19

Air Pollution

Forest burning in Sumatra, 2013. This fire was one of thousands of fires, many of them intentionally set, in Sumatran rain forests in 2013.

For the past decade, Indonesia, Malaysia, Thailand, and other areas in Southeast Asia have suffered from periods of severe air pollution. Although air pollution in many places is associated with industry and transportation, agriculture and **silviculture** (commercial production of forest products) are often the culprits in Southeast Asia. Farmers set fires to clear forested areas for use as plantations. These fires can burn uncontrolled for days and weeks, creating a smoky haze that covers entire countries and causing extremely hazardous conditions.

Throughout Southeast Asia, serious smoke problems have been an annual problem since 1997. In 2006, two cargo ships collided in a Singapore harbor due to poor visibility. The following year, Malaysia, Singapore, and Indonesia agreed to reduce fires by 75% by 2012 and 90% by 2025, but despite increased law enforcement, the 2012 goal was not met. In 2014, more than 3,000 individual fires were thought to have been intentionally set on the island of Sumatra (**see photo**). These caused respiratory damage to as many as 50,000 people in Indonesia, as well as property and other damage. It is unclear whether the resulting agricultural benefits exceeded the costs associated with the smoke.

Our changing climate—both increased temperature and shifting precipitation—has led to increased smoke from wildfires. In California, wildfires endanger homes and spread smoke over suburban and urban populations. Likewise, extreme temperatures likely attributable to climate change destroyed forests across Russia, where plumes of smoke traveled hundreds of miles and enveloped Moscow in a haze.

Smoke, whether from fireplaces or forests, is hazardous. Small particles settle deep in the lungs, causing infection as well as reduced ability to breathe. Incomplete combustion of carbon-containing materials releases volatile organic chemicals and carbon monoxide, which interfere with oxygen uptake. Smoke can contain toxic amounts of phosphorus, potassium, nitrogen, sulfur, and metals. In addition, fires release substantial amounts of carbon dioxide—the most significant greenhouse gas.

Smoke is even a problem around San Francisco, California, which has some of the strictest air quality regulations in the world. On still winter nights, thousands of fireplaces provide comfort to people in their homes, raising smoke and carbon monoxide levels outside. And in the late summer, legal agriculture-related fires are set throughout California's Central Valley.

One of the earliest recorded environmental laws can be traced to 13th-century London: a ban on burning soft coal that resulted in dense, acidic smoke. Yet London's air quality continued to be notoriously bad for the ensuing seven centuries. Smoke is a major pollutant, from indoor wood smoke in Kenya to fluorine-laden coal smoke in central China to pesticide-laden smoke from California's wildfires.

In this chapter, we explore a range of sources, types, and effects of air pollutants, including smoke. We will see that, while technological improvements have reduced air pollution substantially in some areas, increased fuel use and industry continue to cause environmental damage, especially in less-developed countries.

In Your Own Backyard...

Does agricultural burning take place where you live? If so, for which crops?

The Atmosphere as a Resource

LEARNING OBJECTIVE

- Describe the composition of the atmosphere.

The atmosphere is a gaseous envelope surrounding Earth (see Figure 4.11). Excluding water vapor, four gases comprise most of the atmosphere: nitrogen (N_2, 78.08%), oxygen (O_2, 20.95%), argon (Ar, 0.93%), and carbon dioxide (CO_2, 0.04%). Other gases and particles, including those we call **pollutants**, occur in much smaller concentrations. The two atmospheric gases most important to humans and other organisms are carbon dioxide and oxygen. During *photosynthesis*, plants, algae, and certain bacteria use carbon dioxide to manufacture sugars and other organic molecules; this process produces oxygen. During *cellular respiration*, most organisms use oxygen to break down food molecules and supply themselves with chemical energy; this process produces carbon dioxide. Nitrogen gas is an important component of the nitrogen cycle. The atmosphere performs additional **ecosystem services**, namely, blocking Earth's surface from much of the ultraviolet (UV) radiation coming from the sun, moderating the climate, and redistributing water in the hydrologic cycle.

Living at the interface of Earth's surface and atmosphere, humans think of the atmosphere as an unlimited resource, but we should reconsider. **Ulf Merbold**, a German space shuttle astronaut, felt differently about the atmosphere after viewing it in space (**Figure 19.1**). "For the first time in my life, I saw the horizon as a curved line. It was accentuated by the thin seam of dark blue light—our atmosphere. Obviously, this wasn't the 'ocean' of air I had been told it was so many times in my life. I was terrified by its fragile appearance."

REVIEW

1. What are the primary constituents of the atmosphere?

SPL/Science Source

Figure 19.1 The atmosphere. The "ocean of air" is an extremely thin layer compared to the size of Earth. In this photo the atmosphere is a thin blue layer that separates the planet from the blackness of space.

Types and Sources of Air Pollution

LEARNING OBJECTIVES

- List the seven major classes of air pollutants, including ozone and hazardous air pollutants, and describe their effects.
- Explain how ozone-related air quality has changed in southern California over the past half century.

Air pollution consists of gases, liquids, or solids present in the atmosphere in high enough levels to harm humans, other organisms, or materials. Although air pollutants can come from natural sources, such as forest fires and volcanoes, human activities release many substances into the atmosphere and make a major contribution to air pollution. Some of these substances are harmful when they precipitate (form a solid) and settle on land and surface waters, whereas other substances are harmful because they alter the chemistry of the atmosphere. From the standpoint of human health, probably more significant than the overall human contribution to air pollution is the fact that much of the air pollution released by humans is concentrated in densely populated urban areas.

air pollution Various chemicals added to the atmosphere by natural events or human activities in high enough concentrations to be harmful.

Although many different air pollutants exist, we will focus on the seven most important types from a regulatory perspective: particulate matter, nitrogen oxides, sulfur oxides, carbon oxides, hydrocarbons, ozone, and air toxics (**Table 19.1**). Air pollutants are often divided into two categories, primary and secondary (**Figure 19.2**). **Primary air pollutants** are harmful chemicals that enter directly into the atmosphere. The major ones are carbon oxides, nitrogen oxides, sulfur dioxide, particulate matter, and hydrocarbons. **Secondary air pollutants** are harmful chemicals that form from other substances released into the atmosphere. Ozone and sulfur trioxide are secondary air pollutants because both are formed by chemical reactions that take place in the atmosphere.

primary air pollutant A harmful substance, such as soot or carbon monoxide, that is emitted directly into the atmosphere.

secondary air pollutant A harmful substance formed in the atmosphere when a primary air pollutant reacts with substances normally found in the atmosphere or with other air pollutants.

MAJOR CLASSES OF AIR POLLUTANTS

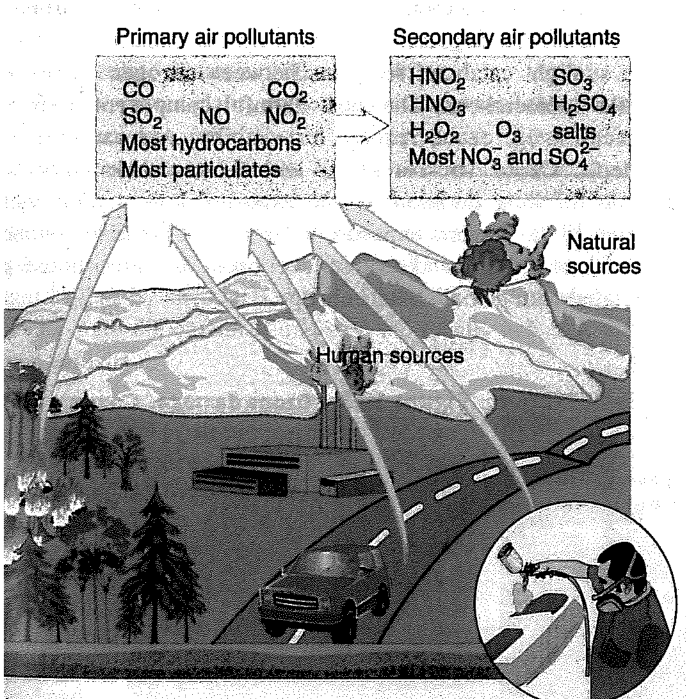
Particulate matter consists of thousands of different solid and liquid particles suspended in the atmosphere, and includes solid particulate matter (dust) and liquid suspensions (mists). Particulate matter includes soil particles, soot, lead, asbestos, sea salt, and sulfuric acid droplets. It reduces visibility by scattering and absorbing sunlight. Urban areas receive less sunlight than rural areas, partly as a result of greater quantities of particulate matter in the air. Particulate matter corrodes metals, erodes buildings and sculptures when the air is humid, and soils clothing and draperies.

Particulate matter can be dangerous to health in two ways. First, it may contain materials—such as heavy metals, asbestos, or organic chemicals—that have toxic or carcinogenic effects. These toxins, upon contacting or being absorbed into the body, have a range of effects. Second, extremely small particles, even if not toxic, can damage lung tissue and arteries. Microscopic particles

able 19.1 Major Air Pollutants

llutant	Composition	Primary or Secondary	Characteristics
rticulate Matter			
Dust	Variable	Primary	Solid particles
Lead	Pb	Primary	Solid particles
Sulfuric acid	H_2SO_4	Secondary	Liquid droplets
trogen Oxides			
Nitrogen dioxide	NO_2	Primary	Reddish-brown gas
lfur Oxides			
Sulfur dioxide	SO_2	Primary	Colorless gas with strong odor
rbon Oxides			
Carbon monoxide	CO	Primary	Colorless, odorless gas
Carbon dioxide*	CO_2	Primary	Colorless, odorless gas
drocarbons			
Methane	CH_4	Primary	Colorless, odorless gas
Benzene	C_6H_6	Primary	Liquid with sweet smell
one	O_3	Secondary	Pale-blue gas with acrid odor
r Toxics			
Chlorine	Cl_2	Primary	Yellow-green gas

iscussed in Chapter 20.
urce: Environmental Protection Agency. Compiled by authors.



gure 19.2 Primary and secondary air pollutants. Primary pollutants are emitted, unchanged, from a source directly into the mosphere, whereas secondary air pollutants are produced in the atmohere from chemical reactions involving primary air pollutants or other bstances normally found in the atmosphere.

ay be classified as PM-10 (particular matter less than 10 μm icrometers] in diameter) or PM-2.5 (particular matter less than 5 μm in diameter). The Environmental Protection Agency (EPA) mples microscopic particulate matter at about 1000 locations ound the United States so that it can better understand its comsition, which varies with location and season.

ENVIRONEWS

Dust and Prehistoric Art

Air pollution can cause aesthetic damage in a number of ways. In Oxford, England, acidic deposition is pitting centuries-old limestone statues. In Utah, dust has begun to obscure rock art, some of which is as much as 1000 years old.

Dust is often thought to be a natural problem in deserts, but undisturbed desert soils can be quite stable. However, as people drive cars and motorcycles in the desert, their tires disturb the soil, both generating dust and loosening earth that can become airborne with the next heavy wind. In some parts of Utah, magnesium chloride is applied to dirt roads to reduce dust. Unfortunately, the magnesium chloride can also settle on, and corrode, rock art.

Lead, a soft metal that is used in industrial and chemical processes, has a variety of health impacts. Acute lead poisoning rarely results from outdoor exposure, but chronic effects can include permanently reduced cognitive ability, behavioral problems, slowed growth, hearing problems, and headaches. Airborne lead can be a problem both when it is inhaled and when it settles—in water and on surfaces, including foods.

Nitrogen oxides are gases produced by the chemical interactions between atmospheric nitrogen and oxygen when a source of energy, such as combustion of fuels, produces high temperatures. Collectively known as NO_x, nitrogen oxides consist mainly of nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O). Nitrogen oxides inhibit plant growth and, when breathed, aggravate health problems such as asthma, a disease in which breathing is wheezy and labored because of airway constriction. They are involved in the production of photochemical smog and acid deposition (when nitrogen dioxide reacts with water to form nitric acid and nitrous acid). Nitrous oxide is associated with global warming (nitrous oxide traps heat in the atmosphere and is therefore a **greenhouse gas**) and depletes ozone in the stratosphere. Nitrogen oxides cause metals to corrode and textiles to fade and deteriorate.

Sulfur oxides are gases produced by the chemical interactions between sulfur and oxygen. Sulfur dioxide (SO_2), a colorless, nonflammable gas with a strong, irritating odor, is a major sulfur oxide emitted as a primary air pollutant. Another major sulfur oxide is sulfur trioxide (SO_3), a secondary air pollutant that forms when sulfur dioxide reacts with oxygen in the air. Sulfur trioxide, in turn, reacts with water to form another secondary air pollutant, sulfuric acid. Sulfur oxides cause acid deposition, and they corrode metals and damage stone and other materials. Sulfuric acid and sulfate salts produced in the atmosphere from sulfur oxides damage plants and irritate the respiratory tracts of humans and other animals.

Carbon oxides are the gases carbon monoxide (CO) and carbon dioxide (CO_2). Carbon monoxide, a colorless, odorless, and tasteless gas produced in larger quantities than any atmospheric pollutant except carbon dioxide, is poisonous and interferes with the blood's ability to transport oxygen. Carbon dioxide, also colorless, odorless, and tasteless, is a greenhouse gas; its buildup in the atmosphere is associated with global climate change.

Hydrocarbons are a diverse group of organic compounds that contain only hydrogen and carbon; the simplest hydrocarbon is methane (CH_4). Small hydrocarbon molecules are gaseous at room temperature. Methane is a colorless, odorless gas that is the principal component of natural gas. (The odor of natural gas comes from sulfur compounds deliberately added so that humans can indirectly detect the presence of the explosive methane gas by smelling the sulfur-containing compounds.) Medium-sized hydrocarbons such as benzene (C_6H_6) are liquids at room temperature, although many are volatile and evaporate readily. The largest hydrocarbons, such as the waxy substance paraffin, are solids at room temperature. The many different hydrocarbons have a variety of effects on human and animal health. Some cause no adverse effects, others injure the respiratory tract, and still others cause cancer. All except methane are important in the production of photochemical smog. Methane is a potent greenhouse gas linked to global climate change.

Ozone (O_3) is a form of oxygen considered an essential component in one part of the atmosphere but a pollutant in another. In the **stratosphere**, which extends from 12 to 50 km (7.5 to 30 mi) above Earth's surface, oxygen reacts with UV radiation coming from the sun to form ozone. Stratospheric ozone prevents much of the solar UV radiation from penetrating to Earth's surface. Unfortunately, certain human-made pollutants (chlorofluorocarbons, or CFCs) react with stratospheric ozone, breaking it down into molecular oxygen, O_2.

ozone A pale blue gas that is an essential com ponent that screens ou UV radiation in the upp atmosphere (stratosphere) but is a polluta in the lower atmosphe (troposphere).

Unlike stratospheric ozone, ozone in the **troposphere**—the layer of atmosphere closest to Earth's surface—is a human-made air pollutant. (Ground-level ozone does not replenish the ozone depleted from the stratosphere because ground-level ozone breaks down to form oxygen long before it drifts up to the stratosphere.) Ozone in the troposphere is a secondary air pollutant that forms when sunlight catalyzes reactions between nitrogen oxides and volatile hydrocarbons. The most harmful component of photochemical smog, ozone reduces air visibility and causes health problems. Ozone stresses plants and reduces their vigor, and chronic (of long duration) ozone exposure lowers crop yields (**Figure 19.3**). Chronic exposure to ozone is a possible contributor to forest decline, and ground-level ozone is a greenhouse gas associated with global climate change.

(a) (b)

Figure 19.3 Ozone damage. Compare the grape leaf grown in clean air (a) with the one damaged by ozone (b). Note the yellow/brown color and black spots on the damaged leaf. In contrast, the healthy leaf is a dark and even green, indicating that it has more chlorophyll. Plants exposed to ozone pollution exhibit other symptoms, including reduced root growth and a lowered productivity. Grapes exposed to ozone pollution exhibit a substantial reduction in yield.

