central
CASE STUDY

Clearing the Air in L.A. and Mexico City

I left L.A. in 1970, and one of the reasons I left was the horrible smog. And then they cleaned it up. That was one of the greatest things the government has ever done for me. You have beautiful days now. It's a much, much nicer place to live.

Actor and comedian Steve Martin, speaking to *Los Angeles Magazine*

This city can be a model for others.

Mexico City Mayor Miguel Ángel Mancera

For Americans, Los Angeles has long symbolized air pollution. Smog—that unhealthy mix of air pollutants resulting from fossil fuel combustion—has blanketed the city for decades. Exhaust from millions of automobiles clogging L.A.'s freeways regularly becomes trapped by the mountains that surround the city, and the region's warm sunshine turns the pollutants to smog. In response, Los Angeles has worked hard to fight air pollution and has succeeded in improving its air quality notably, thanks to policy efforts and new technologies. Today L.A. still suffers the nation's worst smog, but its skies are clearer than in decades.

One city that looked to Los Angeles's efforts as it planned its own responses to smog is Mexico City, the capital of Mexico and one of the world's largest metropolises. Not long ago, Mexico City suffered the most polluted air in the world. On days of poor air quality throughout the 1990s, residents wore face masks on the streets, teachers kept students inside at recess, and outdoor sports events were canceled. Children drawing pictures would use brown crayons to color the sky. Each year thousands of deaths and tens of thousands of hospital visits were blamed on pollution. Mexican novelist Carlos Fuentes called his capital "Makesicko City."

As in Los Angeles, traffic generates most of the pollution in Mexico City, where motorists in nearly 7 million cars sputter across miles of urban sprawl. And like L.A., Mexico City lies in a valley surrounded by mountains, vulnerable to temperature inversions that trap pollutants over the city. Moreover, at Mexico City's high altitude—2240 m (7350 ft) above sea level—solar radiation is intense, which worsens smog formed by the interaction of pollutants with sunlight. Mexico City environmental chemist Armando Retama likens his hometown to "a casserole dish with a lid on top."

Despite the challenges facing the world's sixth-largest metropolis, Mexico City's 21 million people fought back and made notable improvements in air quality. A succession of mayors took bold action to clean up the air, and in recent years Mexico City has been enjoying a renaissance. As the smog began to clear, revealing beautiful views of the snow-capped peaks that ring the valley, Mexico City became an international model for other cities seeking to fight pollution.

Efforts began in the 1990s, when city leaders shut down an oil refinery in the city and pushed factories

Testing emissions at a vehicle inspection station in Los Angeles ▲

Upon completing this chapter, you will be able to:

- Describe the composition, structure, and function of Earth's atmosphere
- Relate weather and climate to atmospheric conditions
- Identify major outdoor air pollutants and outline the scope of air pollution
- Assess strategies and solutions for control of outdoor air pollution
- Explain stratospheric ozone depletion and identify steps taken to address it
- Describe acid deposition, discuss its consequences, and explain how we are addressing it
- Characterize the scope of indoor air pollution and assess solutions

Mexico City on a smoggy day

and power plants to shift to cleaner-burning natural gas. Policymakers reduced sources of key pollutants by mandating that lead be removed from gasoline, that the sulfur content of diesel fuel be lowered, and that pollution control technologies such as catalytic converters be phased in for new vehicles.

Levels of many pollutants fell, but as the city's population continued to grow, smog from automobile traffic persisted. In response, city officials stepped up vehicle emissions testing and upgraded taxis and city vehicles to cleaner models. To monitor air quality, 34 sampling stations were set up across the city, sending real-time data to city engineers.

In 2007 Mayor Marcelo Ebrard accelerated efforts as part of a 15-year sustainability plan he launched aiming to make Mexico City "the greenest city in the Americas." New lines were added to the subway system, and 800 exhaust-spewing minibuses were replaced with fuel-efficient buses. More than 450,000 people now use these buses each day, cutting carbon dioxide emissions by an estimated 80,000 tons per year.

In 2010 Ebrard introduced a bicycle-sharing program to free short-distance commuters from dependence on cars. With 1000 bikes at rental stations throughout the city, people can rent a bike cheaply at one location and drop it off at another. In Ebrard's most popular initiative, every Sunday morning the city's main boulevard, the Paseo de la Reforma, is closed to car traffic, creating a safe and pleasant community space for pedestrians, bikers, joggers, and skateboarders.

After 2012, Ebrard's successor as mayor, Miguel Ángel Mancera, built on these efforts by expanding the bicycle program and putting electric buses and taxis on the roads. Mancera also rolled out a car-sharing program, aiming to remove 40,000 vehicles from circulation. Private entrepreneurs are now getting in on the act; recent university graduates have launched companies providing car-sharing and carpooling services, some using electric vehicles.

All these changes paid off with cleaner air. In 1991, Mexico City's air was deemed hazardous to breathe on all but 8 days of the year. By 2010–2015, most pollutants had been slashed by more than 75%, and the air was meeting health standards on one of every two days.

However, plenty of hurdles remain. Rampant development is challenging efforts to plan for sustainable growth. New highway construction is inducing more people to drive. The typical driver still spends three hours a day stuck in traffic that averages just 13 mph. Worst of all, smog still contributes to an estimated 4000 deaths each year. In 2016, a monthlong spell of hot, windless weather brought back foul air conditions that the city had not suffered in over a decade. Angry residents complained that the city's politicians had become overconfident and were failing to follow through on further reforms. In response, Mexico's president, Enrique Peña Nieto, urged leaders to buckle down anew and tighten emissions testing on vehicles. The hope is that Mexico City will continue to follow in the footsteps of Los Angeles, making steady progress toward cleaner air.

L.A. and Mexico City typify cities of developed and developing nations today. Nations that are industrializing as they try to build wealth for their citizens are confronting the same air quality challenges that plagued the United States and other wealthy nations a generation and more ago. We will examine the solutions sought in Los Angeles, Mexico City, and elsewhere as we learn about Earth's atmosphere and how to reduce the pollutants we release into it.

