards are established using human health criteria and not according to their impact on other species or on atmospheric chemistry.

By the year 2002 an estimated 146 million people in the United States resided in counties that did not meet one or more air-quality standards (Figure 13-8). It is clear from Figure 13-8 why the EPA describes ozone as our “most pervasive ambient air pollution problem.” The number of people living in counties that exceeded the ozone standard is greater than the total number of those living in counties affected by the other five pollutants.

The fact that air-quality standards have not yet been met in a large number of places does not mean that progress has not been made. The United States has made significant strides in reducing air pollution. In 2004 emissions of the five major primary pollutants shown in Figure 13-5 totaled about 139 million tons. By contrast, in 1970, when the first Clean Air Act became law, the same five pollutants totaled about 301 million tons. The 2004 total is about 54 percent lower than 1970. This progress is also shown in Figure 13-9,

FIGURE 13-8 Number of people living in counties with air-quality concentrations above the levels of the National Ambient Air Quality Standards (NAAQS) in 2002. For example, 15 million people live in counties where PM₁₀ concentrations exceed the national standard. Despite substantial progress in reducing emissions, there were still approximately 146 million people nationwide who lived in counties with monitored air-quality levels above the primary national standards. (After U.S. Environmental Protection Agency)



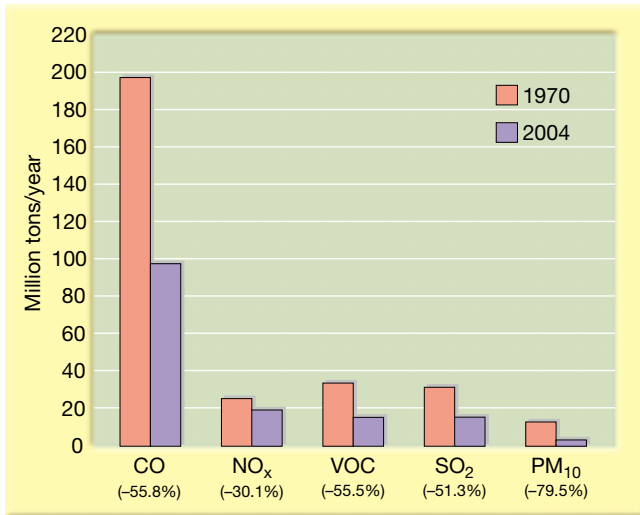
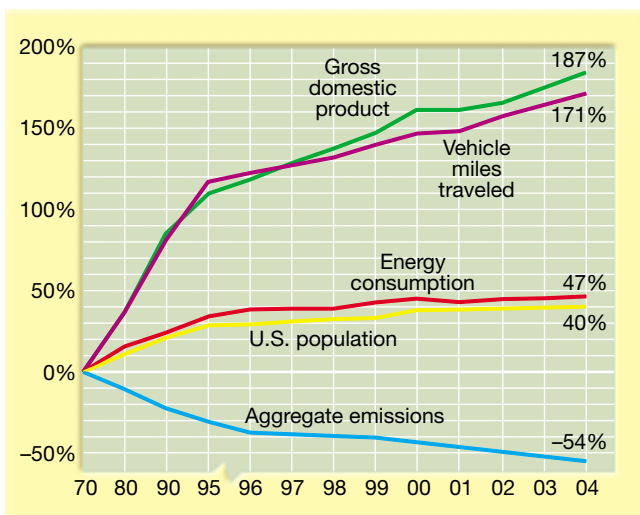


FIGURE 13-9 Comparison of 1970 and 2004 emissions. (After U.S. Environmental Protection Agency).

where downward trends in all pollutants are evident. This improvement in air quality has been achieved during a time when urban growth has been substantial. However, methods of control have not been as effective as expected in upgrading urban air quality.

An important reason for the slower than expected progress in bettering air quality is related to growth. For example, *on a per-car basis*, emissions of primary pollutants have dramatically improved. However, at the same time this was occurring, the U.S. population increased by 40 percent and vehicle miles traveled went up by 171 percent (Figure 13-10).

FIGURE 13-10 Comparison of growth areas and emissions. Between 1970 and 2004 gross domestic product increased 187 percent, vehicle miles traveled increased 171 percent, energy consumption increased 47 percent, and U.S. population increased 40 percent. At the same time, total emissions of the six principal air pollutants decreased about 54 percent. (After U.S. Environmental Protection Agency)



In other words, pollution controls have improved air quality, but the positive effects have been partly offset by an increase in the number of vehicles on the road. This is borne out in Los Angeles, where, despite significant progress in reducing emissions, the city still faces substantial air-quality problems. Since the 1950s, when serious efforts to alleviate air pollution began, the population of the area has more than tripled and the number of motor vehicles has more than quadrupled.