Most of the hundreds of other air pollutants—such as chlorine, hydrochloric acid, formaldehyde, radioactive substances, and fluorides—are present in low concentrations, although it is possible to have high local concentrations of specific pollutants. Some of these air pollutants, known as **hazardous air pollutants (HAPs)**, or **air toxics**, are potentially harmful. HAPs come from many industrial, commercial, and residential activities, including bakeries, distilleries, dry cleaners, furniture makers, gasoline service stations, hospitals, auto paint shops, print shops, and barbeques.

hazardous air pollutants Air pollutants that are potentially harmful and may pose long-term health risks to people who live and work around chemical factories, incinerators, or other facilities that produce or use them.

SOURCES OF OUTDOOR AIR POLLUTION

The main human sources of primary air pollutants are transportation (**mobile sources**) and industries (**stationary sources**) (**Figure 19.4**), although intentional fires can also contribute significantly. Automobiles and trucks, known as mobile sources, generate significant quantities of nitrogen oxides, carbon oxides, particulate matter, and hydrocarbons as a result of the combustion of gasoline. Although diesel engines in trucks, buses, trains, and ships consume less fuel than other types of combustion engines, they produce more air pollution. One heavy-duty truck emits as much particulate matter as 150 automobiles.

Electric power plants and other industrial facilities, known as stationary sources, emit most of the particulate matter and sulfur oxides released in the United States; they emit sizable amounts of nitrogen oxides, hydrocarbons, and carbon oxides. The combustion of fossil fuels, especially coal, is responsible for most of these emissions. The top three industrial sources of toxic air pollutants—that is, chemicals released into the air that are fatal to humans—are the chemical industry, the metals industry, and the paper industry.

URBAN AIR POLLUTION

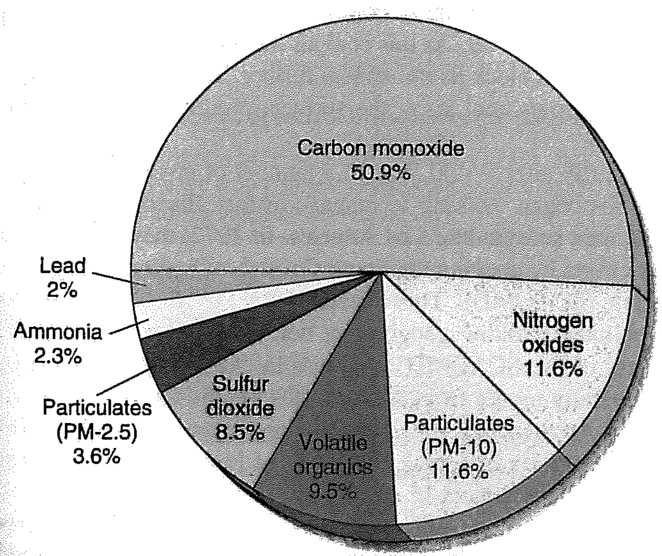
Air pollution localized in urban areas, where it reduces visibility, is often called **smog**. The word *smog* was coined at the beginning of the 20th century for the smoky fog that was so prevalent in London because of coal combustion. Smoke pollution is sometimes called **industrial smog**. The principal pollutants in industrial smog are sulfur oxides and particulate matter. The worst episodes of industrial smog typically occur during winter months, when combustion of household fuel such as heating oil or coal is high.

In December 1952, 4000 Londoners died in the world's worst industrial smog incident. An additional 8000 people died within the next two months, possibly due to the lingering effects of the smog, although the exact causes of death for these people have never been explained.

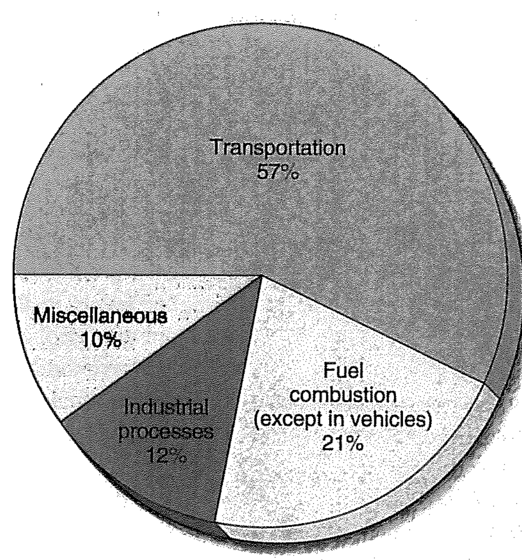
Because of air quality laws and pollution-control devices, industrial smog is generally not a significant problem in highly developed countries today, but it is often serious in many communities and industrial regions of developing countries.

Another important type of smog is **photochemical smog**. This brownish-orange smog is called photochemical because sunlight initiates several chemical reactions that collectively form its ingredients. First noted in Los Angeles in the 1940s, photochemical smog is generally worst during the summer months. Both nitrogen oxides and hydrocarbons are involved in its formation. One of the photochemical reactions occurs among nitrogen oxides (largely from automobile exhaust), volatile hydrocarbons, and oxygen in the atmosphere to produce ground-level ozone; this reaction requires solar energy (**Figure 19.5**). The ozone formed in this way then reacts with other air pollutants, including hydrocarbons, to form more than 100 different secondary air pollutants that injure plant tissues, irritate eyes, and aggravate respiratory illnesses in humans.

photochemical smog A brownish-orange haze formed by chemical reactions involving sunlight, nitrogen oxide, and hydrocarbons.

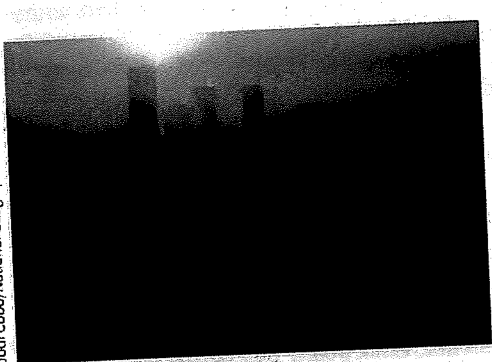


(a) Air pollutants. The concentrations of nitrogen oxides and volatile organics are an indirect measure of ozone, which is a secondary air pollutant formed in their presence.



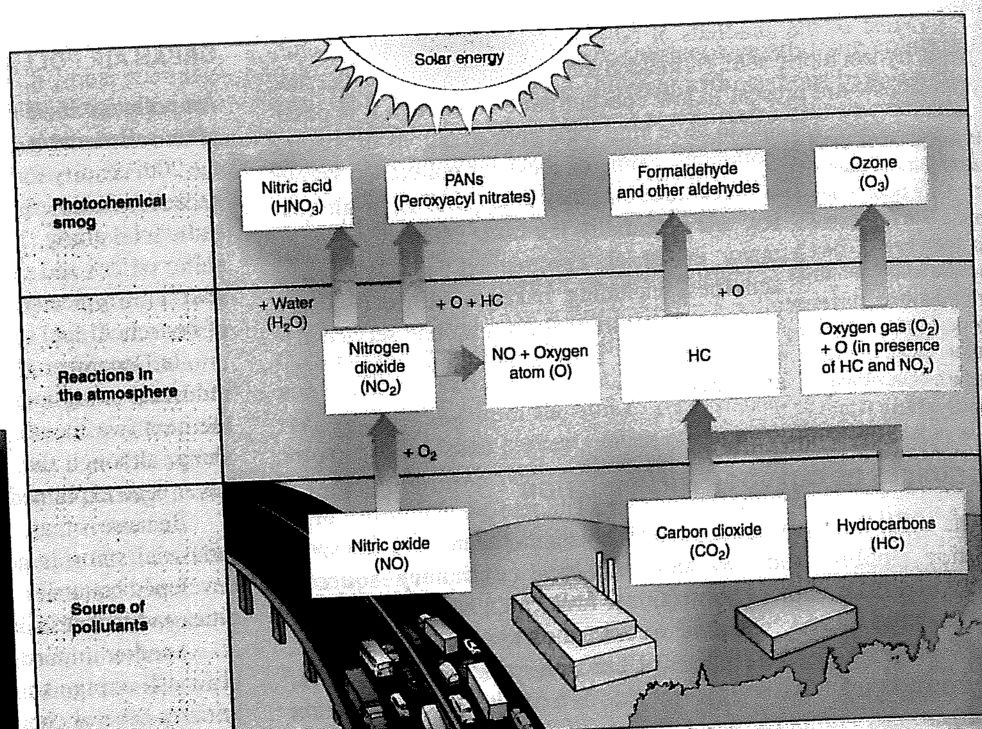
(b) Sources of air pollutants. Transportation and industrial fuel combustion (such as electric power plants) are major contributors of pollutants.

Figure 19.4 Air pollutants in the United States. (Environmental Protection Agency)



Jodi Cobb/National Geographic Creative

(a) Smog in Los Angeles is sometimes so bad it blocks out the sun.



(b) Several chemical reactions result in the complex mixture known as smog: ozone, peroxyacyl nitrates (PANs), nitric acid, and various organic compounds such as formaldehyde.

Figure 19.5 Photochemical smog.

CASE IN POINT

EFFORTS TO REDUCE OZONE IN SOUTHERN CALIFORNIA

Many human sources contribute to the ingredients of photochemical smog. Automobiles, as well as emissions from gasoline stations and oil refineries, are major significant contributors. But any process that releases **volatile organic compounds (VOCs)** contributes to smog production. For this reason, in many places where ozone is a problem there are restrictions on paints, cleaning products, dry cleaners, and even bakeries (when bread is baked, yeast byproducts that are VOCs are released to the atmosphere).

Both weather and topography affect air pollution. Variation in temperature during the day usually results in air circulation patterns that help dilute and disperse air pollutants. As the sun increases surface temperatures, the air near the ground is warmed. This heated air expands and rises to higher levels in the atmosphere (warm air is lighter and more buoyant than cool air), causing a low-pressure area near the ground. The surrounding air then moves into the low-pressure area. Thus, under normal conditions, air circulation patterns prevent toxic pollutants from increasing to dangerous levels near the ground.

During periods of **temperature inversion** polluting gases and particulate matter remain trapped in high concentrations close to the ground, where people live and breathe. Temperature inversions usually persist for only a few hours before being broken up by solar heating that warms the air near the ground. Sometimes, however, atmospheric stagnation caused by a stalled high-pressure air mass allows a temperature inversion to persist for several days.

Certain types of topography (surface features) increase the likelihood of temperature inversions. Cities located in valleys, near the coast, or on the leeward side of mountains (the side toward which the wind blows) are prime candidates for temperature inversions. The Los Angeles Basin is a plain that lies between the Pacific Ocean and mountains to the north and east. During the summer, the sunny climate produces a layer of warm, dry air at upper elevations. However, a region of upwelling occurs just off the Pacific coast, bringing cold ocean water to the surface and cooling the ocean air. As this cool air blows inland over the basin, the mountains block its movement further. Thus, a layer of warm, dry air overlies cool air at the surface, producing a temperature inversion.

Shortly after World War II, a number of governmental organizations began working to manage historically poor air quality in the area surrounding Los Angeles. In 1977, they consolidated their efforts by creating the South Coast Air Quality Management District (SCAQMD). This special agency was needed because air pollutants follow geographic, not political, boundaries. The borders of the SCAQMD represent an "air basin" in which the air generally moves from the west (the Pacific Ocean) to the east (toward Arizona and Nevada). It covers an area of nearly 18,000 km² (7,000 mi²), including part or all of four southern California counties, where almost 15 million people live.

While the rules and regulations of the SCAQMD comprise several large books, evidence suggests that just a few major regulations have been responsible for substantial improvements in air quality over the past five decades (**Figure 19.6**). In 1976, after a decade of improvement, ozone levels in the air basin still exceeded the federal "safe" standard of 0.12 ppm on 194 days and the state

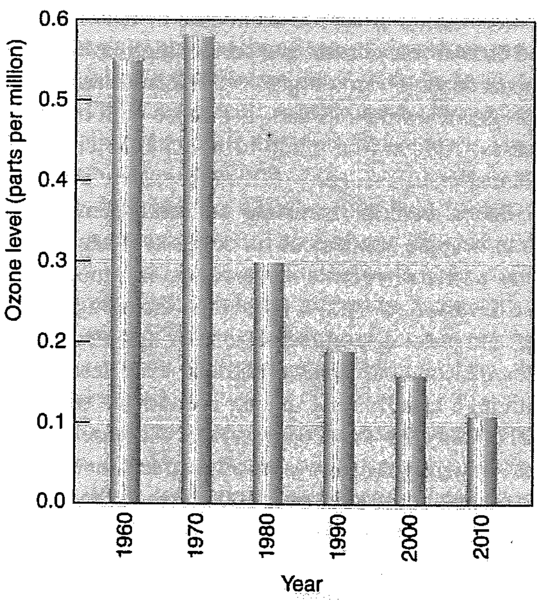


Figure 19.6 Peak ozone concentrations in southern California, 1960–2010. Peak ozone is the highest level of ozone recorded on any single day during the year. Average daily ozone, number of days above federal and state standards, and other measures show similar patterns. Air quality has improved steadily over the past half century but still presents a health threat. (South Coast Air Quality Management District)

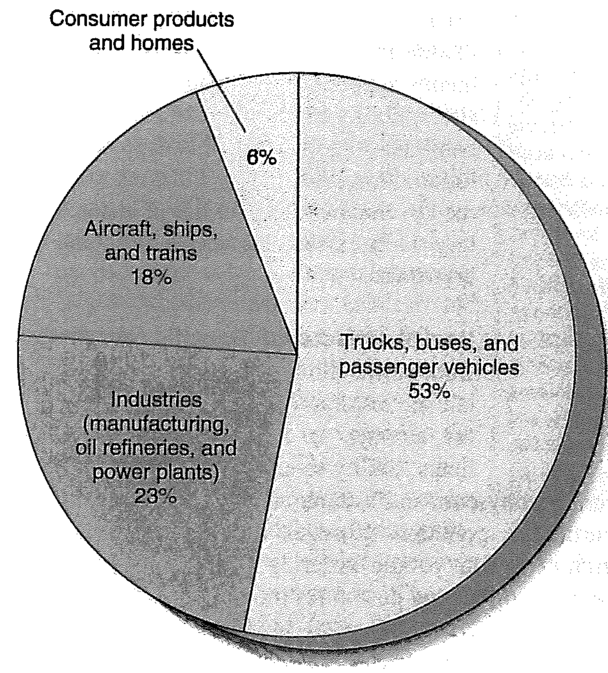


Figure 19.7 Sources of smog in Los Angeles. Trucks, buses, and passenger vehicles account for more than half of the emissions that produce smog.

standard of 0.09 ppm on 237 days. This means that the ozone levels were considered unsafe nearly two-thirds of the year! Ozone levels appeared to have reached a plateau from 1998 to 2003, but they dropped from 2003 to 2010.

Since ozone is created by a combination of high temperature, sunlight, hydrocarbons, water vapor, and oxides of nitrogen, some of those have to be controlled to reduce ozone. Only two of these components, hydrocarbons and oxides of nitrogen, can be controlled. Regulations to limit ozone formation have required restrictions on everything from combustion engines and oil refineries to charcoal lighter fluid and spray paints (**Figure 19.7**). ■

REVIEW

1. What are some effects of each of the seven major classes of air pollutants?
2. How and why have tropospheric ozone concentrations changed in southern California since World War II?

Effects of Air Pollution

LEARNING OBJECTIVES

- Describe the adverse health effects of specific air pollutants.
- Explain why children are particularly susceptible to air pollution.