The Atmosphere

Every breath we take reaffirms our connection to the **atmosphere,** the layer of gases that envelops our planet. The atmosphere moderates our climate, provides oxygen, helps to shield us from meteors and hazardous solar radiation, and transports and recycles water and nutrients.

Earth's atmosphere consists of 78% nitrogen (N_2) and 21% oxygen (O_2) by volume of dry air. The remaining 1% is composed of argon (Ar) and minute concentrations of other gases (**FIGURE 17.1**). The atmosphere also contains water vapor (H_2O) in concentrations that vary with time and place from 0% to 4%.

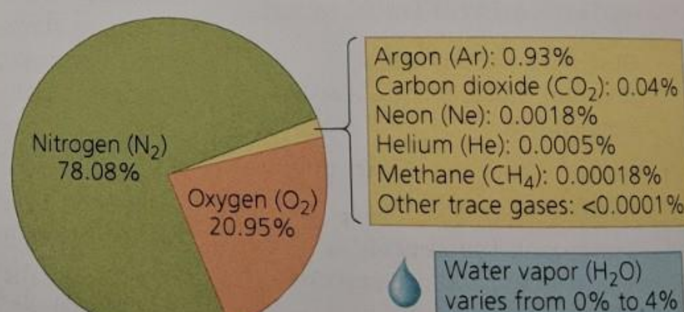


FIGURE 17.1 Earth's atmosphere consists of nitrogen, oxygen, argon, and a mix of gases at dilute concentrations.

Over our planet's long history, the atmosphere's composition has changed. When Earth was young, our atmosphere was dominated by carbon dioxide (CO_2), nitrogen, carbon monoxide (CO), and hydrogen (H_2), but about 2.7 billion years ago, oxygen began to build up with the emergence of microbes that emitted oxygen by photosynthesis (p. 30). Today, human activity is altering the quantities of some atmospheric gases, such as carbon dioxide, methane (CH_4), and ozone (O_3). Before exploring how our pollutants change the air we breathe and how we strive to control pollution, we will begin with an overview of Earth's atmosphere.

The atmosphere is layered

The atmosphere that stretches so high above us and seems so vast is actually just 1/100 of Earth's diameter—a thin coating like the fuzzy skin of a peach. It consists of four layers that differ in temperature, density, and composition (**FIGURE 17.2**).

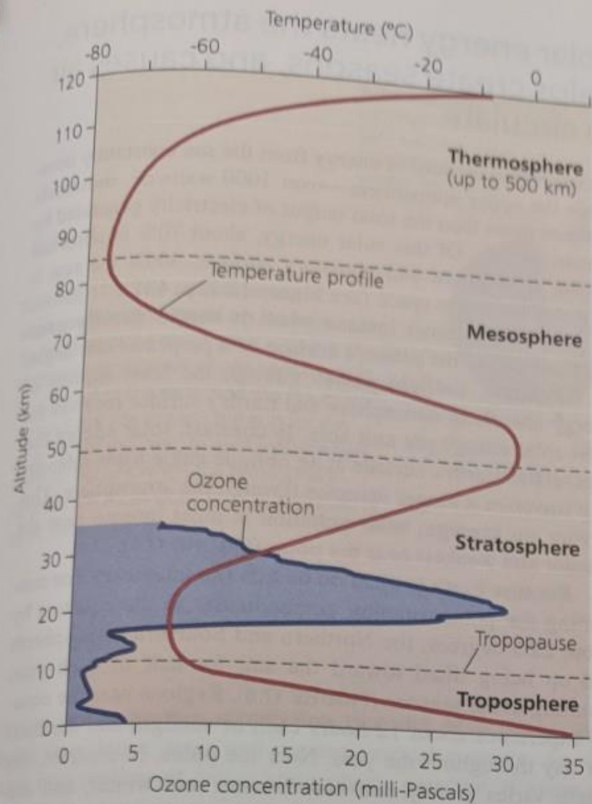


FIGURE 17.2 The atmosphere is layered. Temperature (**red line**) drops with altitude in the troposphere, rises with altitude in the stratosphere, drops in the mesosphere, and rises in the thermosphere. The tropopause separates the troposphere from the stratosphere. Ozone (**blue area**) is densest in the lower stratosphere. *Adapted from Jacobson, M.Z., 2002. Atmospheric pollution: History, science, and regulation. Cambridge, U.K.: Cambridge University Press; and Parson, E.A., 2003. Protecting the ozone layer: Science and strategy. Oxford, U.K.: Oxford University Press.*

The bottommost layer, the **troposphere,** blankets Earth's surface and provides us the air we breathe. Movement of air within the troposphere drives our planet's weather. Although it is thin (averaging 11 km or 7 mi high) relative to the atmosphere's other layers, the troposphere contains three-quarters of the atmosphere's mass. This is because gravity pulls mass downward, making air denser near Earth's surface. Tropospheric air gets colder with altitude, dropping to roughly −52°C (−62°F) at the top of the troposphere. At this point, temperatures stabilize, marking a boundary called the *tropopause*. The tropopause acts like a cap, limiting mixing between the troposphere and the atmospheric layer above it, the stratosphere.

The **stratosphere** extends 11–50 km (7–31 mi) above sea level. Similar in composition to the troposphere, the stratosphere is much drier and less dense. Its gases experience little vertical mixing, so once substances (including pollutants) enter it, they tend to remain for a long time. The stratosphere warms with altitude, because its ozone and oxygen absorb the sun's ultraviolet (UV) radiation (p. 30). Most of the atmosphere's ozone concentrates in a portion of the stratosphere roughly 17–30 km (10–19 mi) above sea level, a region we call the **ozone layer.** By absorbing and scattering incoming UV radiation, the ozone layer greatly reduces the amount of this radiation that reaches Earth's surface. UV light can damage living tissue and induce mutations in DNA, and life has evolved to rely on the protective presence of the ozone layer.