Late in 1990 Congress passed the Clean Air Act Amendments. The lengthy technical legislation is broad in scope and organized into several different parts called *titles*. The amendments impose the following:

1. Tighter controls on air quality, including more stringent standards on the emission of sulfur dioxide produced by coal combustion.
2. Lower limits on automobile emissions, which include the use of cleaner-burning fuels.
3. Greater constraints on hazardous air pollutants, which are aimed at greatly reducing urban smog.
4. Controls on water-quality degradation from acid rain.
5. Clean-air research that authorizes the continuation of the National Acid Precipitation Assessment Program.
6. Limits on and the eventual abolishment of chlorofluorocarbons and other ozone-depleting compounds.
7. Data collection on greenhouse gases that contribute to global climate change.

Regulations and standards regarding these titles are periodically established and revised. For example, in December 1999 the EPA announced new standards that require lower nitrogen oxide emissions from motor vehicles and reduced sulfur levels in gasoline. Recall that nitrogen oxides play a significant role in the formation of photochemical smog. Sulfur in gasoline diminishes the effectiveness of catalytic converters (devices that reduce pollution from tailpipes). By significantly reducing sulfur, the catalytic converter becomes more effective, and tailpipe emissions improve.

Students Sometimes Ask...

Besides the radon discussed in Box 13-3, what are some other indoor air pollutants?

There are many possibilities. A partial list includes environmental tobacco smoke ("secondhand smoke") and biological contaminants such as mold, mildew, and animal dander. In addition, formaldehyde (often from the glue in building materials such as particle board), organic chemicals from household products such as paint and varnish, and fumes from unventilated kerosene or gas space heaters can cause serious problems.

Meteorological Factors Affecting Air Pollution

Certainly, the most obvious factor influencing air pollution is the quantity of contaminants emitted into the atmosphere. Still, experience shows that even when emissions remain relatively steady for extended periods, we often find wide variations in air quality from one day to the next. Indeed, when air-pollution episodes occur, they are not generally the result of a drastic increase in the output of pollutants; instead, they occur because of changes in certain atmospheric conditions.

Perhaps you have heard the phrase “The solution to pollution is dilution.” To a significant degree it is true. If the air into which the pollution is released is not dispersed, the air will become more toxic. Two of the most important atmospheric conditions affecting the dispersion of pollutants are (1) the strength of the wind and (2) the stability of the air. These factors are critical because they determine how rapidly pollutants are diluted by mixing with the surrounding air after leaving the source.

Wind As a Factor

The manner in which wind speed influences the concentration of pollutants is shown in Figure 13–11. Assume that a burst of pollution leaves the stack every second. If the wind speed were 10 meters per second, the distance between each pollution “cloud” would be 10 meters. If the wind is reduced to 5 meters per second, the distance between “clouds” will be 5 meters. Consequently, because of the direct effect of wind speed, the concentration of pollutants is twice as great with the 5 meters per second wind as with the 10 meters per second wind. It is easy to understand why air-pollution problems seldom occur when winds are strong but rather are associated with periods when winds are weak or calm.

A second aspect of wind speed influences air quality. The stronger the wind, the more turbulent the air. Thus, strong winds mix polluted air more rapidly with the surrounding air, thereby causing the pollution to be more dilute. Conversely, when winds are light, there is little turbulence and the concentration of pollutants remains high.

The Role of Atmospheric Stability

Whereas wind speed governs the amount of air into which pollutants are initially mixed, atmospheric stability determines the extent to which vertical motions will mix the pollution with cleaner air above. The vertical distance between Earth’s surface and the height to which convective movements extend is called the **mixing depth**. Generally, the greater the mixing depth, the better the air quality. When the mixing depth is several kilometers, pollutants are mixed through a large volume of cleaner air and dilute rapidly. When the mixing depth is shallow, pollutants are confined to a much smaller volume of air and concentrations can reach unhealthy levels.

When air is stable, convective motions are suppressed and mixing depths are small. Conversely, an unstable atmosphere promotes vertical air movements and greater mixing depths. Because heating of Earth’s surface by the Sun enhances convective movements, mixing depths are usually greater during the afternoon hours. For the same reason, mixing depths during the summer months are typically greater than during the winter months.