Air pollution injures organisms, reduces visibility, and attacks and corrodes materials such as metals, plastics, rubber, and fabrics. The respiratory tracts of animals, including humans, are particularly harmed by air pollutants, which worsen existing medical conditions such as chronic lung disease, pneumonia, and cardiovascular problems (**Figure 19.8**). Most forms of air pollution reduce the overall productivity of crop plants, and when combined with other environmental stressors, such as extreme temperatures or prolonged droughts, air pollution causes plants to decline and die. Air pollution is involved in acid deposition, global climate changes, and stratospheric ozone depletion.

AIR POLLUTION AND HUMAN HEALTH

Generally speaking, exposure to even low levels of pollutants such as ozone, sulfur oxides, nitrogen oxides, and particulate matter can

Figure 19.8 Caution: Air pollution is hazardous to your health. How does this cartoon depict a system out of balance?

emphysema A disease in which the air sacs (alveoli) in the lungs become irreversibly distended, decreasing the efficiency of respiration and causing breathlessness and wheezy breathing.

chronic bronchitis A disease in which the air passages (bronchi) of the lungs become permanently inflamed, causing breathlessness and chronic coughing.

irritate eyes and inflame the respiratory tract (**Table 19.2**). Evidence shows that many air pollutants suppress the immune system, increasing susceptibility to infection. In addition, evidence continues to accumulate that exposure to air pollution during respiratory illnesses may result in the development later in life of chronic respiratory diseases, such as **emphysema** and **chronic bronchitis**.

Health Effects of Specific Air Pollutants

Both sulfur dioxide and particulate matter irritate the respiratory tract and, because they cause the airways to constrict, actually impair the lungs' ability to exchange gases. People suffering from emphysema and asthma are sensitive to sulfur dioxide and particulate pollution. Nitrogen dioxide also causes airway constriction and, in people suffering from asthma, an increased sensitivity to pollen and dust mites (microscopic animals found in household dust).

One of the largest studies conducted on the effects of particulate pollution on human health, conducted by the American Lung Association, tracked the causes of death for more than 319,000 people in all 50 states. The study compared mortality data with air pollution levels—specifically, PM-2.5—in their communities. (Coal-fired power plants and diesel engines are the main emitters of tiny airborne soot particles.) Because so many people were included in the study, scientists could discount the effects of tobacco, obesity, diet, and other disease factors related to death rates. The study found that people who live and work in the country's most polluted areas are more likely to die prematurely from specific kinds of heart disease than those living in U.S. cities with the cleanest air. The soot is inhaled and lodges in the lung tissue, causing an inflammation reaction that triggers a number of processes that clog arteries leading to the heart.

Carbon monoxide binds irreversibly with iron in the blood's hemoglobin, eliminating its ability to transport oxygen. At medium concentrations, carbon monoxide causes headaches and fatigue. As the concentration of carbon monoxide increases, reflexes slow down and drowsiness occurs: at a certain high level, carbon monoxide causes death. People at greatest risk from carbon monoxide include pregnant women, infants, and those with heart or respiratory diseases. A four-year study in seven U.S. cities—Chicago, Detroit, Houston, Los Angeles, Milwaukee, New York, and Philadelphia—linked carbon monoxide concentrations in the air to increases in hospital admissions for congestive heart failure.

Ozone and the volatile compounds in smog are irritants that cause a variety of health problems, including burning eyes, coughing, and chest discomfort. Ozone brings on asthma attacks, suppresses the immune system, and can even lead to premature death, although usually only among individuals who are already ill. A 2010 study by the Congressional Research Service suggested that changing the maximum allowable ozone standard from 75 ppb to 60 ppb could save over 1000 lives each year and reduce school days missed by children made ill by ozone by as many as a million.

The health effects of about 150 hazardous air pollutants produced by motor vehicles, businesses, and industries have not been widely studied, although long-term exposure to certain air toxics has been linked to cancer. The Environmental Defense Fund estimates that 360 people out of every million Americans develop cancer as a result of air toxics, although the cancer rate varies widely from one place to another.

Children and Air Pollution

As is true of essentially all environmental stressors, air pollution is a greater health threat to children than it is to adults. Lungs develop throughout childhood, and air pollution can restrict lung development, making children more vulnerable to health problems later in life. In addition, a child has a higher metabolic rate than an adult and needs more oxygen. To obtain this oxygen, a child breathes more air—about two times as much air per pound of body weight as an adult. This means that a child breathes more air pollutants into the lungs. A 1990 study in which autopsies were performed on 100 Los Angeles children who died for unrelated reasons found that more than 80% had early-stage lung disease.

Table 19.2 Health Effects of Several Major Air Pollutants

Pollutant	*Source*	*Effects*
Particulate matter	Industries, electric power plants, motor vehicles, construction, agriculture	Aggravates respiratory illnesses; long-term exposure may cause increased incidence of chronic conditions such as bronchitis; linked to heart disease; suppresses immune system; some particles, such as heavy metals and organic chemicals, may cause cancer or other tissue damage
Nitrogen oxides	Motor vehicles, industries, heavily fertilized farmland	Irritate respiratory tract; aggravate respiratory conditions such as asthma and chronic bronchitis
Sulfur oxides	Electric power plants and other industries	Irritate respiratory tract; same effects as particulates
Carbon monoxide	Motor vehicles, industries, fireplaces	Reduces blood's ability to transport oxygen; headache and fatigue at lower levels; mental impairment or death at high levels
Ozone	Formed in atmosphere (secondary air pollutant)	Irritates eyes; irritates respiratory tract; produces chest discomfort; aggravates respiratory conditions such as asthma and chronic bronchitis

A 10-year study of about 5000 children in 12 communities in southern California examined the effects of chronic exposure to air pollution on children's developing lungs. Results from this study, which ended in 2001, indicate that children who live in high-ozone areas and participate in sports are more likely to develop asthma than children who live there but do not participate in sports. In addition, results indicate that children who breathe the most polluted air (higher concentrations of nitrogen dioxide, particulate matter, and acid vapor) have less lung growth than children who breathe cleaner air. If the children moved to areas with less particulate air pollution, their lung development increased, but if they moved to areas with worse particulate air pollution, their lung development decreased.

Exposure to lead is also a particular concern for young children. It can slow development and lead to permanent reductions in mental ability. While lead levels have been reduced substantially over the past several decades, in 2008 the EPA reduced its acceptable level from 1.5 μg per m^3 to 0.15 μg per m^3, based on evidence of the effects lead has on the very young.

REVIEW

1. What is the general effect of air pollution on the body's immune system?
2. Why are children particularly susceptible to the effects of air pollution?

Controlling Air Pollution in the United States

LEARNING OBJECTIVES

- Provide several examples of air pollution-control technologies.
- Summarize the effects of the Clean Air Act on U.S. air pollution.

There is bad and good news about air pollution in the United States. The bad news is that many locations throughout the country still have unacceptably high levels of one or more air pollutants. Moreover, most health experts estimate that air pollution causes the premature deaths of thousands of people in the United States each year. The good news is that, overall, air quality has improved since 1970. This improvement in air quality is largely due to the U.S. Clean Air Act and state-level air quality initiatives.

CONTROLLING AIR POLLUTANTS

Historically, "command-and-control" technologies have been used to reduce emissions. Usually, this means equipment that limits the emissions after they have been generated. However, this technological approach can be more expensive than alternatives such as changing industrial processes to reduce emissions.

Smokestacks fitted with *electrostatic precipitators*, fabric filters, *scrubbers*, or other technologies remove particulate matter (**Figure 19.9**). In addition, particulate matter is controlled by careful land-excavating activities, such as sprinkling water on dry soil being moved during road construction.

Several methods remove sulfur oxides from flue (chimney) gases, but it is often less expensive simply to switch to a low-sulfur fuel such as natural gas or even to a non–fossil-fuel energy source such as solar energy. Sulfur can be removed from fuels before they are burned, as in coal gasification (see Figure 11.19).

Gasoline is extremely volatile, and gasoline vapors can be a major source of VOCs. To reduce these emissions, gasoline sellers in most urban (and many rural) parts of the world require some form of **vapor recovery**. *Phase I vapor recovery* involves underground storage tanks at gas stations (**Figure 19.10**). As one hose from a delivery truck fills the underground tank, another returns the vapors in the tank—which otherwise would be vented to the atmosphere—to the truck. The truck then returns to the gasoline depot, where the vapors are either combusted or condensed into gasoline. *Phase II vapor recovery* involves removing vapor from gas tanks in cars as the gas is pumped in. These vapors are usually returned to the underground tank for removal in the phase I process.

vapor recovery The removal of unburned gasoline vapors from gasoline containers, including underground tanks at gas stations and automobile gas tanks. Recovered vapors are either burned or condensed.

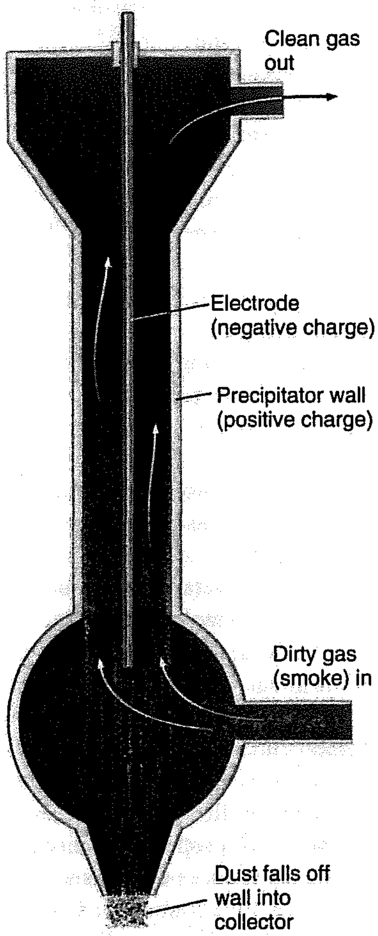
Lower combustion temperature in automobile engines reduces the formation of nitrogen oxides. Mass transit reduces automobile use, thereby decreasing nitrogen oxide emissions. Nitrogen oxides produced during high-temperature combustion processes in industry can be removed from smokestack exhausts. The release of nitrogen oxides from cultivated fields to which nitrogen fertilizers were applied is reduced significantly when no-tillage is practiced.

Advanced furnaces and engines burn more cleanly, reducing production of both carbon monoxide and hydrocarbons. **Catalytic converters**, used immediately following combustion, oxidize most unburned gases, and the use of properly functioning catalytic converters to treat auto exhaust reduces carbon monoxide and volatile hydrocarbon emissions by about 85%. Careful handling of petroleum and hydrocarbons, such as gasoline, paint thinner, and lighter fluid, reduces air pollution from spills and evaporation.

Reducing the sulfur content in gasoline from its current average of 330 parts per million (ppm) could significantly reduce air pollution. (Parts per million is the number of molecules of a particular pollutant found in a million molecules of air, water, or some other material.) Sulfur clogs catalytic converters so that they cannot effectively remove emissions from automobile exhaust. California, Canada, and the European Union have restricted the allowable amount of sulfur in gasoline.

Minivans, sport-utility vehicles (SUVs), and light pickup trucks, which account for almost 50% of new passenger vehicles, currently do not have the same federal standards as automobiles. These larger vehicles produce more than twice the pollution of a car. However, beginning in model year 2009, the **corporate average fuel economy**, or **CAFE**, standard required that the average fuel economy of all covered vehicles sold by a single company be 27.5 miles per gallon (mpg); this average has increased each subsequent year. One strategy to improve mileage is to shift to low carbon fuels (see Meeting the Challenge: States Adopt Low Carbon Fuel Standard).

Many states, such as California, New York, New Jersey, and Connecticut, now require diesel trucks and buses to undergo emissions tests similar to those that these states have required for automobiles for many years. Diesel exhaust, particularly particulate matter, is viewed as a toxic pollutant. Public health advocates maintain that breathing diesel exhaust may contribute to asthma, an increased incidence of lung cancer, and other lung diseases.



(a) In an electrostatic precipitator, the electrode imparts a negative charge to particles in the dirty gas. These particles are attracted to the positively charged precipitator wall and then fall off into the collector.

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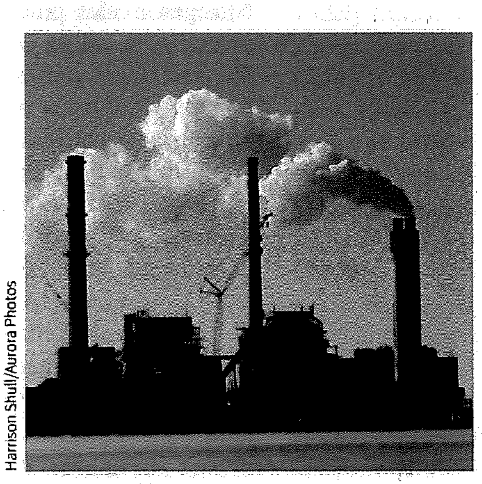
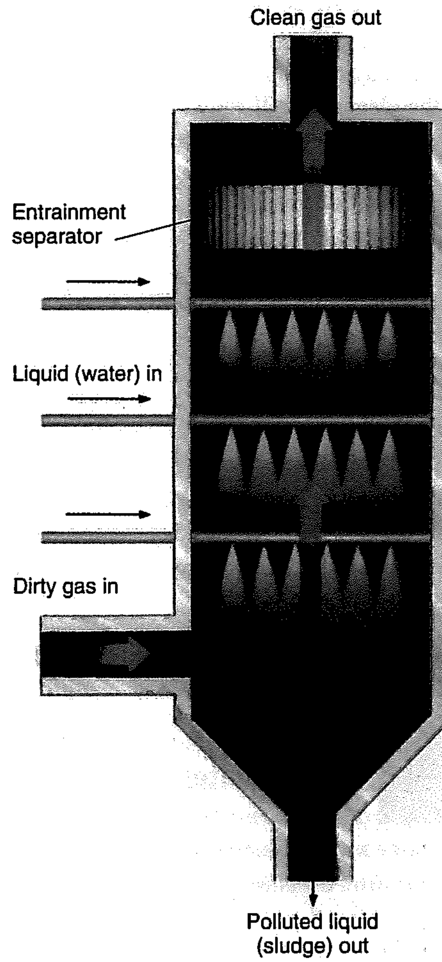
(b) When emissions are not controlled, facilities like this aluminum smelter in China release large amounts of particulate matter.



Harrison Shull/Aurora Photos

(c) With a scrubber system in place, most particulate matter is removed, leaving only steam. Photographed in South Ashville, NC.



(d) In a scrubber, mists of water droplets trap particulates in the dirty gas. The toxic dust produced by electrostatic precipitators and the polluted sludge produced by scrubbers must be safely disposed of or they will cause soil and water pollution. (a and d adapted from M. D. Joesten and J. L. Wood, *World of Chemistry*, 2nd ed. Philadelphia: Saunders College Publishing [1996])

Figure 19.9 Electrostatic precipitator and scrubber.

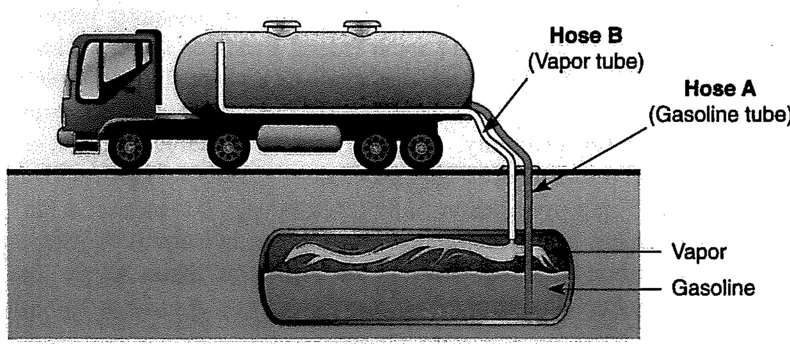
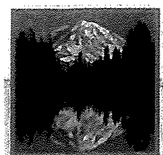


Figure 19.10 Phase I vapor recovery. Phase I vapor recovery removes vapors from the empty space above the gasoline in underground gasoline tanks.