Above the stratosphere lies the mesosphere, where temperatures decrease with altitude and where incoming meteors burn up. Above this, the thermosphere extends upward to an altitude of 500 km (300 mi). Still higher, the atmosphere merges into space in a region called the exosphere.

Pressure, humidity, and temperature vary within the atmosphere

Air moves dynamically within the lower atmosphere as a result of differences in the physical properties of air masses. Among these properties are pressure and density, relative humidity, and temperature.

Gravity pulls gas molecules toward Earth's surface, causing air to be most dense near the surface and less dense as altitude increases. **Atmospheric pressure,** which measures the force per unit area produced by a column of air, also decreases with altitude, because at higher altitudes there are fewer molecules being pulled down by gravity (**FIGURE 17.3**). At sea level, atmospheric pressure averages

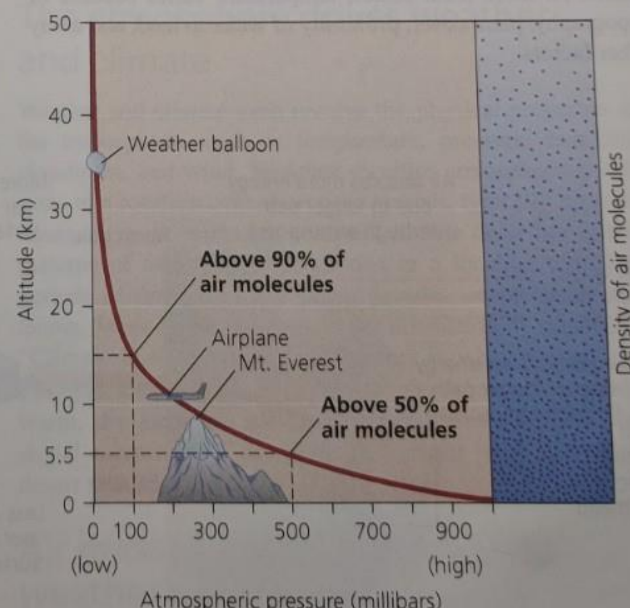


FIGURE 17.3 As one climbs higher through the atmosphere, gas molecules become less densely packed, and atmospheric pressure decreases. One needs to be only 5.5 km (3.4 mi) high to be above half the planet's air molecules. *Adapted from Ahrens, C.D., 2007. Meteorology today, 8th ed., Figure 1.9. © 2007. Belmont, CA: Brooks/Cole. By permission of Cengage Learning.*

14.7 lb/in.^{2} or 1013 millibars (mb). Mountain climbers trekking to Mount Everest, the world's highest mountain, can look up and view their destination from Kala Patthar, a nearby peak, at roughly 5.5 km (18,000 ft) in elevation. At this altitude, pressure is 500 mb, and half the atmosphere's air molecules are above the climber, whereas half are below. A climber who reaches Everest's peak at 8.85 km (29,035 ft) in elevation, where the "thin air" is just over 300 mb, stands above two-thirds of the molecules in the atmosphere! When we fly on a commercial jet airliner at a typical cruising altitude of 11 km (36,000 ft), we are above 80% of the atmosphere's molecules.

Another property of air is **relative humidity**, the ratio of water vapor that air contains at a given temperature to the maximum amount it *could* contain at that temperature. Average daytime relative humidity in June in the desert at Phoenix, Arizona, is only 31% (meaning that the air contains less than a third of the water vapor possible at its temperature), whereas on the tropical island of Guam, relative humidity rarely drops below 88%.

People are sensitive to changes in relative humidity because we perspire to cool our bodies. When humidity is high, the air is already holding nearly as much water vapor as it can, so sweat evaporates slowly and the body cannot cool itself efficiently. This is why high humidity makes it feel hotter than it actually is. Conversely, low humidity speeds evaporation and makes it feel cooler than it actually is.

The temperature of air also varies with location and time. At the global scale, temperature varies over Earth's surface because the sun's rays strike some areas more directly than others. At more local scales, temperature varies because of topography, plant cover, proximity of water to land, and many other factors.

Solar energy heats the atmosphere, helps create seasons, and causes air to circulate

An enormous amount of energy from the sun constantly bombards the upper atmosphere—over 1000 watts/m^2, thousands of times more than the total output of electricity generated by human society. Of this solar energy, about 70% is absorbed by the atmosphere and planetary surface, while the rest is reflected back into space (see Figure 18.2, p. 481).

Sunlight is most intense when it shines directly overhead and meets the planet's surface at a perpendicular angle. At this angle, sunlight passes through the least amount of energy-absorbing atmosphere and Earth's surface receives the most solar energy per unit area. In contrast, solar energy that approaches Earth's surface at an oblique angle loses intensity as it traverses a longer distance through the atmosphere. This is why, on average, solar radiation is most intense near the equator and weakest near the poles (**FIGURE 17.4**).

Because Earth is tilted on its axis (an imaginary line connecting the poles, running perpendicular to the equator) by about 23.5 degrees, the Northern and Southern Hemispheres end up being tilted toward the sun for half of each year, resulting in the seasons (**FIGURE 17.5**). Regions near the equator experience about 12 hours each of sunlight and darkness per day throughout the year. Near the poles, in contrast, day length varies greatly between summer and winter, and seasonality is pronounced.