Temperature inversion represents a situation in which the atmosphere is very stable and the mixing depth is significantly restricted. Warm air overlying cooler air acts as a lid and prevents upward movement, leaving the pollutants trapped in a relatively narrow zone near the ground. This effect is dramatically illustrated by the photograph in Figure 13–12. Most of the air-pollution episodes cited earlier were linked to the occurrence of temperature inversions.

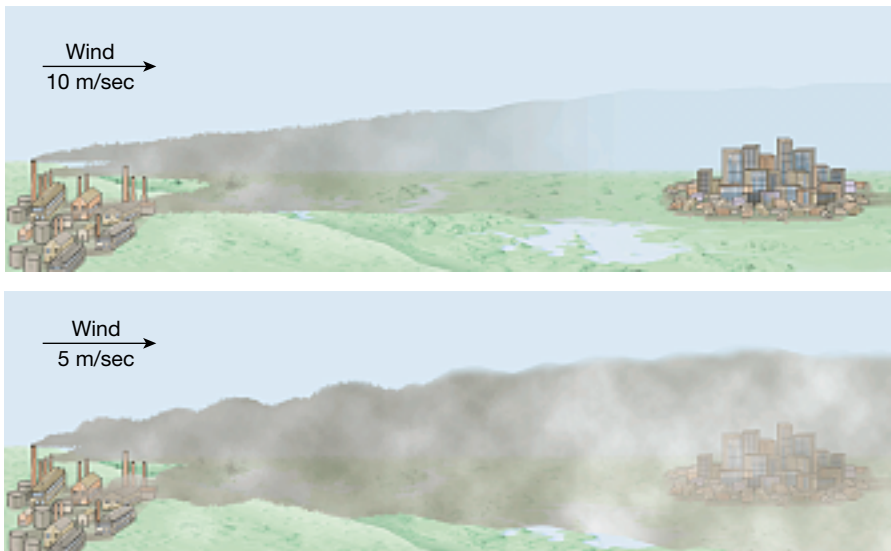


FIGURE 13-11 Effect of wind speed on the dilution of pollutants. The concentration of pollutants increases as wind speed decreases.

FIGURE 13-12 Air pollution in downtown Los Angeles. Temperature inversions act as lids to trap pollutants below. (Photo by Ted Spiegel/Black Star)



Surface Temperature Inversions. Solar heating can result in high surface temperatures during the late morning and afternoon that increase the environmental lapse rate and render the lower air unstable. During nighttime hours, however, just the opposite situation may occur; temperature inversions, which result in very stable atmospheric conditions, can develop close to the ground. These surface inversions form because the ground is a more effective radiator than the air above.

This being the case, radiation from the ground to a clear night sky causes more rapid cooling at the surface than higher in the atmosphere. Consequently, the coldest air is found next to the ground, yielding a vertical temperature profile resembling the one shown in the upper portion of Figure 13-13. Once the Sun rises, the ground is heated and the inversion disappears.

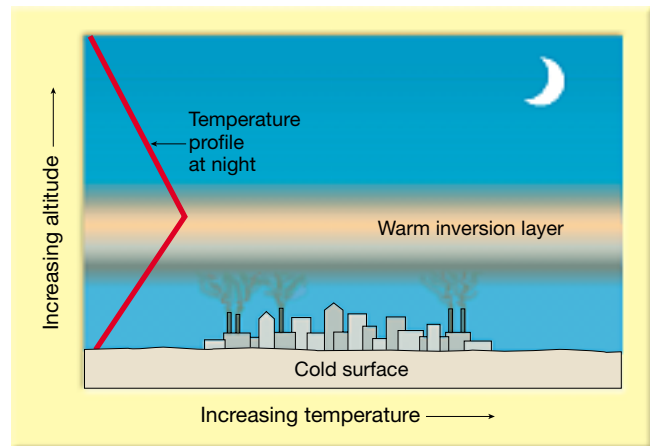
Although usually rather shallow, surface inversions may be very deep in regions where the land surface is uneven. Because cold air is denser than warm air, the chilled air near the surface gradually drains from the uplands and slopes into adjacent lowlands and valleys. As might be expected, this deeper surface inversion will not dissipate as quickly after sunrise. Thus, although valleys are often preferred sites for manufacturing because they afford easy access to water transportation, they are also more likely to experience relatively thick surface inversions that in turn will have a negative effect on air quality.