MEETING THE CHALLENGE

States Adopt Low Carbon Fuel Standard

Historically, many of the world's environmental regulations have begun with a few states or cities deciding to deal with their own environmental problems and generating solutions that were subsequently adopted by other states, the United States as a whole, and other countries. This innovation continues with California's decision to adopt a **low carbon fuel standard (LCFS)** for fuel sold in the state beginning in 2020. Several states, including Florida and Oregon, as well as the Canadian province of British Columbia, have adopted similar approaches.

The California standard, established by an executive order of the governor, is based on two concerns: global climate change and reliance on foreign oil. Currently, oil is the energy source for 96% of the state's transportation and contributes 40% of its carbon emissions. And while California produces some oil, it imports the majority of what it uses, making it one of the largest oil importers in the world.

The goal of the LCFS is to reduce the **carbon intensity**, or amount of carbon produced per unit of energy, of fuel used in passenger vehicles by 10% or more by 2020. This means that alternative fuels—including biomass, hydrogen, and electricity—would represent a larger share of the fuel supply. Natural gas, a fossil fuel, could also play a role, since it has a lower carbon intensity than does gasoline.

Reducing the carbon content of fuels simultaneously reduces other air pollutants with local or region effects. Ground-level ozone, oxides of nitrogen, and particulates are the most impacted, but some reductions in oxides of sulfur can be expected as well. The expected effect on ozone is twofold. First, less carbon also means fewer of the precursors to ozone—recall that ozone is a secondary pollutant, produced by a combination of oxides of nitrogen and carbon-containing volatile organic compounds. Second, reducing carbon should mean less atmospheric warming. Since ozone formation requires not only chemicals but also high temperatures, less warming will mean fewer days with high enough temperatures to allow ozone formation.

THE CLEAN AIR ACT

The first air quality legislation in the United States was the Air Pollution Control Act of 1955. However, the **Clean Air Act** of 1970 (with updates in 1977 and 1990) set the standard for modern air quality regulation. This law authorizes the EPA to set limits on the amount of specific air pollutants permitted everywhere in the United States. Individual states are responsible for meeting deadlines for air pollution standards. States may pass stronger pollution controls than the EPA authorizes, but they cannot mandate weaker limits than those stipulated in the Clean Air Act.

Based on the Clean Air Act, the EPA has established maximum acceptable concentrations for lead, particulate matter, sulfur dioxide, carbon monoxide, nitrogen oxides, and ozone. The most dramatic improvement is in the amount of lead in the atmosphere, which showed a 98% decrease between 1970 and 2006, primarily because of the switch from leaded to unleaded gasoline. Atmospheric levels of the other pollutants are also reduced (**Figure 19.11**). For example, between 1970 and 2012, sulfur dioxide emissions declined 80%. During this same period, energy consumption increased by about 50%.

Although air quality is gradually improving, over 80 million metric tons of pollutants are emitted into U.S. air each year. The atmosphere in many urban areas still contains higher levels of pollutants than are recommended on the basis of health standards, although air quality regulations over the past several decades have led to significant improvements in many metropolitan areas (**Table 19.3**). In EPA language, these cities are classified as nonattainment areas for one or more criteria air pollutants. Nonattainment areas are classified on the basis of how badly polluted they are. This classification ranges from marginal (somewhat polluted and relatively easy to clean up) to extreme (so polluted that it will take many years to clean up the air). The EPA estimates that over 200 million Americans currently live in nonattainment areas.

The Clean Air Act and its amendments required progressively stricter controls of motor vehicle emissions. The provisions of the

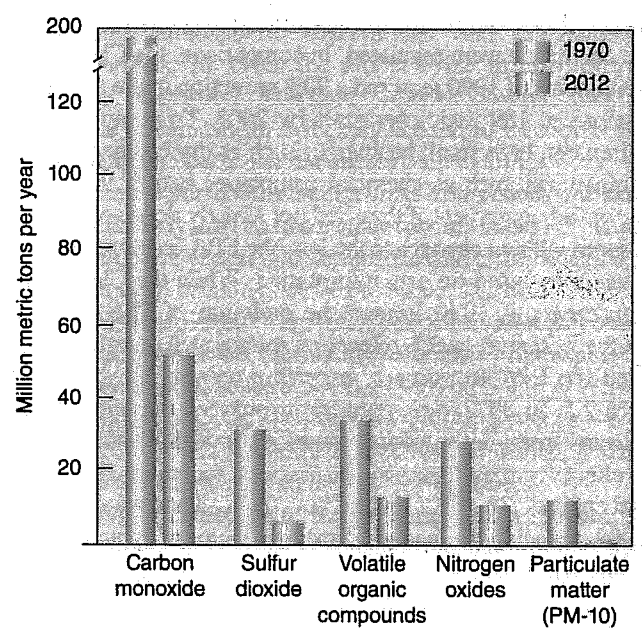


Figure 19.11 Emissions in the United States, 1970 and 2012. Carbon monoxide, sulfur dioxide, volatile organic compounds (many of which are hydrocarbons), particulate matter, and nitrogen oxides showed decreases. PM-10 applies to particles less than or equal to 10 μm (10 micrometers) in size. Since 1990, the EPA has also monitored PM-2.5, which are small particles less than or equal to 2.5 μm. (Air Quality Planning and Standards, Office of Air and Radiation, EPA.)

Clean Air Act Amendments of 1990 include the development of "superclean" cars, which emit lower amounts of nitrogen oxides and hydrocarbons, and the use of cleaner-burning gasoline in the most polluted cities in the United States. These changes were phased in gradually by the year 2000. More recent automobile models do not produce as many pollutants as older models. Yet despite the increasing percentage of newer automobile models on the road, air

Table 19.3 U.S. Urban Areas with the Worst Air Quality in 1999 (Ozone Nonattainment Areas), and Conditions in the Same Locations in 2009.

	1999	*2013*
Los Angeles South Coast Air Basin, California	Extreme	Extreme
Chicago, Gary, and Lake County, Illinois–Indiana	Very severe	Marginal
Houston, Galveston, and Brazoria, Texas	Very severe	Marginal
Milwaukee and Racine, Wisconsin	Very severe	No longer listed
New York City, northern New Jersey, and Long Island, New York –New Jersey–Connecticut	Very severe	Marginal
Baltimore, Maryland	Severe	Moderate
Philadelphia, Wilmington, Trenton, Pennsylvania–New Jersey –Delaware–Maryland	Severe	Marginal
Sacramento, California	Severe	Severe
San Joaquin Valley, California	Severe	No longer listed
Ventura County (between Santa Barbara and Los Angeles), California	Severe	Serious

quality has not improved in some areas of the United States because of the large increase in the number of cars being driven.

The Clean Air Act Amendments of 1990 focus on industrial airborne toxic chemicals in addition to motor vehicle emissions. Between 1970 and 1990, the airborne emissions of only seven toxic chemicals were regulated. In comparison, the Clean Air Act Amendments of 1990 required a 90% reduction in the atmospheric emissions of 189 toxic chemicals by 2003. To comply with this requirement, both small businesses such as dry cleaners and large manufacturers such as chemical companies had to install pollution-control equipment if they had not already done so.

Even without changes to the law, the EPA continues to change its standards based on new information. While the Clean Air Act Amendments of 1990 limited the emission of PM-10, concern over the potential health effects of microscopic particulate matter led the EPA to propose separate standards on the emission of PM-2.5. In 2007, new regulations reduced the allowable soot emissions from diesel trucks, and in 2012, a similar change went into effect for diesel tractors, bulldozers, locomotives, and other diesel engines. The EPA revised both the lead and ozone standards in 2008, reducing the lead standard by a factor of 10 and the ozone standard by about 5%.

REVIEW

1. What are some technologies that reduce air pollution? Some policies?
2. What is the U.S. Clean Air Act, and how has it reduced outdoor air pollution?

Ozone Depletion in the Stratosphere

LEARNING OBJECTIVES

- Define *stratospheric ozone thinning* and explain how chlorofluorocarbons and other chemicals reduce stratospheric ozone.
- Describe some of the harmful effects of ozone depletion.
- Explain the policy response to ozone depleting chemicals.

Ozone (O_3) is a form of oxygen that is a human-made pollutant in the troposphere but a naturally produced, essential component in the stratosphere, which encircles our planet some 10 to 45 km (6 to 28 mi) above the surface. The relatively high concentrations of ozone in the stratosphere form a layer that shields the surface from much of the **ultraviolet (UV) radiation** coming from the sun (**Figure 19.12**).

ultraviolet (uv) radiation That part of the electromagnetic spectrum with wavelengths just shorter th visible light.

Scientists divide UV radiation into three bands: UV-A (with wavelengths of 320 to 400 nm), UV-B (280 to 320 nm), and UV-C (200 to 280 nm). (A nanometer, abbreviated nm, is one-billionth of a meter.) The shorter the wavelength, the more energetic and more dangerous UV radiation is. Fortunately, oxygen and ozone in the atmosphere absorb all incoming UV-C (the most lethal wavelengths). The ozone layer absorbs most incoming UV-B radiation. UV-A is not affected by ozone, and most of it reaches the surface.

STRATOSPHERIC OZONE THINNING

The ozone layer over Antarctica thins naturally for a few months each year. In 1985, however, **stratospheric ozone thinning** was first observed to be greater than could be explained by natural causes. This increased thinning, which occurs each September, is commonly referred to as the *ozone hole* (**Figure 19.13**). During the 1990s, the ozone-thin area continued to grow. By 2000 it had reached the record size of 29.2 million km^2 (11.4 million mi^2). A smaller thinning has also been detected in the stratospheric ozone layer over the Arctic. In addition, world levels of stratospheric ozone have decreased for several decades. According to the National Center for Atmospheric Research, ozone levels over Europe and North America dropped almost 10% between the 1970s and the early 2000s. Since about 2005, data suggest a slow but consistent increase in stratospheric ozone.

stratospheric ozone thinning The accelerated destruction of ozone in the stratosphere by human-produced chlorine- an bromine-containing chemicals.

Both chlorine- and bromine-containing substances catalyze ozone destruction. The primary chemicals responsible for release of chlorine in the stratosphere, thus causing ozone depletion, are

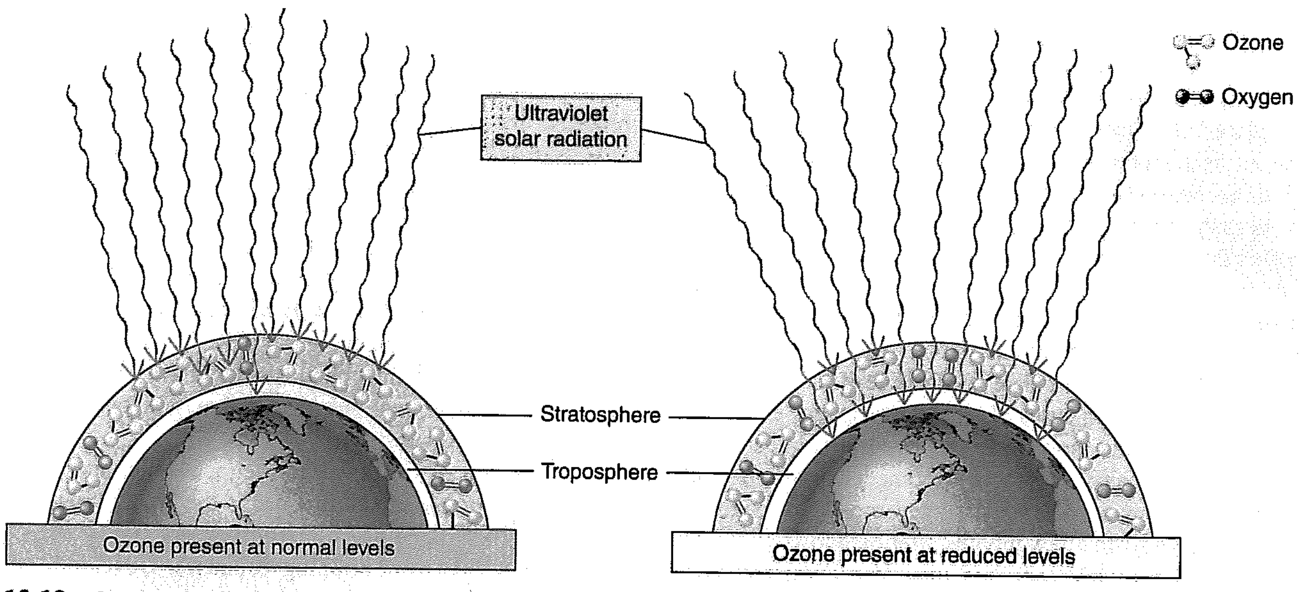
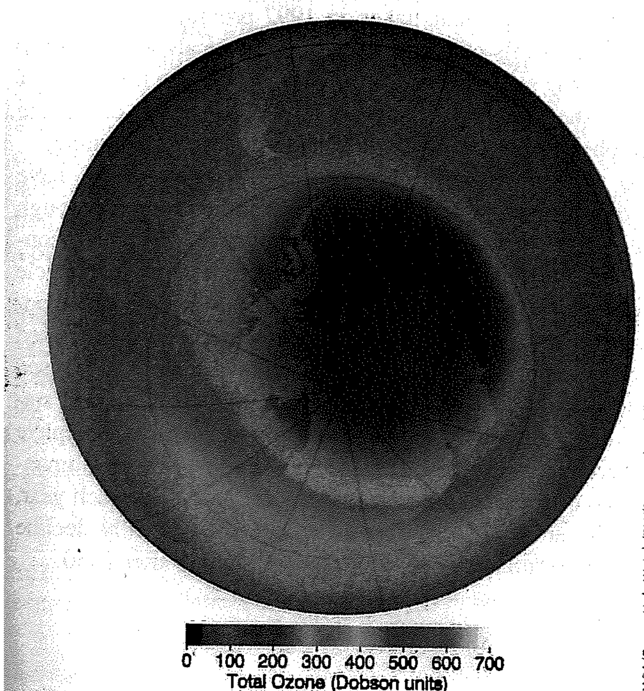


Figure 19.12 Stratospheric ozone layer.



NASA/Ozone Hole Watch/REX/Features/ AP Photos

Figure 19.13 Ozone thinning. A computer-generated image of part of the Southern Hemisphere, taken in October 2013, reveals ozone thinning (bluish-purple area over Antarctica). The ozone-thin area is not stationary but moves about as a result of air currents.

orofluorocarbons (CFCs) Human-made anic compounds of rbon, chlorine, and rine that had many industrial and comial applications but re banned because y attack the stratopheric ozone layer.

chlorofluorocarbons (CFCs). Chlorofluorocarbons were used as propellants for aerosol cans, as coolants in air conditioners and refrigerators (e.g., Freon), as foam-blowing agents for insulation and packaging, and as solvents.

Halons, methyl bromide, methyl chloroform, and carbon tetrachloride also release chlorine or bromine and thus lead to ozone depletion. Halons are used as fire retardants and methyl bromide is used as a pesticide. Methyl chloroform and carbon tetrachloride are industrial solvents.

The evidence linking CFCs and other human-made compounds to stratospheric ozone destruction includes laboratory measurements, atmospheric observations, and calculations by computer models. In 1995, the Nobel Prize in chemistry was awarded to **Sherwood Rowland**, **Mario Molina**, and **Paul Crutzen**, the scientists who first explained the connection between the thinning ozone layer and chemicals such as CFCs.