On the surface of our planet, land and water absorb solar energy and then emit thermal infrared radiation, which warms the air and causes some water to evaporate. As a result, air near Earth's surface tends to be warmer and moister than air at higher altitudes. These differences set into motion a

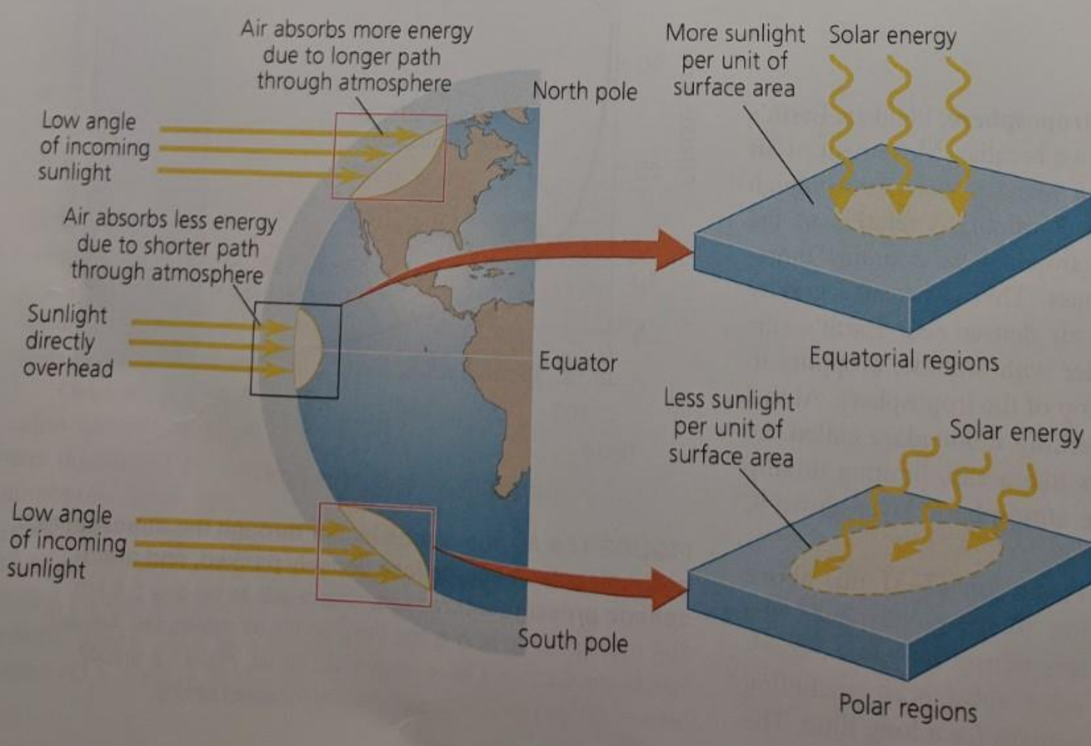


FIGURE 17.4 Because of Earth's curvature, polar regions receive less solar energy than equatorial regions. One reason is that sunlight gets spread over a larger area when striking the surface at an angle. Another reason is that sunlight approaching at a lower angle near the poles must traverse a longer distance through the atmosphere, causing more energy to be absorbed or reflected. These patterns represent year-round averages; the latitude at which radiation approaches the surface perpendicularly varies with the seasons (see Figure 17.5).

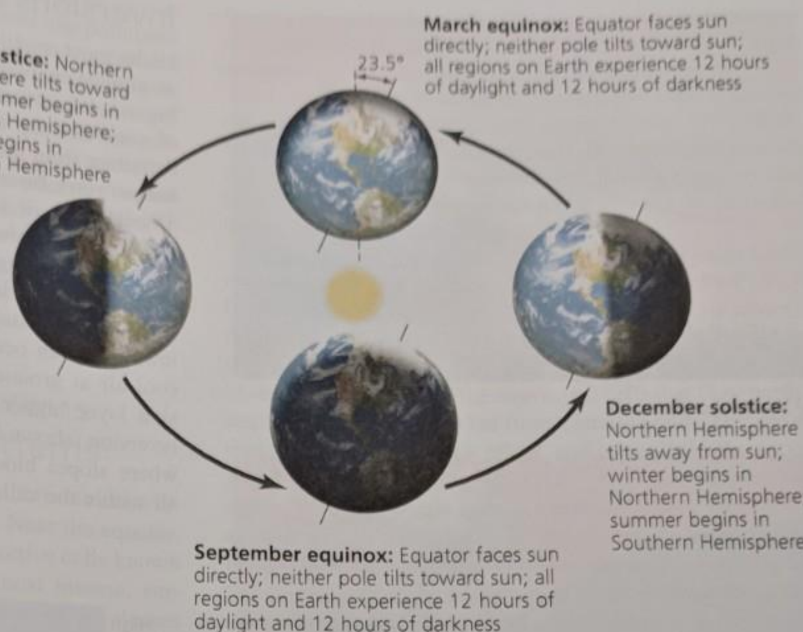


FIGURE 17.5 The seasons occur because Earth is tilted on its axis. As Earth revolves around the sun, the Northern Hemisphere tilts toward the sun for one-half of the year, and the Southern Hemisphere tilts toward the sun for the other half of the year. In each hemisphere, summer occurs when the hemisphere receives the most solar energy because of its tilt toward the sun.

process of **convective circulation** (FIGURE 17.6). Warm air, being less dense, rises and creates vertical currents. As air rises into regions of lesser atmospheric pressure, it expands and cools, causing moisture to condense and fall as rain. Once the air cools, it descends and becomes denser, replacing warm air that is rising. The descending air picks up heat and moisture near ground level and prepares to rise again, continuing the process. Convective circulation patterns occur in ocean waters (p. 422), in magma beneath Earth's surface (pp. 35–36), and even in a simmering pot of soup. Convective circulation influences both weather and climate.