Inversions Aloft. Many extensive and long-lived air-pollution episodes are linked to temperature inversions that develop in association with the sinking air that characterizes centers of high air pressure (anticyclones). As the air sinks to lower altitudes, it is compressed and so its temperature rises. Because turbulence is almost always present near the ground, this lowermost portion of the atmosphere is generally prevented from participating in the general subsidence. Thus, an inversion develops aloft between the lower turbulent zone and the subsiding warmer layers above (Figure 13-14).

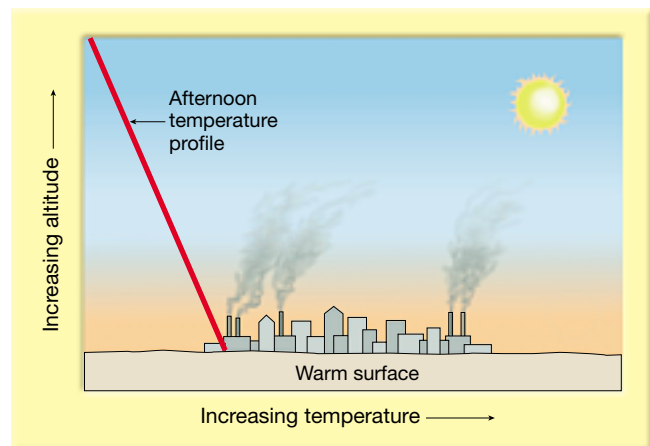
The air pollution that plagues Los Angeles is frequently related to inversions associated with the subsiding eastern portion of the subtropical high in the North Pacific. In addition,

the adjacent cool waters of the Pacific Ocean and the mountains surrounding the city compound the problem. When winds move cool air from the Pacific into Los Angeles, the warmer air that is pushed aloft creates or strengthens an inversion aloft that acts as an effective lid. Because the surrounding mountains keep the smog from moving

FIGURE 13-13 (a) A generalized temperature profile for a surface inversion. (b) Temperature-profile changes after the Sun has heated the surface.



(a)



(b)

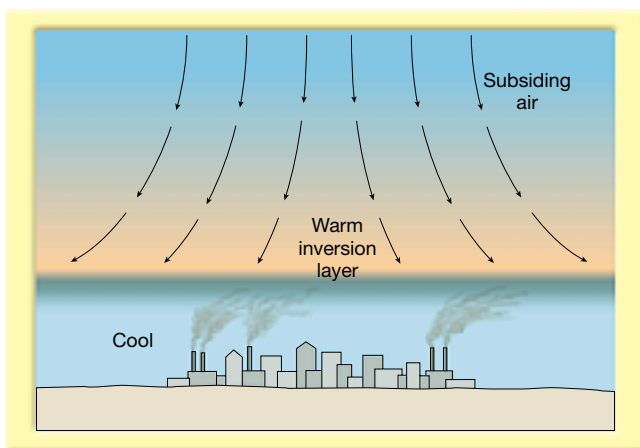


FIGURE 13-14 Inversions aloft frequently develop in association with slow-moving centers of high pressure, where the air aloft subsides and warms by compression. The turbulent surface zone does not subside as much. Thus, an inversion often forms between the lower turbulent zone and the subsiding layers above.

farther inland, air pollution is trapped in the basin until a change in weather brings relief. Clearly, the geographic setting of a place can significantly contribute to air-quality problems. The Los Angeles area is an excellent example.

In summary, we have seen that when the wind is strong and an unstable environmental lapse rate prevails, the diffusion of pollutants is rapid and high pollution concentrations will not occur except perhaps near a major source. In contrast, when an inversion exists and winds are light, diffusion is inhibited and high pollution concentrations are to be expected in areas where there are sources. Air pollution is especially acute in urban areas experiencing frequent and prolonged temperature inversions.

Students Sometimes Ask...

I've heard that in some places wood-burning fireplaces and stoves can be significant sources of air pollution. Is that actually the case?

Yes. Woodsmoke can build up in areas where it is generated and expose people to high levels of air pollution, especially on cold nights when there is a temperature inversion. Woodsmoke contains significant quantities of particulates and much higher levels of hazardous air pollutants, including some cancer-causing chemicals, than smoke from oil- and gas-fired furnaces. For example, in the Bay Area of California, woodsmoke is the largest source of particulate pollution. On an average winter night, 40 percent or more of the fine particulates are from woodsmoke. Some communities now ban the installation of conventional fireplaces or woodstoves that are not EPA-certified. In addition, in many localities people are asked to refrain from burning wood on evenings when air-pollution levels are expected to be high.