CFCs and other chlorine-containing compounds released at ground level slowly drift up to the stratosphere, where UV radiation breaks them down, releasing chlorine. Similarly, the breakdown of halons and methyl bromide releases bromine. The hole in the ozone layer that was discovered over Antarctica occurs annually between September and November (spring in the Southern Hemisphere). At this time, two important conditions are present: Sunlight returns to the polar region, and the **circumpolar vortex** develops—a mass of cold air that circulates around the southern polar region and isolates it from the warmer air on the rest of the planet.

The cold air causes polar stratospheric clouds to form; these clouds contain ice crystals to which chlorine and bromine adhere, making them available to destroy ozone. The sunlight catalyzes the chemical reaction in which chlorine or bromine breaks ozone molecules apart, converting them into oxygen molecules. The chemical reaction that destroys ozone does not alter the chlorine or bromine, and one chlorine or bromine atom can break down many thousands of ozone molecules. When the circumpolar vortex breaks up, the ozone-depleted air spreads northward, diluting ozone levels in the stratosphere over South America, New Zealand, and Australia.

THE EFFECTS OF OZONE DEPLETION

With depletion of the ozone layer, higher levels of UV radiation reach Earth's surface. A study conducted in Toronto from 1989 to 1993 showed that wintertime levels of UV-B increased more than 5% each year as a result of lower ozone levels. A study in New Zealand showed that summertime levels of peak UV-B radiation were 12% higher during the 1998–1999 summer than during similar periods a decade earlier.

Excessive exposure to UV radiation is linked to several health problems in humans, including cataracts, skin cancer, and weakened immunity. The lens of the eye contains transparent proteins that are replaced at a slow rate. Exposure to excessive UV radiation damages these proteins; over time, the damage accumulates so that the lens becomes cloudy, forming a cataract. Cataracts can be cured by surgery, but millions of people in developing countries cannot afford the operation and so remain partially or totally blind.

Excessive, chronic exposure to UV radiation causes most cases of skin cancer. Ultraviolet B radiation causes mutations, or changes, in the deoxyribonucleic acid (DNA) residing in skin cells. Such changes gradually accumulate and may lead to skin cancer. Globally, about 2.2 million cases of skin cancer occur each year. Malignant melanoma, the most dangerous type of skin cancer, is increasing faster than any other type of cancer (**Figure 19.14**). Some forms of malignant melanoma spread rapidly through the body and may cause death a few months after diagnosis.

Increased levels of UV radiation may also disrupt ecosystems. For example, the productivity of Antarctic phytoplankton, the microscopic drifting algae that are the base of the Antarctic food web, has declined from increased exposure to UV radiation. In the Antarctic, increased DNA mutations in ice-fish eggs and larvae (young fish) were matched to increased levels of UV radiation. Because organisms live in interdependent ecosystems, a negative effect on one species has ramifications throughout the system. High levels of UV radiation may also damage crops and forests. For example, exposure to higher levels of UV radiation makes cucumber crops more susceptible to disease.

FACILITATING THE RECOVERY OF THE OZONE LAYER

In 1978 the United States, the world's largest user of CFCs, banned the use of CFC propellants in products such as antiperspirants and hair sprays. Although this ban was a step in the right direction, it did not solve the problem. Most nations did not follow suit, and besides, propellants represented only the tip of the iceberg in terms of CFC use.

ISM/Phototake

Figure 19.14 Malignant melanoma on the back of the leg. These tumors of pigmented cells sometimes, but not always, arise from preexisting moles. Early diagnosis is important because this form of skin cancer spreads to other parts of the body and can be fatal.

In 1987, representatives from many countries met in Montreal to sign the **Montreal Protocol**, an agreement that originally stipulated a 50% reduction of CFC production by 1998. After scientists reported that decreases in stratospheric ozone occurred over the heavily populated midlatitudes of the Northern Hemisphere in all seasons, the Montreal Protocol was modified to include stricter measures to limit CFC production.

Industrial companies that manufacture CFCs quickly developed substitutes, such as hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs). HFCs do not attack ozone, although they are potent greenhouse gases. HCFCs attack ozone but are not as destructive as the chemicals they have replaced. HFCs and HCFCs are transitional substances that will be used only until industry develops substitutes.

Production of CFCs, carbon tetrachloride, and methyl chloroform was completely phased out in the United States and other highly developed countries in 1996, except for a relatively small amount exported to developing countries. Developing countries phased out CFC use in 2005. Methyl bromide was phased out in 2005. HCFCs will be phased out in 2030.

Satellite measurements taken in 1997 provided the first evidence that the levels of ozone-depleting chemicals were starting to decline in the stratosphere. In the early 2000s, the first signs of recovery of the ozone layer were evident: Measurement of the rate of stratospheric ozone depletion indicated that it was declining.

Two chemicals—CFC-12 and halon-1211—may have increased and still represent a threat to ozone recovery. Although highly developed countries no longer manufacture CFC-12, it continues to leak into the atmosphere from old refrigerators and vehicle air conditioners discarded in those countries. Moreover, developing countries such as China, India, and Mexico have increased their production of CFC-12. In contrast, halon use has been phased out worldwide since 2006. Unfortunately, CFCs are extremely stable, and those being used today probably will continue to deplete stratospheric ozone for at least 50 years. Scientists expect human-exacerbated ozone thinning to reappear over Antarctica each year, although the area and degree of thinning will gradually decline over time, until full recovery takes place sometime after 2050.

REVIEW

1. What is the stratospheric ozone layer?
2. How does stratospheric ozone thinning occur?
3. How did the Montreal Protocol reverse ozone depletion?

Acid Deposition

LEARNING OBJECTIVES

- Explain how acid deposition develops and describe some of its effects.
- Define *forest decline* and explain its possible causes.
- Describe the challenges associated with reducing acid deposition.

What do fishless lakes in the Adirondack Mountains, recently damaged Mayan ruins in southern Mexico, and dead trees in the Czech Republic have in common? The answer is that these damages are

acid deposition Sulfur dioxide and nitric oxide emissions react with water vapor in the atmosphere to form acids that return to the surface as either dry or wet deposition.

the result of acid precipitation or, more properly, **acid deposition**. It includes sulfuric and nitric acids in precipitation **(wet deposition)** as well as dry particles of sulfuric acid and nitric acid that settle out of the air (**dry deposition**).

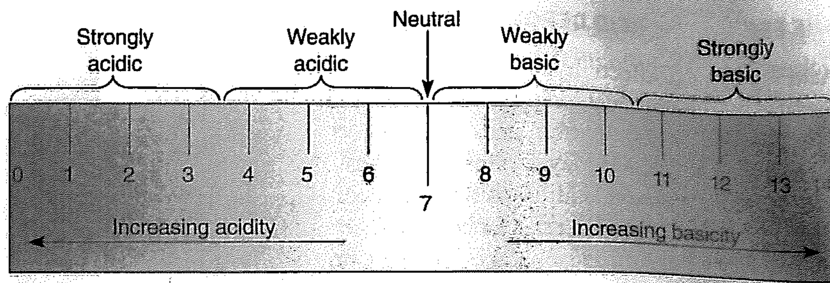


Figure 19.15 The pH scale. This scale, which includes values between 0 and 14, expresses the concentrations of acidic and basic solutions. Pure water, which is neutral, has a pH of 7. Each decrease of one pH unit represents a tenfold increase in acidity.

HOW ACID DEPOSITION DEVELOPS

Robert Angus Smith, a British chemist, coined the term *acid rain* in 1872 after he noticed that buildings in areas with heavy industrial activity were being worn away by rain. Until recently, industrialized countries in the Northern Hemisphere had been hurt the most by acid deposition, especially the Scandinavian countries, Central Europe, Russia, and North America. More recently, largely due to high-sulfur coal, acid rain has become a major concern in China, where SO_2 releases doubled between 1995 and 2005. While SO_2 emissions in China have diminished since 2005, they remain high.

The **pH scale**, which runs from 0 to 14, expresses the relative degree of acidity or basicity of a substance (**Figure 19.15**). A pH of 7 is neither acidic nor basic, whereas a pH less than 7 indicates an acidic solution. The pH scale is logarithmic, so a solution with a pH of 6 is 10 times more acidic than a solution with a pH of 7. Similarly, a solution with a pH of 5 is 10 times more acidic than a solution with a pH of 6 and 100 times more acidic than a solution with a pH of 7. A solution with a pH greater than 7 is basic, or alkaline.

For purposes of comparison, distilled water has a pH of 7, tomato juice has a pH of 4, vinegar has a pH of 3, and lemon juice has a pH of 2. Normally, rainfall is slightly acidic (with a pH from 5 to 6) because CO_2 and other naturally occurring compounds in the air dissolve in rainwater, forming dilute acids. However, the pH of precipitation in the northeastern United States averages 4 and is often 3 or even lower.

Acid deposition occurs when sulfur dioxide and nitrogen oxides are released into the atmosphere, combine with moisture to form acids, and then are deposited on land through rain, snow, or condensate (dew) (**Figure 19.16**). Motor vehicles are a major source of nitrogen oxides. Coal-burning power plants, large smelters, and industrial boilers are the main sources of sulfur dioxide emissions and produce substantial amounts of nitrogen oxides as well. Sulfur dioxide and nitrogen oxides, released into the air from tall smokestacks, are carried long distances by winds. Tall smokestacks were an early attempt to control local air pollution—under the premise that "the solution to pollution is dilution." Tall smokestacks allow England to "export" its acid deposition problem to the Scandinavian countries and the midwestern United States to "export" its acid emissions to New England and Canada.

During their stay in the atmosphere, sulfur dioxide and nitrogen oxides react with water to produce dilute solutions of sulfuric acid (H_2SO_4), nitric acid (HNO_3), and nitrous acid (HNO_2). Acid deposition returns these acids to the ground, causing the pH of surface waters and soil to decrease.

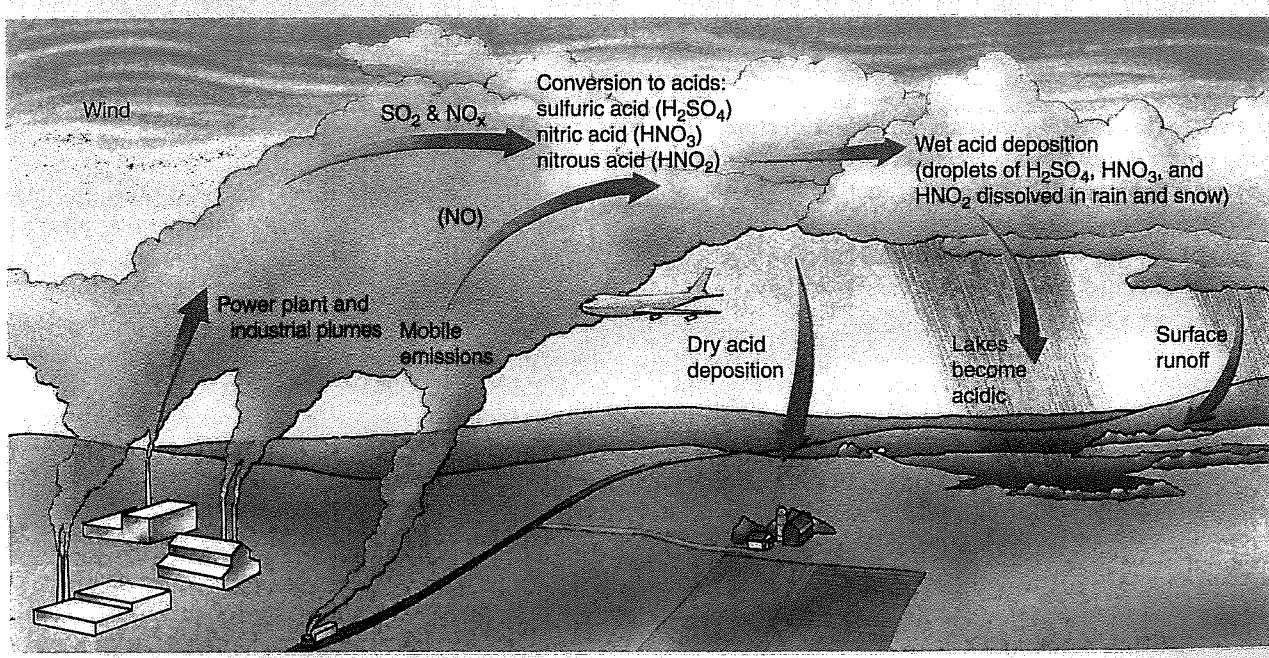


Figure 19.16 Acid deposition. Sulfur dioxide and nitrogen oxide emissions react with water vapor in the atmosphere to form acids that return to the surface as either dry or wet deposition.

THE EFFECTS OF ACID DEPOSITION

Acid deposition affects living and nonliving things. It corrodes metals and building materials, damaging, for example, the Washington Monument in Washington, D.C., historic sites in Venice and Rome, and ancient Mayan ruins in southern Mexico.

The link between acid deposition and declining aquatic animal populations is well established. Field investigations were conducted by the Adirondack Lakes Survey Corporation (ALSC), a nonprofit group that works with various universities, the EPA, and various state and local organizations. Of the 1469 Adirondack lakes and ponds examined, 352 had pH values of 5.0 or less, and 346 of those acidified lakes and ponds had no fish populations. Toxic metals such as aluminum dissolve in acidic lakes and streams and enter food webs. This increased concentration of toxic metals may explain how acidic water adversely affects fishes.

Although impacts on fish have received the lion's share of attention regarding acid deposition, other animals are also harmed. Several studies have found that birds living in areas with pronounced acid deposition were much more likely to lay eggs with thin, fragile shells that break or dry out before the chicks hatch. The inability to produce strong eggshells was attributed to reduced calcium in the birds' diets. Calcium is unavailable because in acidic soils it becomes soluble and is washed away, with little left for plant roots to absorb. A smaller amount of calcium in plant tissues means a smaller amount of calcium in the insects and snails that eat the plants. Less calcium is therefore available to the birds that eat these insects and snails.

Forest surveys in the Black Forest of southwestern Germany indicate that up to 50% of trees in the areas surveyed are dead or severely damaged. (Monitoring the loss of leaves and needles from trees determines the damage.) The same is true for trees in many other European forests. More than half of the red spruce trees in the mountains of the northeastern United States have died since the mid-1970s, and sugar maples in eastern Canada and the United States are dying. Beginning in the late 1990s, the Northern Hardwood Damage Survey has observed and mapped tree death at higher elevations of the Appalachian Mountains from Georgia to Maine.

Many living trees exhibit symptoms of **forest decline**. The general symptoms of forest decline are reduced vigor and growth, but some plants exhibit specific symptoms, such as yellowing of needles in conifers. Forest decline is more pronounced at higher elevations, possibly because most trees growing at high elevations are at the limits of their normal range and are less vigorous and more susceptible to stressors of any type (**Figure 19.17a**).

Many factors interact to decrease the health of trees, and no single factor accounts for the recent instances of forest decline (**Figure 19.17b**). Although acid deposition correlates well with areas experiencing tree damage, it is only partly responsible. Several other human-induced air pollutants are implicated, including tropospheric (surface-level) ozone and toxic heavy metals such as lead, cadmium, and copper. Power plants, ore smelters, refineries, and motor vehicles produce these pollutants in addition to the sulfur and nitrogen oxides that interact to form acid deposition. Insects and weather factors such as drought and severe winters (cold and wind can injure susceptible plants) may also be important.

To complicate matters further, the actual causes of forest decline may vary from one tree species to another and from one location to another. Thus, forest decline appears to result from the combination of multiple stressors—acid deposition, tropospheric ozone, UV radiation (which is more intense at higher altitudes), insect attack, drought, and so on. When one or more stressors weaken a tree, then an additional stressor, such as air pollution, may be decisive in causing its death.