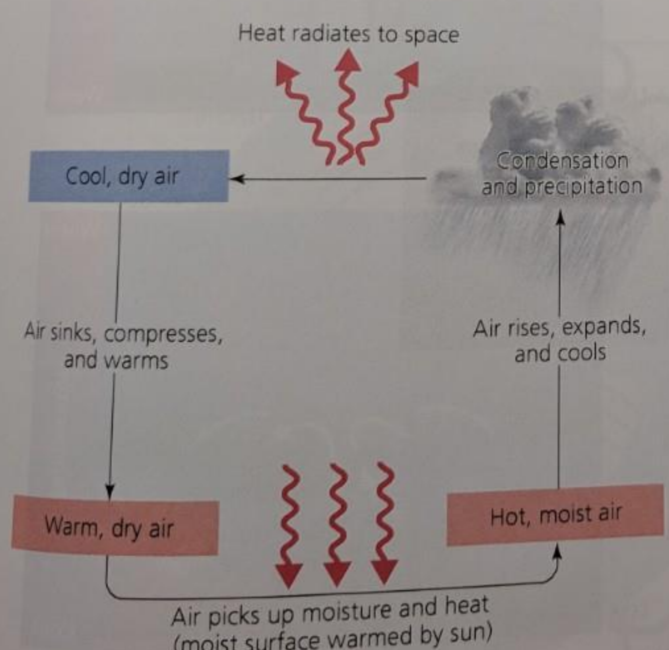


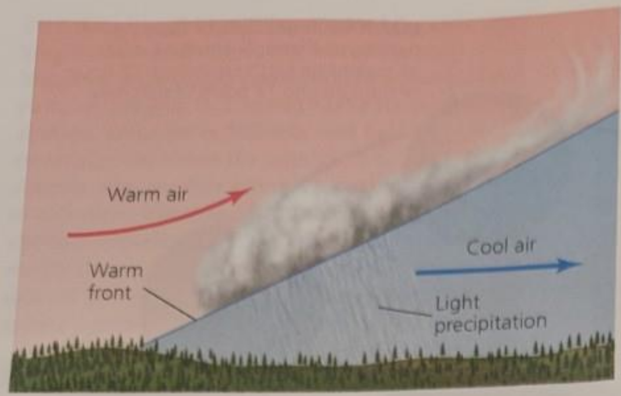
FIGURE 17.6 Convective circulation helps to drive weather. Air heated near Earth's surface picks up moisture and rises. Once aloft, this air cools and moisture condenses, forming clouds and precipitation. Cool, drying air begins to descend, compressing and warming in the process. Warm, dry air near the surface begins the cycle anew.

The atmosphere drives weather and climate

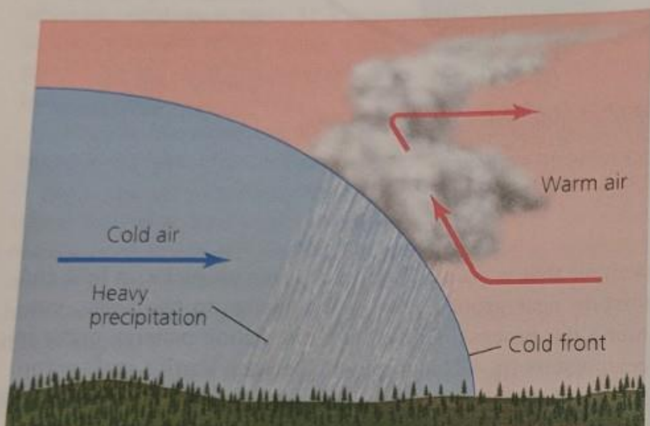
Weather and climate each involve the physical properties of the troposphere, such as temperature, pressure, humidity, cloudiness, and wind. **Weather** specifies atmospheric conditions in a location over short time periods, typically minutes, hours, days, or weeks. In contrast, **climate** describes typical patterns of atmospheric conditions in a location over long periods of time, typically years, decades, centuries, or millennia. Mark Twain once noted the distinction by remarking, "Climate is what we expect; weather is what we get." For example, Los Angeles has a climate characterized by reliably warm, dry summers and mild, rainy winters, yet on occasional autumn days, dry Santa Ana winds blow in from the desert and bring extremely hot weather.

Air masses interact, producing weather

Weather can change quickly when air masses with different physical properties meet. The boundary between air masses that differ in temperature and moisture (and therefore density) is called a **front.** The boundary along which a mass of warmer, moister air replaces a mass of colder, drier air is



(a) Warm front



(b) Cold front

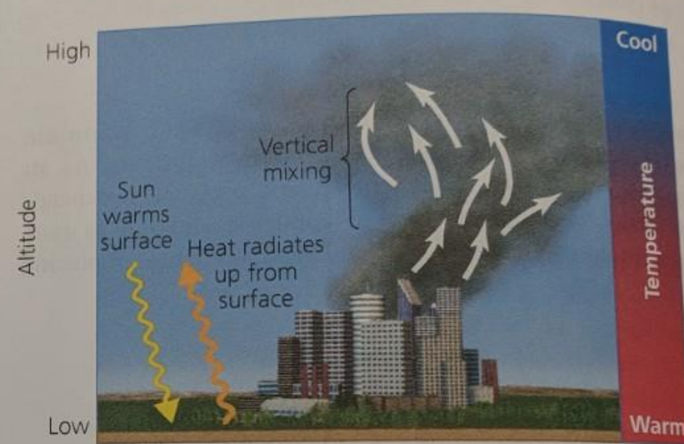
FIGURE 17.7 Fronts occur where air masses meet. When a warm front approaches **(a)**, warmer air rises over cooler air, causing light or moderate precipitation as moisture in the warmer air condenses. When a cold front approaches **(b)**, colder air pushes beneath warmer air, and the warmer air rises, resulting in condensation and heavy precipitation.

termed a **warm front** (FIGURE 17.7a). Some of the warm, moist air along the leading edge of a warm front usually rises over the cooler air mass that is blocking its progress. As it rises, the warm air cools and the water vapor within condenses, forming clouds and light rain. A **cold front** (FIGURE 17.7b) is the boundary along which a colder, drier air mass displaces a warmer, moister air mass. The colder air, being denser, tends to wedge beneath the warmer air. The warmer air rises, expands, then cools to form clouds and thunderstorms. Once a cold front passes through, the sky usually clears, and temperature and humidity drop.