Acid Precipitation

As a consequence of burning large quantities of fossil fuels, primarily coal and petroleum products, about 40 million tons of sulfur and nitrogen oxides are released into the atmosphere each year in the United States. The major sources of these emissions include power-generating plants, industrial processes, such as ore smelting and petroleum refining, and motor vehicles of all kinds. Through a series of complex chemical reactions, some of these pollutants are converted into acids that then fall to Earth's surface as rain or snow. Another portion is deposited in dry form and subsequently converted into acid after coming in contact with precipitation, dew, or fog.

In 1852 the English chemist Angus Smith coined the term *acid rain* to refer to the effect that industrial emissions had on precipitation in the British Midlands. A century and a half later this phenomenon is not only the focus of research for many environmental scientists but also a topic having substantial international political importance. Although Smith clearly realized that acid rain caused environmental damage, large-scale effects were not recognized until the middle part of the twentieth century. Eventually, widespread public concern in the late 1970s led to significant government-sponsored studies of the problem. Such research activities continue to examine this still unresolved environmental problem.

Extent and Potency of Acid Precipitation

Rain is naturally somewhat acidic. When carbon dioxide from the atmosphere dissolves in water, it becomes weak carbonic acid. Small amounts of other naturally occurring acids also contribute to the acidity of precipitation. It was once thought that unpolluted rain has a pH of about 5.6 on the pH scale (Figure 13-15). However, studies in uncontaminated remote areas have shown that precipitation usually has a pH closer to 5. Unfortunately, in most areas within several hundred kilometers of large centers of human activity, precipitation has much lower pH values. This rain or snow is called **acid precipitation**.

Widespread acid rain has been known in northern Europe and eastern North America for some time (Figure 13-16). Studies have also shown that acid rain occurs in many other regions, including western North America, Japan, China, Russia, and South America. In addition to local pollution sources, a portion of the acidity found in the northeastern United States and eastern Canada originates hundreds of kilometers away in industrialized regions to the south and southwest. This situation occurs because many pollutants remain in the atmosphere for periods as long as five days, during which time they may be transported great distances.

One contributing factor is, of all things, a technology that is used to reduce pollution in the immediate vicinity of a source. Taller chimney stacks improve local air quality by releasing pollutants into the stronger and more persistent winds that exist at greater heights (Figure 13-17). Although such stacks enhance dilution and dispersion, they also promote the long-distance transport of these unwanted

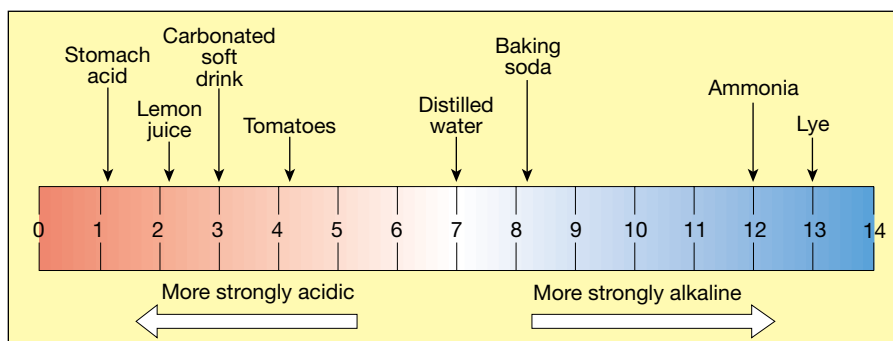


FIGURE 13-15 The *pH scale* is a common measure of the degree of acidity or alkalinity of a solution. The scale ranges from 0 to 14, with a value of 7 denoting a solution that is neutral. Values below 7 indicate greater acidity, whereas numbers above 7 indicate greater alkalinity. The pH values of some familiar substances are shown on the diagram. Although distilled water is neutral (pH 7), rainwater is naturally acidic. It is important to note that the pH scale is logarithmic; that is, each whole number increment indicates a tenfold difference. Thus, pH 4 is 10 times more acidic than pH 5 and 100 times (10×10) more acidic than pH 6.

emissions. In this way, individual stack plumes with pollution concentrations considered too dilute to be a direct health or environmental threat locally contribute to inter-regional pollution problems. Unfortunately, because atmospheric processes in eastern North America lead to a thorough mixing of pollutants, it is not yet possible to distinguish clearly between the relative impact of distant sources compared with local sources.