One way in which acid deposition harms plants is well established: Acid deposition alters the chemistry of soils, which affects the development of plant roots as well as their uptake of dissolved minerals and water from soil. Essential plant minerals such as calcium and potassium readily wash out of acidic soil, whereas others, such as nitrogen, become available in larger amounts. Heavy metals such as manganese and aluminum dissolve in acidic soil water, becoming available for absorption in toxic amounts. A study completed in 1989 in Central Europe, which has experienced greater forest damage than North America, found a strong correlation between forest damage and soil chemistry altered by acid deposition.

MANAGING ACID DEPOSITION

One reason acid deposition is so hard to combat is that it does not occur only in the locations where the gases that cause it are emitted. Acid deposition does not recognize borders between states or countries; it is entirely possible for sulfur and nitrogen oxides released in one spot to return to the ground hundreds of kilometers from their source.

The United States has wrestled with this issue. Coal burning in several Midwest and Eastern states—Illinois, Indiana, Missouri, Ohio, Pennsylvania, Tennessee, and West Virginia—produces between 50% and 75% of the acid deposition that contaminates New England and southeastern Canada. When legislation was formulated to deal with the problem, arguments ensued about who should pay for the installation of expensive air pollution devices to reduce emissions of sulfur and nitrogen oxides. Despite these difficulties, and thanks to a cap-and-trade approach that restricts emissions of sulfur and nitrogen to the atmosphere, the total amount of SO_2 generated in the United States has declined since the 1980s (**Figure 19.18**).

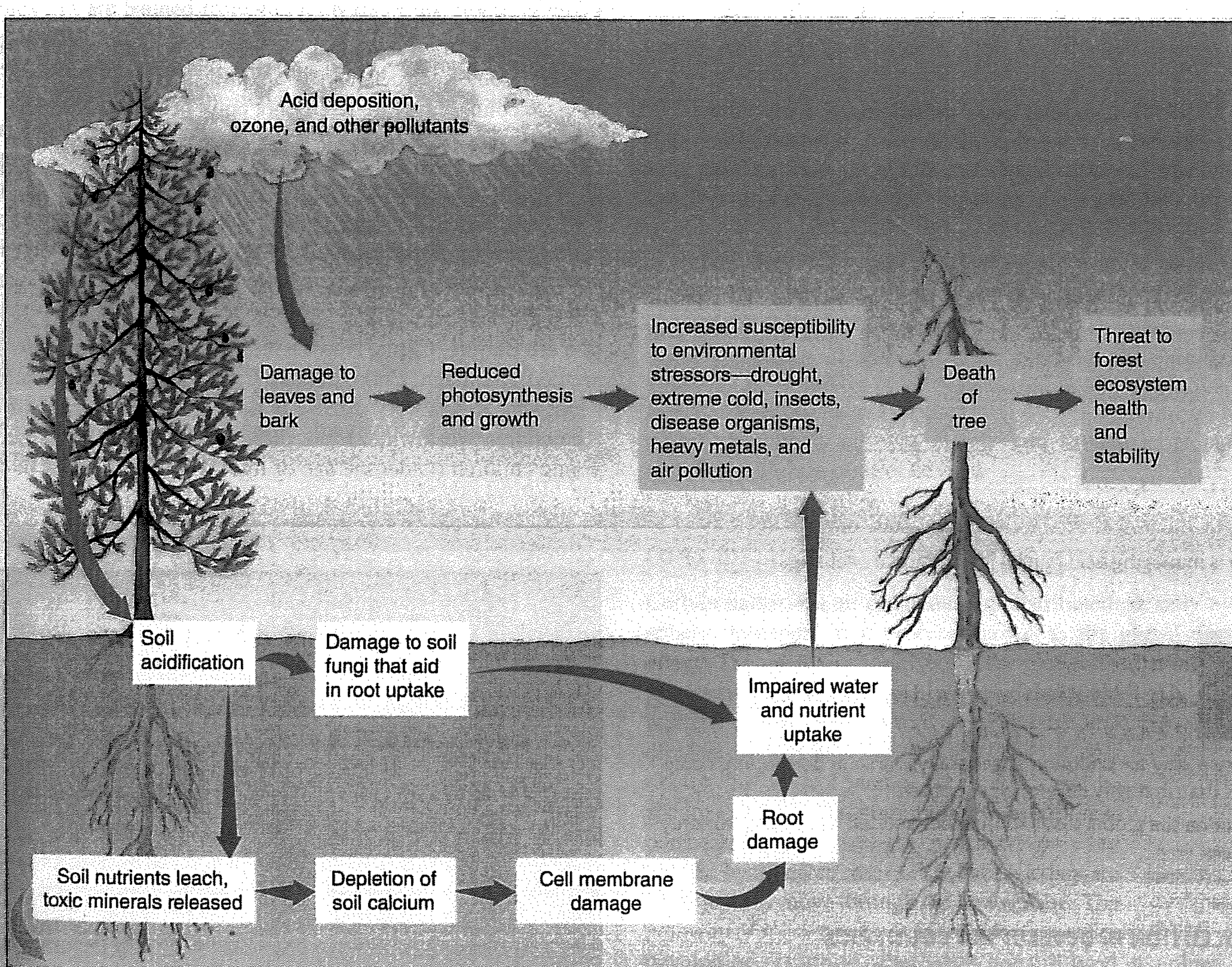
Pollution-abatement issues are magnified in international disputes. For example, gases from coal-burning power plants in England move eastward with prevailing winds and return to the surface as acid deposition in Sweden and Norway. Similarly, emissions from mainland China produce acid deposition in Japan, Taiwan, and North and South Korea.

The basic concept of acid deposition control is straightforward: Reducing emissions of sulfur dioxide and nitrogen oxides curbs acid deposition. Simply stated, if sulfur dioxide and nitrogen oxides are not released into the atmosphere, they cannot come down as acid deposition. Installation of scrubbers in the smokestacks of coal-fired power plants (see Figure 19.9) and use of clean-coal technologies to burn coal without excessive emissions effectively diminish acid deposition (see Chapter 11). In turn, a decrease in acid deposition prevents surface waters and soil from becoming more acidic than they already are.

a) These trees, photographed in the Black Forest, Germany, show signs ıf forest decline due to acid rain.

Despite the fact that the United States, Canada, and many European countries have reduced emissions of sulfur, acid precipitation remains a serious problem. Acidified forests and bodies of water have not recovered as quickly as hoped. Many northeastern streams and lakes, such as those in New York's Adirondack Mountains, remain acidic. A primary reason for the slow recovery is probably that the past 30 or more years of acid rain have profoundly altered soil chemistry in many areas. Essential plant minerals such as calcium and magnesium have leached from forest and lake soils. Because soils take hundreds or even thousands of years to develop, it may be decades or centuries before they recover from the effects of acid rain.

Many scientists are convinced that ecosystems will not recover from acid rain damage until substantial reductions in nitrogen oxide emissions occur, a trend that seems to be under way. Nitrogen oxide emissions are harder to control than sulfur dioxide emissions because motor vehicles produce a substantial portion of nitrogen oxides. Engine improvements may reduce nitrogen oxide emissions, but as the population continues to grow,



(b) Acid deposition is one of several stressors that interact, contributing to the decline and death of trees. Acid deposition increases soil acidity, causing certain essential mineral ions, such as calcium, to leach out of the soil.

Figure 19.17 Forest decline.

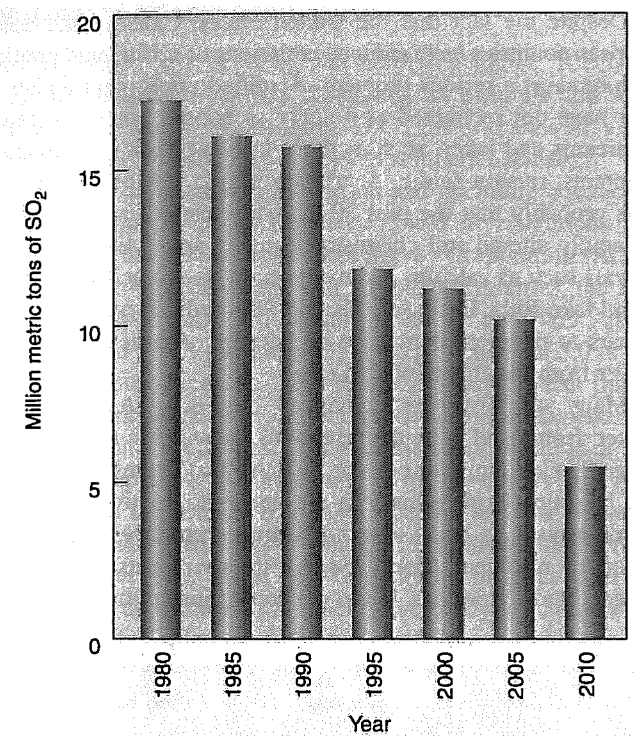


Figure 19.18 SO_2 emitted in the United States, 1980–2010. Sulfur dioxide (SO_2) is a major contributor to acid rain. Total sulfur emissions in the United States have been declining, initially as the result of strict SO_2 emission controls and more recently as a result of a cap-and-trade regulatory approach. (U.S. DOE, 2014)

the engineering gains may be offset by an increase in the number of motor vehicles. Dramatic cuts in nitrogen oxide emissions will require a reduction in high-temperature energy generation, especially in gasoline and diesel engines.

REVIEW

1. What is acid deposition and what causes it?
2. How is forest decline related to acid deposition?
3. Why is managing acid rain an international challenge?

Air Pollution around the World

LEARNING OBJECTIVES

- Explain why air pollution is generally worse in developing countries than in highly developed countries.
- Describe the global distillation effect and tell where it commonly occurs.

AIR POLLUTION IN DEVELOPING COUNTRIES

As developing countries become more industrialized, they produce more air pollution. The leaders of most developing countries believe they must become industrialized rapidly to compete economically with highly developed countries. Environmental quality is usually a low priority in the race to develop. Less expensive, outdated technologies are often adopted, and air pollution laws, where they exist, are not enforced. Thus, air quality is deteriorating rapidly in many developing countries.

Many cities in China have so many smokestacks releasing coal smoke (coal is burned to heat many homes) that residents see the sun only a few weeks of the year (**Figure 19.19**). The rest of the time residents are choked in a haze of orange-colored coal dust. In other developing countries, such as India and Nepal, biomass (wood or animal dung) is burned indoors, often in stoves with little or no outside ventilation, thereby exposing residents to serious indoor air pollution. Scientists have determined that one of the principal causes of acute respiratory infections, a serious worldwide health threat, is exposure to the pollutants in biomass fuels when they are burned indoors.

The growing number of automobiles in developing countries contributes to air pollution, particularly in urban areas. Many vehicles in these countries are 10 or more years old and have no pollution-control devices. Motor vehicles produce about 60% to 70% of the air pollutants in urban areas of Central America and 50% to 60% in urban areas of India. Since the mid-1990s, the most rapid proliferation of motor vehicles worldwide has occurred in Latin America, Asia, and Eastern Europe.

Lead pollution from heavily leaded gasoline is an especially serious problem in developing countries. The gasoline refineries in these countries are generally not equipped to remove lead from gasoline. (The same situation occurred in the United States until federal law mandated that the refineries upgrade their equipment.) In Cairo, children's blood lead levels are more than two times higher than the level considered at-risk in the United States. Lead can retard children's growth and cause brain damage.

According to a World Health Organization study, the five worst cities in the world in terms of exposing children to air pollution are Beijing, China; New Delhi, India (Beijing and New Delhi are tied); Santiago, Chile; Mexico City, Mexico; and Ulaanbaatar, Mongolia. Respiratory disease is now the leading cause of death for children worldwide. More than 80% of these deaths occur in young children (under the age of five) who live in cities in developing countries.

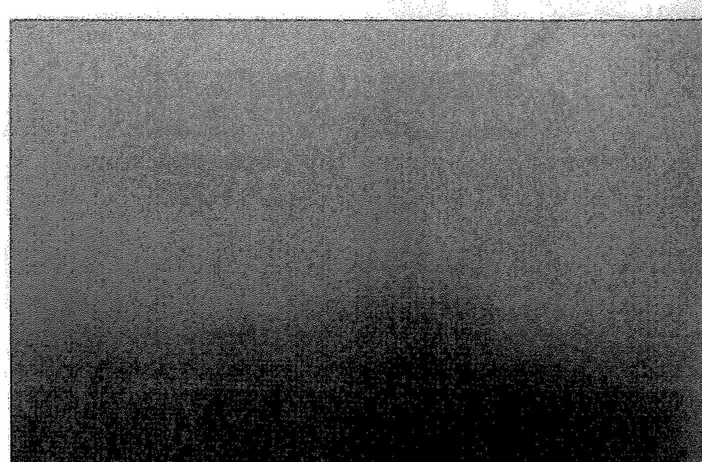


Figure 19.19 Air pollution in Liaoning Province, China. Coal smoke pollutes the air above workers' houses in Liaoning Province, China. All forms of pollution are increasing threats as China becomes industrialized. China has many of the worlds' most polluted cities, including Beijing.

CASE IN POINT

AIR POLLUTION IN BEIJING, NEW DELHI, AND MEXICO CITY

Los Angeles, California, was once known for the worst smog in the world. However, while L.A. smog is still some of the worst in the United States, six decades of regulation have significantly reduced the problem. Now Beijing and New Delhi are tied for having the worst air quality in the world. Mexico City, which just a few years ago had the worst air in the world, continues to have severe air quality problems. Many of the world's worst cities for air pollution can be found in China and India.

In Beijing, automobiles, dust from construction sites, and electricity generated with coal outside of town are the biggest culprits. In preparation for hosting the 2008 summer Olympics, Beijing took steps to curb its air pollution. However, the improvements were temporary, and even as Beijing passes some regulations designed to improve air quality, other rules undermine those efforts. Beijing was once known as a town where bicycles ruled; now bicycles are banned from certain parts of the city to improve the flow of automobile traffic.

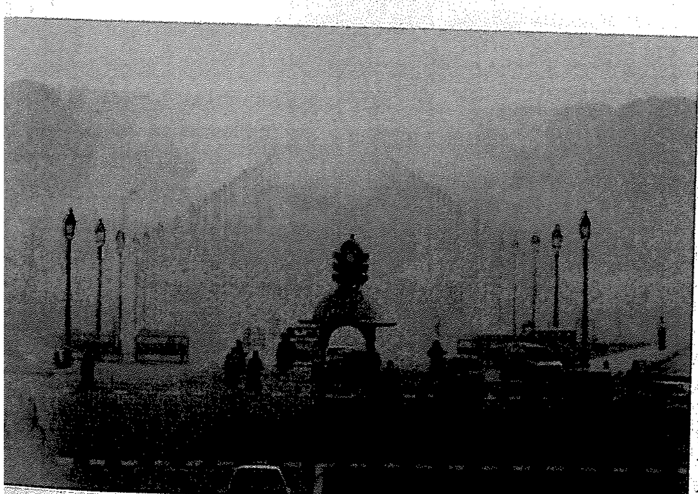
Not even on the list of the 10 worst cities for air pollution a few years ago, New Delhi is now tied for worst (**Figure 19.20**). A 2014 World Health Organization report found that in addition to other pollutants, residents of New Delhi are exposed to an annual average of 153 micrograms of small particles per cubic meter of air. A major source of this pollution is the rapid growth of motor vehicles with inefficient engines and no emissions control devices. Indian officials argue that the annual average is a misleading number, since India's monsoon weather patterns mean that air pollution has high seasonal variability. Even so, air pollution is thought to lead to tens of thousands of premature deaths in New Delhi each year.

Mexico City has moved from worst to fourth worst on the world listing over the past decade. This is not because its air pollution problem has improved but because pollution elsewhere has gotten so much worse. Average visibility has dropped from 11 km (7 mi) in the 1940s, when surrounding snow-capped volcanoes were commonly seen, to 1.6 km (1 mi). Mexico City's air pollution is due in part to its large population growth in the past several decades (the city grew from 5.4 million in 1960 to 21.2 million in 2014) and in part to its location. Mexico City is in a bowl-shaped valley ringed on three sides by mountains; winds coming in from the open northern end are trapped in the valley. Air quality is at its worst from October to January, largely as a result of temperature inversions caused by seasonal variations in atmospheric conditions.