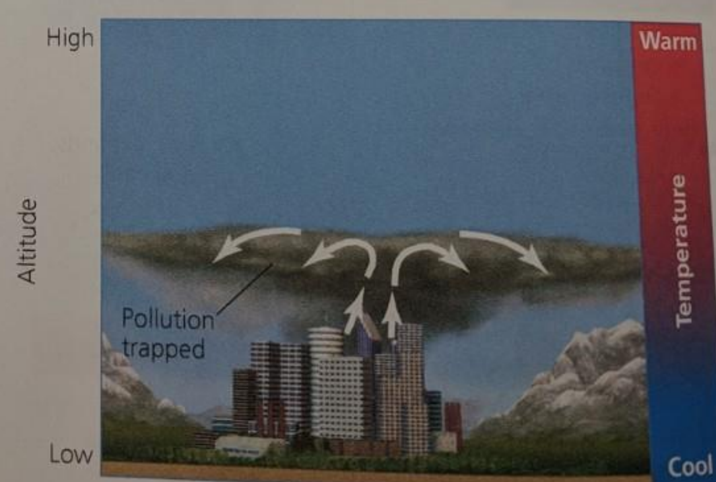
Adjacent air masses may also differ in atmospheric pressure. A **high-pressure system** contains air that descends because it is cool and then spreads outward as it nears the ground. High-pressure systems typically bring fair weather. In a **low-pressure system,** warmer air rises, drawing air inward toward the center of low atmospheric pressure. The rising air expands and cools, and clouds and precipitation often result.

Inversions affect air quality

Under most conditions, air in the troposphere becomes cooler as altitude increases. Because warm air rises, vertical mixing results (FIGURE 17.8a). Occasionally, however, a layer of cool air may form beneath a layer of warmer air. This departure from the normal temperature profile is known as a **temperature inversion,** or thermal inversion (FIGURE 17.8b). The band of air in which temperature rises with altitude is called an **inversion layer** (because the normal direction of temperature change is inverted). The cooler air at the bottom of the inversion layer is denser than the warmer air above, so it resists vertical mixing and remains stable. Temperature inversions can occur in different ways, sometimes involving cool air at ground level and sometimes involving an inversion layer higher above the ground. One common type of inversion (shown in Figure 17.8b) occurs in mountain valleys where slopes block morning sunlight, keeping ground-level air within the valley shaded and cool.



(a) Normal conditions



(b) Temperature inversion

FIGURE 17.8 Temperature inversions trap air and pollutants. Under normal conditions **(a)**, air becomes cooler with altitude and air of different altitudes mixes, dispersing pollutants upward. In a temperature inversion **(b)**, dense cool air remains near the ground, and air warms with altitude within the inversion layer. Little mixing occurs, and pollutants are trapped.

Vertical mixing allows pollutants in the air to be carried upward and diluted, but temperature inversions trap pollutants near the ground. As a result, cities such as Los Angeles and Mexico City suffer their worst pollution when inversions prevent pollutants from being dispersed. As noted earlier, both of these metropolitan areas are encircled by mountains that promote inversions, interrupt air flow, and trap pollutants. Los Angeles experiences inversions most often when a "marine layer" of air cooled by the ocean moves inland. In Mexico City in 1996, a persistent temperature inversion sparked a five-day crisis in which pollution killed at least 300 people and sent 400,000 to hospitals. Desperate for a solution, some people proposed dynamiting a hole in the mountains and installing immense fans to blow out the air!

Large-scale circulation systems produce global climate patterns

At large geographic scales, convective air currents contribute to broad climate patterns (**FIGURE 17.9**). Near the equator, solar radiation sets in motion a pair of convective cells known as *Hadley cells*. Here, where sunlight is most intense, surface air warms, rises, and expands. As it does so, it releases moisture, producing the heavy rainfall that gives rise to tropical rainforests. After releasing much of its moisture, this air diverges and moves in currents heading north and south. The air in these currents cools and descends at about 30 degrees latitude north and south. Because the descending air is now dry, the regions around 30 degrees latitude are quite arid, giving rise to deserts. Two additional pairs of convective cells, *Ferrel cells* and *polar cells*, lift air and create precipitation around 60 degrees latitude north and south and cause air to descend at 30 degrees latitude and in the polar regions.

Together these three pairs of convective cells create wet climates near the equator, arid climates near 30° latitude, moist regions near 60° latitude, and dry conditions near the poles. These patterns, combined with temperature variation, help explain why biomes tend to be arrayed in latitudinal bands (see Figure 4.16, p. 92).

The Hadley, Ferrel, and polar cells interact with Earth's rotation to produce global wind patterns (see Figure 17.9). As Earth rotates on its axis, regions of the planet's surface near the equator move west to east more quickly than regions near the poles. As a result, from the perspective of an Earth-bound observer, air currents of the convective cells that flow north or south appear to be deflected from a straight path. This deflection is called the **Coriolis effect,** and it results in the curving global wind patterns in Figure 17.9. Near the equator lies a region with few winds known as the *doldrums*. Between the equator and 30° latitude, *trade winds* blow from east to west. From 30° to 60° latitude, *westerlies* blow from west to east. For centuries, people made use of these patterns to facilitate ocean travel by wind-powered sailing ships.

The atmosphere interacts with the oceans to affect weather, climate, and the distribution of biomes. Winds and convective circulation in ocean water together maintain ocean currents (p. 419). Trade winds weaken periodically, leading to El Niño conditions (p. 423). And oceans and atmosphere sometimes interact to create violent storms that can threaten life and property.