Effects of Acid Precipitation

For many years acid precipitation had not been directly linked to any adverse effects on human health. This is no longer true. A growing body of evidence shows that acid aerosols affect people's health. Exposure may impair the ability of the upper respiratory tract and the deep parts of the lungs to clear themselves of harmful particles. A link

FIGURE 13-16 Precipitation pH values for the United States in the year 2003. Unpolluted rain has a pH of about 5. In the United States acid precipitation is most severe in the Northeast. (Data from National Atmospheric Deposition Program)

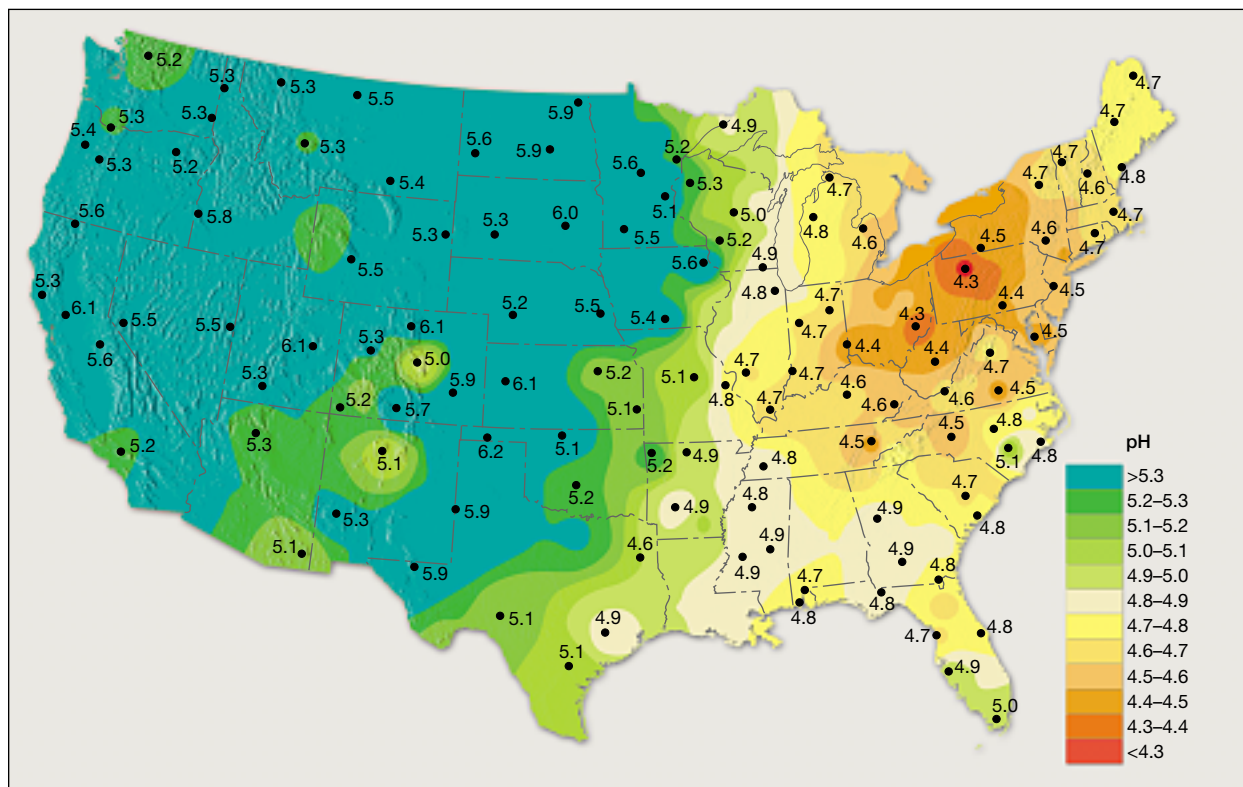




FIGURE 13-17 Tall stacks improve local air quality by releasing pollutants at greater heights where winds are stronger. However, such stacks promote the long-distance transport of pollutants that may ultimately contribute to acid precipitation far from their source. (Photo by Sandra Baker/Liaison Agency, Inc.)

has also been made with the incidence of bronchitis among children.