In 2014, the city had more than 6 million passenger vehicles (up from half that number in 2000), fueled at over 400 gasoline stations, as well as about 36,000 businesses, which the Mexican government says release over 4 million metric tons (4.5 million tons) of pollutants into the air each year. Mexican gasoline contains a lot of contaminants, and the average automobile is 10 years old and produces more pollutants than do newer cars. The air contains particles of dried fecal matter from the millions of gallons of sewage dumped onto land near the city. In addition, liquefied petroleum gas—a major source of energy for cooking and heating—escapes unburned into the atmosphere from thousands of leaks, increasing the level of hydrocarbons in the city's air. Simply breathing the air in Mexico City is equivalent to smoking two packs of cigarettes a day.

During the 1990s, Mexico embarked on an ambitious plan to improve Mexico City's air quality. It spent more than $5 billion to replace old buses, taxis, delivery trucks, and cars with cleaner vehicles, such as those with catalytic converters. Mexico switched to unleaded gasoline and reforested some of the nearby hillsides to reduce particulate matter produced by wind erosion. Driving restrictions apply when the air quality is particularly poor, and exhaust emissions are periodically checked on autos.

In addition, Pemex, Mexico's national oil company, has upgraded its refineries and increased gas imports from the United States, which produces a cleaner fuel. An old, polluting oil refinery within the city limits was closed, and several large industries installed pollution-control devices. ■



Adam Jones/Science Source

igure 19.20 Smog in New Delhi, India. A busy intersection in ew Delhi shows the variety of vehicles on the roads, and the limited sibility caused by particulate matter.

LONG-DISTANCE TRANSPORT OF AIR POLLUTION

Certain hazardous air pollutants are distributed globally by atmospheric transport in a process known as the **global distillation effect**. The air toxics involved in the global distillation effect are persistent compounds, such as polychlorinated biphenyls (PCBs, industrial compounds) and dichlorodiphenyltrichloroethane (DDT, a pesticide), that do not readily break down and so accumulate in the environment. Many of these persistent compounds are restricted or even banned by many countries. Yet because they are volatile, they move through the atmosphere. The pathway of movement is generally from warmer developing countries, where they are still used, to colder, highly developed countries, where they condense and are deposited on land and surface water (**Figure 19.21**). A recent study suggests that a decrease in sea ice associated with climate change will increase the amount of air pollution in far northern regions, a phenomenon referred to as *arctic haze*.

global distillation effect The process whereby volatile chemicals evaporate from land as far away as the tropics and are carried by air currents to higher latitudes, where they condense and fall to the ground.

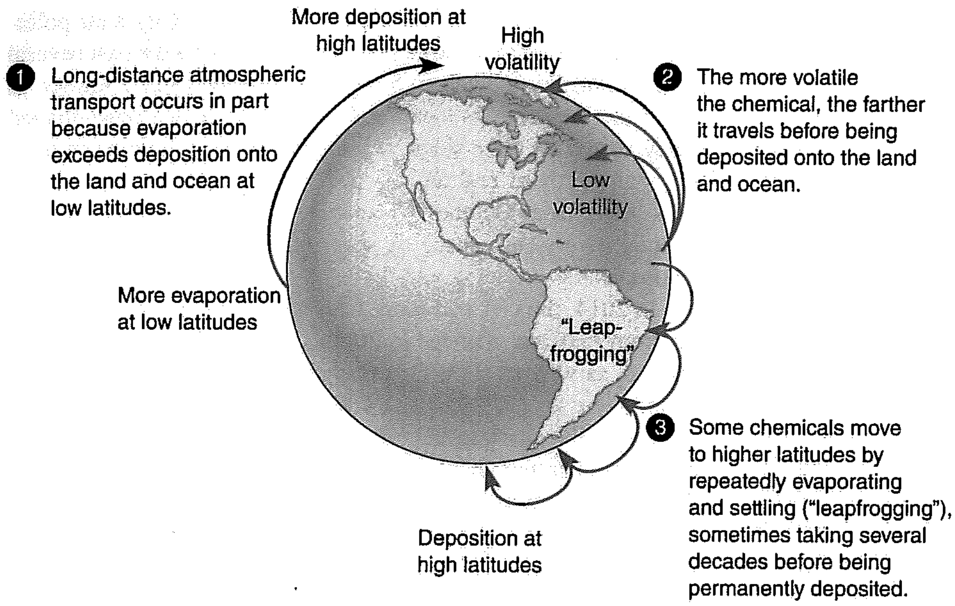


Figure 19.21 Global distillation effect. (Adapted from F. Wania, and D. Mackay. "Tracking the Distribution of Persistent Organic Pollutants." *Environmental Science and Technology,* Vol.30 [1996])

Many industrialized countries remain highly contaminated by persistent compounds despite their restricted use. The effect is more pronounced where it is colder—that is, at higher latitudes and higher elevations. Dangerous levels of certain persistent toxic compounds have been measured in the Yukon (northwestern Canada) and in other pristine arctic regions. These chemicals enter food webs and become concentrated in the body fat of animals at the top of the food chain (see the discussion of biological magnification in Chapter 7). Fishes, seals, polar bears, and arctic people such as the Inuit are particularly vulnerable. An Inuit who consumes a single bite of raw whale skin ingests more PCBs than scientists think should be consumed in a week. The level of PCBs in the breast milk of an Inuit woman is five times higher than that in the milk of women who live in southern Canada.

The Indian Ocean has generally been considered one of the world's cleanest areas because the countries that surround it are not heavily industrialized. During a six-week study in the winter of 1999, scientists from the National Science Foundation and the Scripps Institution of Oceanography reported that a large portion of the Indian Ocean was covered by hazy, polluted air. The pollution extended over 9.5 million km^2 (3.8 million mi^2), an area the size of the United States. It is thought that prevailing winds during the winter monsoon blow the pollution, which includes particulate matter and sulfur droplets, from the Indian subcontinent, China, and Southeast Asia. The hazy area is expected to increase as industry develops in these areas.

Pollution also travels from one continent to another. Certain atmospheric conditions (i.e., a low-pressure system over the Aleutians and a high-pressure system near Hawaii) cause a strong wind toward North America that allows air pollution from Asia to cross the Pacific Ocean. In 1997, scientists from the University of Washington detected carbon monoxide, particulate matter, and PANs in the atmosphere over the western United States. Computer models suggested that these pollutants were produced in Asia six days earlier. In 1998, more definitive evidence of pollution from Asia affecting air quality in North America occurred when a major dust storm in China produced a visible cloud of particulate matter that was tracked by satellite across the Pacific Ocean. The polluted air was analyzed when it reached the United States a few days later and found to contain arsenic, copper, lead, and zinc from ore smelters in Manchuria.

REVIEW

1. Is air pollution worse in highly developed or in developing countries? Why?
2. What is the global distillation effect? What kinds of air pollutants are involved in the global distillation effect?

Indoor Air Pollution

LEARNING OBJECTIVE

- Describe the major sources of indoor air pollution.
- Explain why tobacco smoke and radon are considered major indoor air pollutants.

The air in enclosed places such as automobiles, homes, schools, and offices may have significantly higher levels of air pollutants than the air outdoors. In congested traffic, levels of harmful pollutants such as carbon monoxide, benzene, and airborne lead may be several times higher inside an automobile than in the air immediately outside. The concentrations of certain indoor air pollutants may be two to five times greater—and sometimes more than 100 times—than outdoors. Indoor pollution is of particular concern to urban residents because they may spend as much as 90% to 95% of their time indoors. The EPA considers indoor air pollution as one of the top five environmental health risks in the United States.

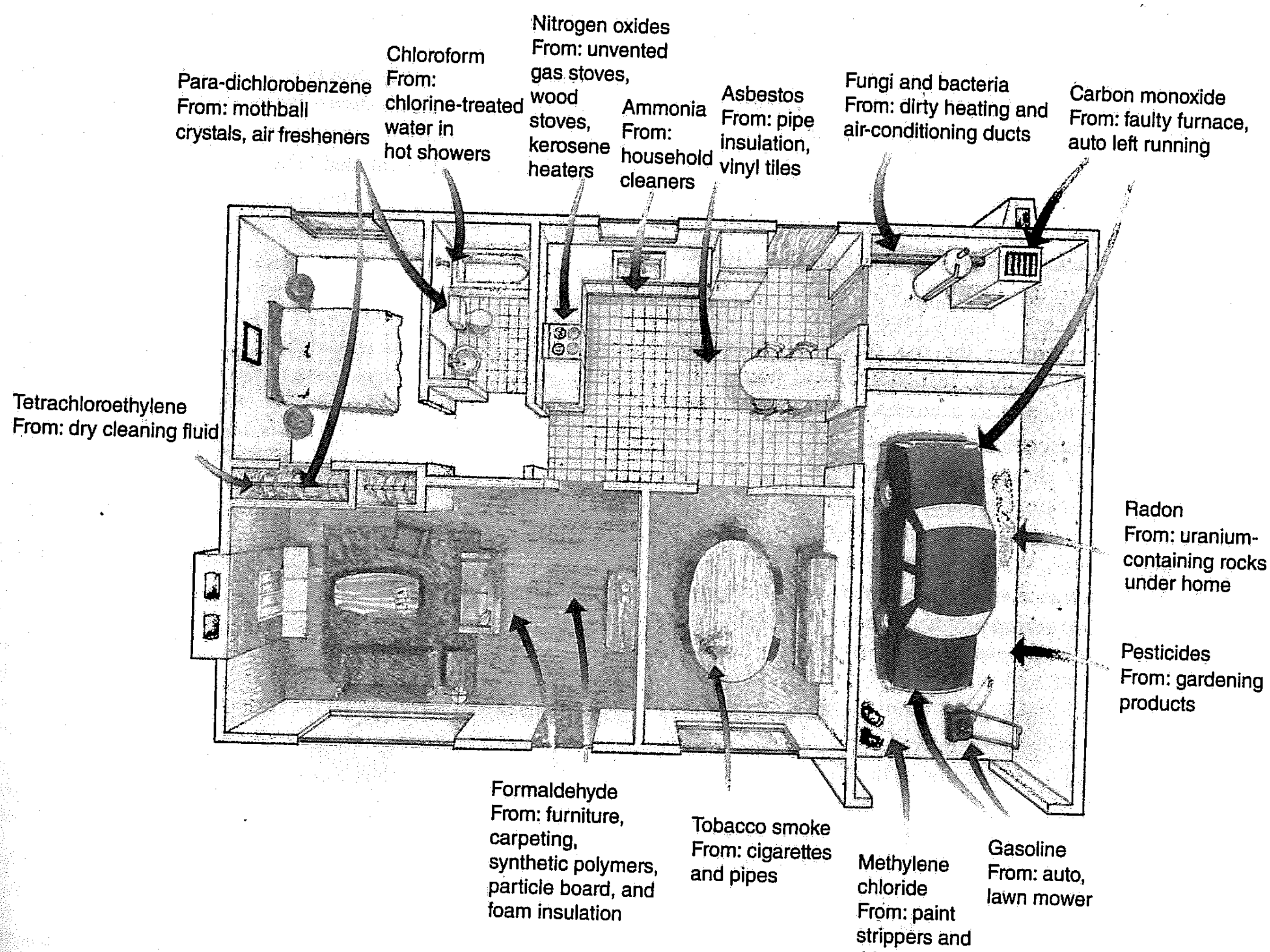
SOURCES AND EFFECTS OF INDOOR AIR POLLUTION

Because illnesses caused by indoor air pollution usually resemble common ailments such as colds, influenza, or upset stomachs, they are often not recognized. The most common contaminants of indoor air are radon (discussed shortly), cigarette smoke, carbon monoxide, nitrogen dioxide (from gas stoves), formaldehyde (from carpeting, fabrics, and furniture), household pesticides, lead, cleaning solvents, ozone (from photocopiers), and asbestos (**Figure 19.22**). In addition, the reaction of indoor ozone, generally present at lower levels than outdoors, with volatile chemicals in air fresheners, aromatherapy candles, and cleaning agents forms secondary air pollutants such as formaldehyde.

Viruses, bacteria, fungi (yeasts, molds, and mildews), dust mites, pollen, and other organisms or their toxic parts are important forms of indoor air pollution often found in heating, air-conditioning, and ventilation ducts. Excessive indoor dampness exacerbates indoor microbial growth (particularly fungal growth), dust mite populations, and cockroach and rodent infestations. A report by the U.S. Institute of Medicine showed that the presence of mold in a damp indoor environment is linked to upper respiratory tract (nose and throat) symptoms, including wheezing and coughing, and to asthma symptoms in people who already have asthma. There was also suggestive evidence of an association between molds, a damp indoor environment, and illness in the lower respiratory tracts in otherwise healthy children.

Asthma was considered a rare disease until the middle of the 20th century, and it is far more common in industrialized nations than in developing countries. Since 1970, the number of people in the United States who suffer from asthma has more than doubled, to more than 20 million; 11 million asthma sufferers are children. Health officials are worried by this trend, which is due in part to indoor air pollution. Indoor exposure to different air pollutants contributes to the development and exacerbation of asthma. Exactly what pollutant(s) is/are causing the increase in asthma is unknown, although some evidence suggests that exposure to allergens (substances that stimulate an allergic reaction) such as dust mites and cockroach feces is a major cause.

A variety of approaches can monitor or reduce indoor air pollution. Carbon monoxide monitors are increasingly common, especially in homes with natural gas appliances. An alarm lets residents know about unsafe levels. One of the best strategies to reduce indoor air pollution is to keep surfaces (especially floors, walls, and ducts) clean and dry. Filters, both free-standing and those that are part of heating and air conditioning, can capture particulates but should be cleaned or replaced regularly.



gure 19.22 Sources of household air pollution. Homes may contain higher levels of toxic pollutants than outside air, even near polluted dustrial sites.

ENVIRONEWS

Indoor Air Pollution in Developing Countries

The World Health Organization (WHO) estimates that 1.6 million people are killed each year by smoke associated with traditional cooking methods that rely on wood, crop wastes, and dung. About 3.5 billion people—half of the world population—rely on traditional cooking, and it is usually women and children who face the most exposure. Smoke from these fires can contain high concentrations of particulates, carbon monoxide, benzene, formaldehyde, and other toxic chemicals, causing both acute (infection, respiratory disease) and chronic (lung cancer) disease. Switching to cleaner technologies including kerosene, solar cookers, and cleaner stoves could save millions of lives. However, such alternatives face both cultural and economic barriers.

TOBACCO SMOKE AND RADON

Smoking, which causes serious diseases such as lung cancer, emphysema, and heart disease, is responsible for the premature deaths of nearly half a million people in the United States each year. Cigarette smoking annually causes about 120,000 of the 140,000 deaths from lung cancer in the United States. Smoking also contributes to heart attacks, strokes, male impotence, and cancers of the bladder, mouth, throat, pancreas, kidney, stomach, voice box, and esophagus. It also causes substantial property damage through fires, burns, and smoke odor and discoloration.

Cigarette smoke is a mixture of air pollutants that includes hydrocarbons, carbon dioxide, carbon monoxide, particulate matter, cyanide, and a small amount of radioactive materials that come from the fertilizer used to grow the tobacco plants. Smokers exhale tobacco smoke into the air we all breathe. Passive smoking, which is the nonsmokers' chronic breathing of smoke from cigarette smokers, also increases the risk of cancer, especially in business settings (bars, casinos, restaurants) and homes. For this reason, it has been banned as a workplace hazard in many locations. Passive smokers suffer more cancer, respiratory infections, allergies, and other chronic respiratory diseases than other nonsmokers. Passive smoking is particularly harmful to infants and young children, pregnant women, the elderly, and people with chronic lung disease. When parents of infants smoke, the infant has double the chance of pneumonia or bronchitis in its first year of life. Smoking during pregnancy adversely affects fetal development, leading to lower birth weights and smaller head circumferences.