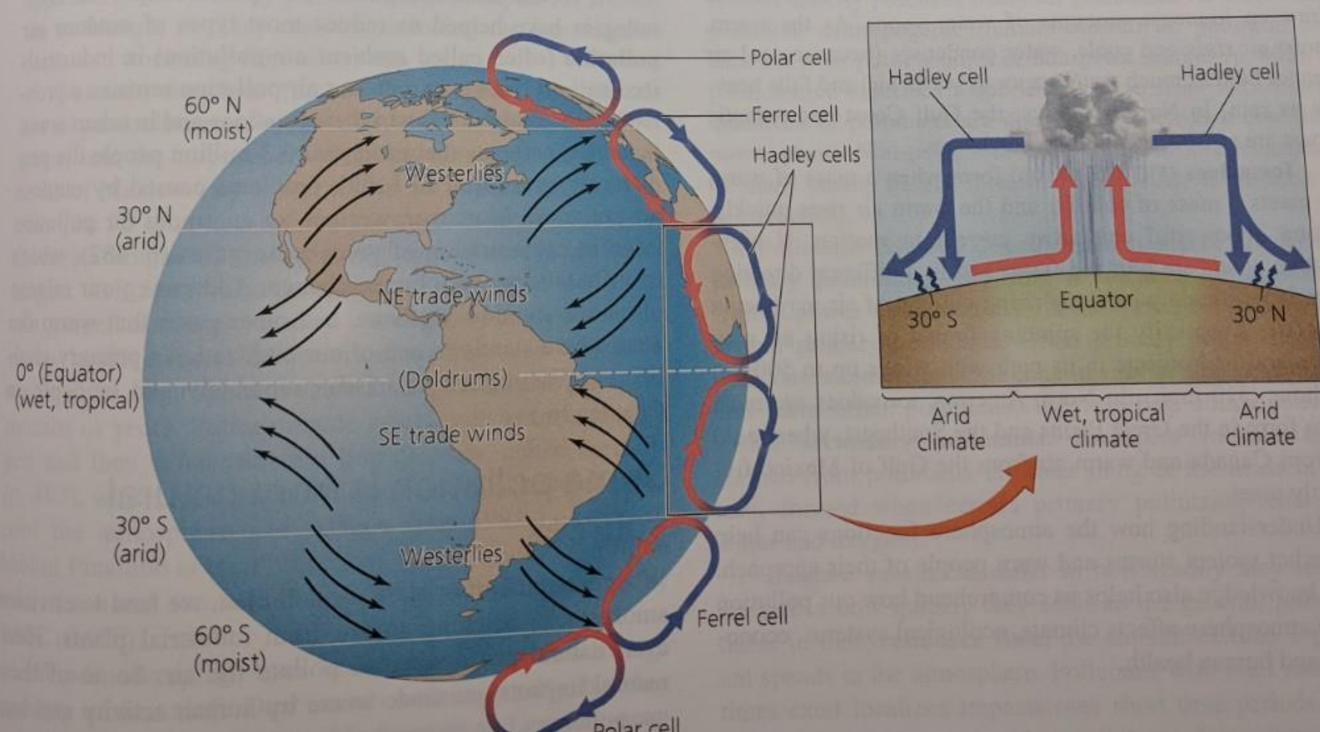


FIGURE 17.9 Large-scale convective cells create global patterns of moisture and wind. These cells give rise to a wet climate in tropical regions, arid climates around 30° latitude, moist climates around 60°, and dry climates near the poles. Surface air movement of these cells interacts with the Coriolis effect to create global wind currents.

(a) Satellite image of a hurricane

(b) Photograph of a tornado

FIGURE 17.10 **Hurricanes and tornadoes are cyclonic storms that pose hazards to life and property.**

Storms pose hazards

Hurricanes (FIGURE 17.10a) form when warm, moisture-laden air over tropical oceans rises and winds rush into these areas of low pressure. In the Northern Hemisphere, these winds turn counterclockwise because of the Coriolis effect. In other regions, such cyclonic storms are called *cyclones* or *typhoons*. The powerful convective currents of these storms draw up immense amounts of water vapor. As the warm, moist air rises and cools, water condenses (because cool air cannot hold as much water vapor as warm air) and falls heavily as rain. In North America, the Gulf Coast and Atlantic Coast are most susceptible to hurricanes.

Tornadoes (FIGURE 17.10b) form when a mass of warm air meets a mass of cold air and the warm air rises quickly, setting a powerful convective current in motion. If high-altitude winds are blowing faster and in a different direction from low-altitude winds, the rising column of air may begin to rotate. Eventually the spinning funnel of rising air may lift up soil and objects in its path with winds up to 500 km per hour (310 mph). In North America, tornadoes are most apt to form in the Great Plains and the Southeast, where cold air from Canada and warm air from the Gulf of Mexico frequently meet.

Understanding how the atmosphere functions can help us predict violent storms and warn people of their approach. Such knowledge also helps us comprehend how our pollution of the atmosphere affects climate, ecological systems, economies, and human health.

Outdoor Air Quality

Throughout history, we have made the atmosphere a dumping ground for our airborne wastes. Whether from simple wood fires or modern coal-burning power plants, we have generated **air pollutants,** gases and particulate material added to the atmosphere that can affect climate or harm people or other living things. At the same time, our efforts to control **air pollution,** the release of air pollutants, have brought some of our best successes in confronting environmental problems thus far.

In recent decades, public policy and improved technologies have helped us reduce most types of **outdoor air pollution** (often called *ambient air pollution*) in industrialized nations. However, outdoor air pollution remains a problem, particularly in industrializing nations and in urban areas. Scientists estimate that each year 3.3 million people die prematurely as a result of health problems caused by outdoor air pollution. Moreover, we face an enormous air pollution issue in our emission of greenhouse gases (p. 482), which contribute to global climate change. Addressing our release of carbon dioxide, methane, and other gases that warm the atmosphere stands as one of our civilization's primary challenges. (We discuss this issue separately and in depth in Chapter 18.)

Some pollution is from natural sources

When we think of outdoor air pollution, we tend to envision smokestacks belching smoke from industrial plants. However, natural processes also pollute the air. Some of these natural impacts are made worse by human activity and land use policies.