Beyond these possible impacts on health, the damaging effects of acid rain on the environment are believed to be considerable in some areas and imminent in others. The best-known effect of acid precipitation is the lowering of pH in thousands of lakes and streams in Scandinavia and eastern North America. Accompanying this have been substantial increases in dissolved aluminum that is leached from

FIGURE 13-18 Damage to forests by acid precipitation is well documented in Europe and eastern North America. These trees in the Great Smoky Mountains have been injured by acid-laden clouds. (Photo by Doug Locke/Dembinsky Photo Associates)



the soil by the acidic water and that, in turn, is toxic to fish. Consequently, some lakes are virtually devoid of fish, whereas others are approaching this condition. Furthermore, ecosystems are characterized by many interactions at many levels of organization, which means that evaluating the effects of acid precipitation on these complex systems is difficult and expensive, and far from complete.

Even within small areas, the effects of acid precipitation can vary significantly from one lake to another. Much of this variation is related to the nature of the soil and rock materials in the area surrounding the lake. Because minerals such as calcite in some rocks and soils can neutralize acid solutions, lakes surrounded by such materials are less likely to become acidic. In contrast, lakes that lack this buffering material can be severely affected. Even so, over a period of time the pH of lakes that have not yet been acidified may drop as the buffering material in the surrounding soil becomes depleted.

In addition to the thousands of lakes that can no longer support fish, research indicates that acid precipitation may also reduce agricultural crop yields and impair the productivity of forests. Acid rain not only harms the foliage but also damages roots and leaches nutrient minerals from the soil (Figure 13-18). Finally, acid precipitation is known to promote the corrosion of metals and contributes to the destruction of stone structures (Figure 13-19).

FIGURE 13-19 Acid rain accelerates the chemical weathering of stone monuments and structures. (Photo by Adam Hart-Davis/Science Photo Library/Photo Researchers, Inc.)



In summary, acid precipitation involves the delivery of acidic substances through the atmosphere to Earth's surface. These compounds are introduced into the air as by-products of combustion and industrial activity. The atmosphere is both the avenue by which offending compounds travel from sources to the sites where they are deposited and the medium in which the combustion products are transformed into acidic substances. In addition to its detrimental impact on aquatic systems, acid precipitation has a number of other harmful effects.

Acid precipitation is a complex and multifaceted issue. Because current knowledge regarding many aspects of the

problem is incomplete, additional research continues to be carried out. Yet it has been clear for some time that our understanding is sufficient to take corrective actions as well. One important step occurred with the passage of the Clean Air Act of 1990, which requires a substantial reduction in U.S. emissions of sulfur dioxide and modest cuts in emissions of nitrogen oxides. Canada has agreed to make comparable cuts in its emissions of these air pollutants. Thanks to such controls, precipitation in much of the eastern United States and Canada is less acid than before. Monitoring has shown that improvements from 15 to 25 percent are common.

Chapter Summary

- Air pollution and weather are linked in two ways. One concerns the influence that weather conditions have on the dilution and dispersal of air pollutants. The second connection is the reverse and deals with the effect that air pollution has on weather and climate.
- Air is never perfectly clean. Volcanic ash, salt particles, pollen and spores, smoke and windblown dust are all examples of “natural air pollution.” Although some types of air pollution are recent creations, others, such as London’s infamous smoke pollution, have been around for centuries. One of the most tragic air-pollution episodes occurred in London in December 1952, when more than 4000 people died.
- *Air pollutants* are airborne particles and gasses that occur in concentrations that endanger the health and well-being of organisms or disrupt the orderly functioning of the environment. Pollutants can be grouped into two categories: (1) *primary pollutants*, which are emitted directly from identifiable sources, and (2) *secondary pollutants*, which are produced in the atmosphere when certain chemical reactions take place among primary pollutants. The major primary pollutants include, particulate matter (PM), sulfur dioxide, nitrogen oxides, volatile organic compounds (VOCs), carbon monoxide, and lead. Atmospheric sulfuric acid is one example of a secondary pollutant. Air pollution in urban and industrial areas is often called *smog*. *Photochemical smog*, a noxious mixture of gases and particles, is produced when strong sunlight triggers *photochemical reactions* in the atmosphere. A major component of photochemical smog is *ozone*.
- Although considerable progress has been made in controlling air pollution, the quality of the air we breathe remains a serious public health problem. Economic activity, population growth, meteorological conditions, and regulatory efforts to control emissions, all influence the trends in air pollution. The *Clean Air Act of 1970* mandated the setting of standards for four of the primary pollutants—particulates, sulfur dioxide, carbon monoxide, and nitrogen oxides—as well as the secondary pollutant ozone. In 2004, emissions of the five major primary pollutants in the United States were about 54 percent lower than 1970. In 1990 Congress passed the *Clean Air Act Amendments*, which further tightened controls on air quality. Regulations and standards regarding the provisions of the Clean Air Act Amendments of 1990 are periodically established and revised.
- The most obvious factor influencing air pollution is the quantity of contaminants emitted into the atmosphere. However, when air-pollution episodes take place, they are not generally the result of a drastic increase in the output of pollutants; instead, they occur because of changes in certain atmospheric conditions. Two of the most important atmospheric conditions affecting the dispersion of pollutants are (1) the strength of the wind and (2) the stability of the air. The direct effect of wind speed is to influence the concentration of pollutants. Atmospheric stability determines the extent to which vertical motions will mix the pollution with cleaner air above the surface layer. The vertical distance between Earth’s surface and the height to which convective movements extend is called the *mixing depth*. Generally the greater the mixing depth, the better the air quality. *Temperature inversions* represent a situation in which the atmosphere is very stable and the mixing depth is significantly restricted. When an inversion exists and winds are light, diffusion is inhibited and high pollution concentrations are to be expected in areas where pollution sources exist. *Surface-temperature inversions* form because the ground is a more effective radiator than the air above. *Inversions aloft* are associated with sinking air that characterizes centers of high air pressure.