A worldwide trend is that more total people in developing countries are smoking, even while fewer people in highly developed countries are smoking. According to the Centers for Disease Control, about 18% of U.S. adults were smokers in 2013, compared with a peak of 41% in the mid-1970s. Smoking has also declined in Japan and most European countries. However, more people are taking up the habit in Brazil, Pakistan, and many other developing countries. Tobacco companies in the United States promote smoking abroad, and a substantial portion of our tobacco crop is exported. Cigarette sales in developing countries have increased by 80% since 1990.

The World Health Organization (WHO) estimates that, worldwide, over 5 million people die each year of smoking-related causes, and it wants a global ban on tobacco advertising. To meet this goal, WHO developed the Framework Convention on Tobacco Control, which calls for a ban on cigarette advertising, higher taxes on tobacco products, and restrictions on smoking in public places. This treaty went into effect for signatory nations in 2005. (The United States had not ratified this treaty as we went to press.)

In the United States, Canada, and other highly developed countries, bans on smoking in many public places—including government buildings, restaurants, college campuses, and airplanes—have substantially reduced both smoking and exposure to smoke. Although fewer U.S. citizens are smoking, certain groups in our society still have high numbers of tobacco addicts, including certain minority groups and those with the least education. A need exists to continue educating these groups, as well as all young people (more than 1 million U.S. children and teenagers take up smoking each year), about the dangers of smoking before they become addicted.

Radon is another serious indoor air pollutant in many places in highly developed countries. Radon seeps through the ground and enters buildings, where it sometimes accumulates to dangerous levels (**Figure 19.23**). Although radon is also emitted into the atmosphere, it gets diluted and dispersed and is of little consequence outdoors.

Radon and its decay products emit alpha particles, a form of ionizing radiation that is damaging to tissue but cannot penetrate very far into the body. Consequently, radon harms the body only when it is ingested or inhaled. The radioactive particles lodge in

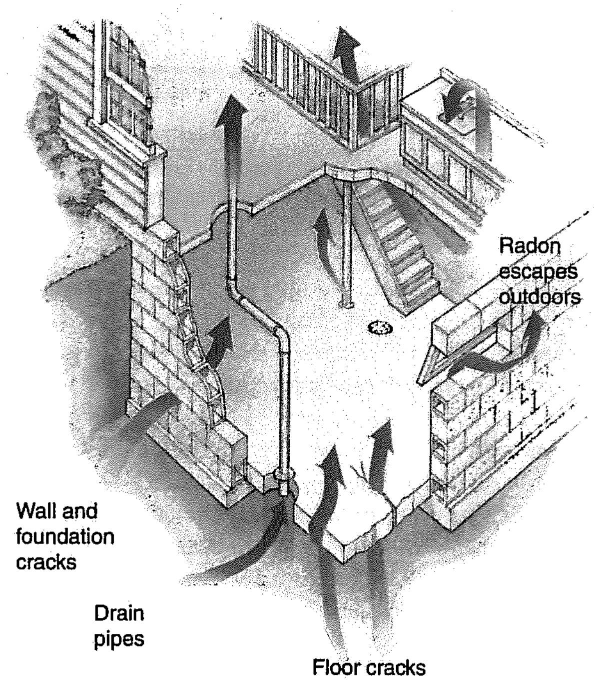


Figure 19.23 Household radon infiltration. Cracks in basement walls or floors, openings around pipes, and pores in concrete blocks provide some of the entries for radon.

the tiny passages of the lungs and damage surrounding tissue. There is compelling evidence, based primarily on several studies of uranium miners, that inhaling large amounts of radon increases the risk of lung cancer. Other studies suggest that people who are exposed to relatively low levels of radon over an extended time are at risk for lung cancer.

In 1998, the National Research Council of the National Academy of Sciences released an extensive evaluation of radon's effects on human health. It estimated that residential exposure to radon causes 12% of all lung cancers—between 15,000 and 22,000 cases of lung cancer annually. Cigarette smoking exacerbates the risk from radon exposure; about 90% of radon-related cancers occur among current or former smokers.

According to the EPA, about 6% of U.S. homes have high enough levels of radon to warrant corrective action—that is, a radon level above 4 picocuries per liter of air. (As a standard of reference, outdoor radon concentrations range from 0.1 to 0.15 picocurie per liter of air.) The highest radon levels in the United States occur in homes on a geologic formation, the Reading Prong, which runs across southeastern Pennsylvania into northern New Jersey and New York. Iowa has the most pervasive radon problem, where 71% of the homes tested in 1989 had radon levels high enough to warrant corrective action.

Ironically, efforts to make our homes more energy-efficient have increased the hazard of indoor air pollutants, including radon. Drafty homes waste energy but allow radon to escape outdoors so that it does not build up inside. Testing for radon can be inexpensive, and corrective actions are generally reasonably priced. Radon concentrations in homes are minimized by sealing basement concrete floors and by ventilating crawl spaces and basements.

REVIEW

1. What are the major sources of indoor air pollution?
2. Why are tobacco smoke and radon considered to be particularly hazardous indoor air pollutants?

REVIEW OF LEARNING OBJECTIVES WITH SELECTED KEY TERMS

- **Describe the composition of the atmosphere.**

Excluding water vapor and trace gases including air **pollutants**, the atmosphere comprises four gases: nitrogen, oxygen, argon, and carbon dioxide. The two atmospheric gases most important to living organisms are carbon dioxide and oxygen. Nitrogen gas is an important component of the nitrogen cycle.

- **List the seven major classes of air pollutants, including ozone and hazardous air pollutants, and describe their effects.**

The main classes of air pollutants produced by human activities are particulate matter, nitrogen oxides, sulfur oxides, carbon oxides, hydrocarbons, ozone, and hazardous air pollutants. **Particulate matter** corrodes metals, erodes buildings, and soils fabrics. **Nitrogen oxides** are associated with photochemical smog and acid deposition; nitrous oxide is associated with global climate change as well as stratospheric ozone depletion; nitrogen oxides corrode metals and fade textiles. **Sulfur oxides** are associated with acid deposition and corrode metals and damage stone and other materials. **Carbon oxides** include carbon monoxide, which is poisonous, and carbon dioxide, a **greenhouse gas**. **Hydrocarbons** include methane, which is a greenhouse gas; some hydrocarbons are dangerous to human health. **Ozone** is a pollutant in the lower atmosphere (the **troposphere**) and an essential component that screens out UV radiation in the upper atmosphere (the **stratosphere**). In the troposphere ozone reduces air visibility, causes health problems, stresses plants, and is a greenhouse gas. **Hazardous air pollutants** are potentially harmful and can pose long-term health risks to people who live and work around chemical factories, incinerators, or other facilities that produce or use them.

- **Explain how ozone-related air quality has changed in southern California over the past century.**

Since the middle of the last half century, California has passed regulations reducing emissions (including **volatile organic compounds**) from many sources. These restrictions had reduced ozone concentrations in the area more than threefold by 2012.

- **Describe the adverse health effects of specific air pollutants.**

Air pollutants irritate the eyes, inflame the respiratory tract, and suppress the immune system. Sulfur dioxide, particulate matter, and nitrogen dioxide constrict airways, impairing the lungs' ability to exchange gases. Carbon monoxide combines with hemoglobin and reduces its ability to transport oxygen; carbon monoxide poisoning can cause death. Adults at greatest risk from air pollution include those with heart and respiratory diseases.

- **Explain why children are particularly susceptible to air pollution.**

Air pollution is a greater health threat to children than it is to adults, in part because air pollution impedes lung development. Children with weaker lungs are more likely to develop respiratory problems, including chronic respiratory diseases.

- **Provide several examples of air pollution-control technologies.**

Electrostatic precipitators use electrodes to impart a negative charge to particulates in the dirty gas. These particles are attracted to the positively charged precipitator wall and then fall off into the collector. In a scrubber, mists of water droplets trap particulates in the dirty gas. The toxic dust produced by electrostatic precipitators and the polluted sludge produced by scrubbers must be safely disposed of or they will cause soil and water pollution. Phase I and II **vapor recovery** capture gasoline vapors that would otherwise be released into the atmosphere. **Catalytic converters** reduce the amount of hydrocarbons and carbon monoxide released in automobile exhaust. Reducing sulfur content of gasoline, increasing fuel mileage, and requiring regular emissions inspections can all reduce pollution associated with cars, trucks, and buses.

- **Summarize the effects of the Clean Air Act on U.S. air pollution.**

Air quality in the United States has slowly improved since passage of the **Clean Air Act** in 1970. This law authorizes the EPA to set limits on how much of specific air pollutants are permitted in the United States. The most dramatic improvement has been the decline in lead in the atmosphere, although levels of sulfur oxides, nitrogen oxides, ozone, carbon monoxide, volatile organic compounds (many of which are hydrocarbons), and particulate matter have also been reduced.

- **Define *stratospheric ozone thinning* and explain how chlorofluorocarbons and other chemicals reduce stratospheric ozone.**

Stratospheric ozone thinning is the accelerated destruction of ozone, a naturally occurring gas, in the stratosphere by human-produced chlorine- and bromine-containing chemicals. With depletion of the ozone layer, higher levels of **ultraviolet (UV) radiation** reach Earth's surface. **Chlorofluorocarbons (CFCs)** are human-made organic compounds of carbon, chlorine, and fluorine that had many industrial and commercial applications. Catalyzed by sunlight, chlorofluorocarbons and other compounds, including halons, methyl bromide, methyl chloroform, carbon tetrachloride, and nitrous oxide, can break protective ozone molecules in the stratosphere apart, converting them into oxygen molecules.

- **Describe some of the harmful effects of ozone depletion.**

In humans, excessive exposure to UV radiation causes cataracts, weakened immunity, and skin cancer. Increased levels of UV radiation may disrupt ecosystems, such as the Antarctic food web, because the negative effect of UV radiation on one species has ramifications throughout the ecosystem.

- **Explain the policy response to ozone depleting chemicals.**

The United States banned some ozone depleting chemicals in the 1980s. However, it was not until the Montreal Protocol created an international strategy to phase out different chemicals that progress was made. The most damaging chemicals have now been banned worldwide, and the ozone layer is recovering.

- **Explain how acid deposition develops and describe some of its effects.**

Acid deposition is a type of air pollution that includes acid that falls from the atmosphere as precipitation or as dry acidic particles. Acid deposition occurs when sulfur dioxide and nitrogen oxides are released into the atmosphere. These pollutants react with water to produce sulfuric acid, nitric acid, and nitrous acid. Acid deposition kills aquatic organisms and may harm forests. Acid deposition attacks materials such as metals and stone.

- **Define *forest decline* and explain its possible causes.**

Forest decline is a gradual deterioration and often death of many trees in a forest; air pollution and acid deposition contribute to forest decline in many areas. No single factor accounts for forest decline, which appears to result from the combination of multiple stressors—acid deposition, tropospheric ozone, UV radiation (which is more intense at higher altitudes), insect attack, drought, climate change, and so on.

- **Describe the challenges associated with reducing acid deposition.**

Reducing acid deposition is a challenge in part because so many different stationary and mobile sources contribute to it. In addition, the deposition often occurs far away from where the pollutants are release.

- **Explain why air pollution is generally worse in developing countries than in highly developed countries.**

Air quality is deteriorating in developing countries. Rapid industrialization, a growing number of automobiles in those countries, and lack of emissions standards are contributing to air pollution, particularly in urban areas.

- **Describe the global distillation effect and tell where it commonly occurs.**

The **global distillation effect** is the process in which volatile chemicals evaporate from land as far away as the tropics and are transported by winds to higher latitudes, where they condense and fall to the ground. Volatile chemicals contaminate some remote polar regions as a result of the global distillation effect.

- **Describe the major sources of indoor air pollution**

Air pollution comes from a variety of sources, including household chemicals (including cleaners and pesticides), human and pet hair, appliances, and furniture, as well as tobacco products and radon-containing rock formations.

- **Explain why tobacco smoke and radon are considered major indoor air pollutants.**

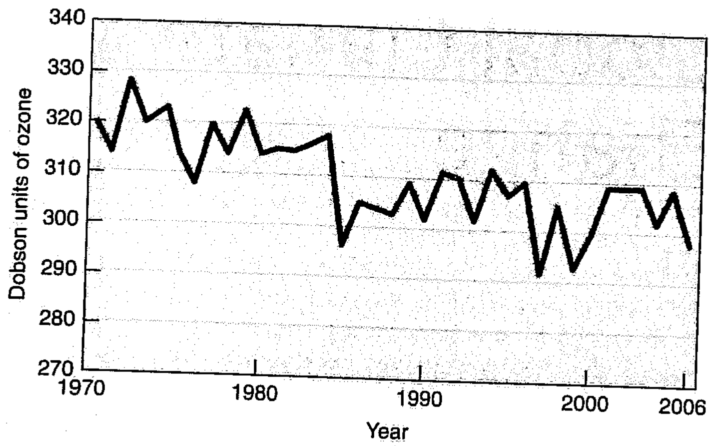
Tobacco smoke contains many hazardous chemicals and causes many diseases in smokers and passive smokers. Indoor tobacco smoke can be a significant workplace hazard to nonsmokers who spend large amounts of time in smoky areas. **Radon**, which enters houses from the surrounding bedrock, is a carcinogen. Radon concentrations can vary greatly from region to region.

Critical Thinking and Review Questions

1. The atmosphere of Earth has been compared to the peel covering an apple. Explain the comparison.
2. List the seven main kinds of air pollutants and briefly describe their sources and effects.
3. Distinguish between primary and secondary air pollutants.
4. What are industrial smog and photochemical smog, and how do they differ?
5. Why might global warming lead to more photochemical smog, even if emissions of nitrogen oxides and volatile organic chemicals remain constant?
6. Which is a more stable atmospheric condition, cool air layered over warm air or warm air layered over cool air? Explain. Which condition is a temperature inversion?
7. What urban areas have the worst air pollution in the world? Is this likely to change in the near future? Why or why not?

8. Distinguish between the benefits of the ozone layer in the stratosphere and the harmful effects of ozone at ground level.

9. The figure below depicts the thickness of the stratospheric ozone layer (measured in Dobson units) above New Zealand. In what year did the average yearly column of ozone above New Zealand first drop below 300 Dobson units?



Average yearly ozone column over New Zealand, 1970–2006. (New Zealand National Institute of Water and Atmospheric Research)

10. The amount of ozone-depleting chemicals released to the atmosphere have been reduced substantially since the late 1980s. Why has the concentration of stratospheric ozone not increased? Do we expect it to?

11. Discuss the harmful effects of acid deposition on forests, materials, aquatic organisms, and soils.

12. Why is the global distillation effect likely to become an increasingly challenging problem in the future?

13. One of the most effective ways to reduce the threat of radon-induced lung cancer is to quit smoking. Explain.

14. Conserving energy by reducing the rate at which indoor air is replaced with outdoor air can improve energy efficiency (less heating and cooling) but can contribute to indoor air pollution. Explain how a systems approach to building design might help solve this problem.

15. Explain why switching away from gasoline-powered vehicles can reduce local, regional, and global environmental problems, including climate change.

Food for Thought

The opening essay in this chapter described the problem of air pollution in Southeast Asia from burning associated with agriculture. Agricultural burning takes place in many parts of the world, including to clear land, destroy diseased trees, and eliminate wastes like rice plant stems and sugar cane. Research agricultural burning near where you live. What are the rules that limit the practice? Who is exposed, when, and how much? What are alternatives to burning?