- In most areas within several hundred kilometers of large centers of human activity, the pH value of precipitation is much lower than the usual value found in unpopulated areas. This acidic rain or snow, formed when sulfur and nitrogen oxides produced as by-products of combustion and industrial activity are converted into acids during complex atmospheric reactions, is called *acid precipitation*. The atmosphere is both the avenue by which offending compounds travel from sources to the sites

where they are deposited and the medium in which the combustion products are transformed into acidic substances. Beyond possible impacts on health, the damaging effects of acid precipitation on the environment include the lowering of pH in thousands of lakes in Scandinavia and eastern North America. Besides producing water that is toxic to fish, acid precipitation has also detrimentally altered complex ecosystems.

Vocabulary Review

acid precipitation (p. 393)

air pollutants (p. 380)

mixing depth (p. 391)

photochemical reaction (p. 386)

primary pollutant (p. 381)

secondary pollutant (p. 381)

smog (p. 386)

temperature inversion (p. 391)

Review Questions

- List two ways in which meteorology and air pollution are linked.
- What is the difference between a primary pollutant and a secondary pollutant?
- Relate the proper primary pollutant to each statement.
 - These are also known as hydrocarbons.
 - Colorless, corrosive gas that originates from burning coal and oil.
 - The most prominent sources of this colorless, odorless, poisonous gas are motor vehicles.
 - This gas has a distinctive reddish-brown color.
- Consult Figure 13-5 to answer the following:
 - Which source category is responsible for the most pollution?
 - What is the single greatest air pollutant by weight?
- What was the original meaning of the term “smog”? What is the current meaning of this term?
- What triggers a photochemical reaction?
- What is the major component in photochemical smog?
- During what part of the day is ozone formation at its peak? When is the “ozone season”?
- In Chapter 1 you learned that we should be concerned about ozone depletion in the atmosphere. Based on what is presented in Chapter 13, it seems like getting rid of ozone would be a good idea. Can you clarify this apparent contradiction?
- Table 13-2 shows trends in air quality and emissions. Explain why ozone (O₃) appears on the “Percent Change in Air Quality” portion of the table but does not appear on the “Percent Change in Emissions” portion.
- The average motor vehicle today emits *much* less pollution than 30 years ago. Why have the positive effects of this sharp reduction *not* been as great as we might have expected?
- Why are air pollution problems more acute when winds are weak or calm?
- How do temperature inversions influence air pollution?
- Describe the formation of a surface inversion and compare it with an inversion that occurs aloft.
- How does the geographic setting of Los Angeles contribute to the air pollution episodes it experiences?
- How much more acidic is a substance with a pH of 4 compared with a substance with a pH of 6? (See Figure 13-15.)
- How has the building of tall smokestacks contributed to interregional air pollution problems?
- List some possible environmental effects of acid precipitation.

Atmospheric Science Online



The *Atmosphere 10e* web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit <http://www.prenhall.com/lutgens> and click on the cover of *The Atmosphere 10e* to find:

Online review quizzes

Critical thinking exercises

Links to chapter-specific web resources

Internet-wide key term searches

<http://www.prenhall.com/lutgens>