Fires from burning vegetation emit soot and gases. Worldwide, more than 60 million hectares (ha; 150 million acres, an area the size of Texas) of forest and grassland burn in a typical year (FIGURE 17.11a). Fires occur naturally, but human influence can make them more severe. In regions

(a) Natural fire in California (b) Mount Saint Helens eruption, 1980 (c) Dust storm blowing dust from Africa to the Americas

FIGURE 17.11 Wildfire, volcanoes, and dust storms are three natural sources of air pollution.

like the Los Angeles basin, residential development has encroached into chaparral ecosystems (p. 98) that are naturally fire-prone, often resulting in costly damage when fires occur. Across North America, the suppression of fire has allowed fuel to build up in forests and eventually feed highly destructive fires (p. 314). In the tropics, many farmers clear forest for farming and grazing using a "slash-and-burn" approach (p. 215). Today climate change (Chapter 18) is leading to drought in many regions, including the Los Angeles basin, and worsening fires as a result.

Volcanic eruptions (pp. 38–39) release large quantities of particulate matter, as well as sulfur dioxide and other gases, into the troposphere (**FIGURE 17.11b**). In 2012, residents of Mexico City went on alert as Popocatepetl, a volcano just 70 km (45 mi) from the city, let loose a series of moderate eruptions, adding to the region's pollution challenges. Ash from volcanic eruptions near populated areas can ground airplanes, destroy car engines, and pose respiratory health dangers. Major eruptions may also blow matter into the stratosphere, where it can circle the globe for months or years. Sulfur dioxide reacts with water and oxygen and then condenses into fine droplets, called aerosols (p. 483), which reflect sunlight back into space and thereby cool the atmosphere and surface. The 1991 eruption of Mount Pinatubo in the Philippines ejected nearly 20 million tons of ash and aerosols and cooled global temperatures by 0.5°C (0.9°F).

Winds sweeping over arid terrain can send huge amounts of dust aloft. Dust storms occur naturally, but they are made worse by unsustainable farming and grazing practices that strip vegetation from the soil and lead to desertification (p. 222). Continental-scale dust storms took place in the United States in the 1930s, when soil from the drought-plagued Dust Bowl states blew eastward to the Atlantic (p. 224). Today, trade winds blow soil across the Atlantic Ocean from Africa to the Americas (**FIGURE 17.11c**). Strong westerlies sometimes lift soil from deserts in Mongolia and China and blow it all the way across the Pacific Ocean to North America.

We create outdoor air pollution

Human activity produces many air pollutants. As with water pollution, anthropogenic (human-caused) air pollution can emanate from point sources or non-point sources (p. 405). A point source describes a specific location from which large quantities of pollutants are discharged (such as a coal-fired power plant). Non-point sources are more diffuse, consisting of many small, widely spread sources (such as millions of automobiles).

Pollutants released directly from a source are termed **primary pollutants.** Ash from a volcano, sulfur dioxide from a power plant, and carbon monoxide from an engine are all primary pollutants. Often primary pollutants react with one another, or with constituents of the atmosphere, and form other pollutants; the resulting compounds are called **secondary pollutants.** Examples include ozone formed from pollutants in urban smog or the acids in acid rain, formed when certain primary pollutants react with water and oxygen.

Because substances differ in how readily they react in air and in how quickly they settle to the ground, pollutants differ in their **residence time,** the amount of time a pollutant spends in the atmosphere. Pollutants with brief residence times exert localized impacts over short time periods. Most particulate matter and most pollutants from automobile exhaust stay aloft only hours or days, which is why air quality in a city like Mexico City or Los Angeles changes from day to day. In contrast, pollutants with long residence times can exert impacts regionally or globally for long periods, even

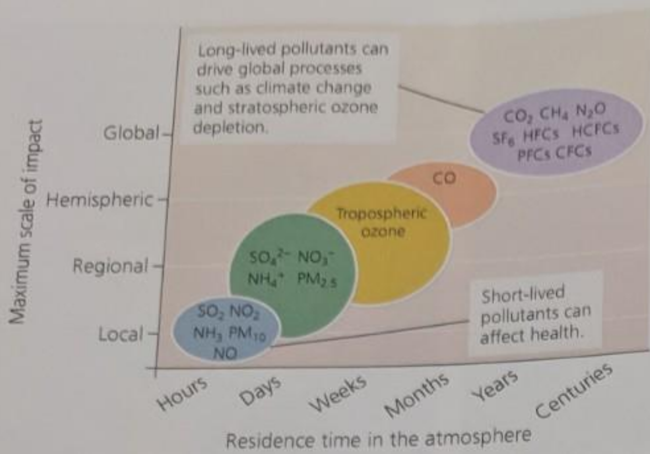


FIGURE 17.12 Substances with short residence times affect air quality locally, whereas those with long residence times affect air quality globally. *Source: United Nations Environment Programme, 2007. Global environment outlook (GEO-4), FIGURE 2.1. Data from European Environment Agency 1995; EPA Center for Airborne Organics 1997.*

centuries (FIGURE 17.12). The pollutants that drive climate change and those that deplete Earth's ozone layer (two separate phenomena!—see **FAQ,** p. 468) are each able to cause these global and long-lasting impacts because they persist in the atmosphere for so long.

The Clean Air Act addresses pollution

To address air pollution in the United States, Congress has passed a series of laws, most notably the **Clean Air Act.** First enacted in 1963, the Clean Air Act has been amended multiple times, chiefly in 1970 and 1990. This body of legislation funds research into pollution control, sets standards for air quality, and encourages emissions standards for automobiles and for stationary point sources such as industrial plants. It also imposes limits on emissions from new sources, funds a nationwide air quality monitoring system, and enables citizens to sue parties violating the standards. The 1990 amendments introduced an emissions trading program for sulfur dioxide.

Under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) sets nationwide standards for (1) emissions of several key pollutants and (2) concentrations of major pollutants in ambient air. It is largely up to the states to monitor emissions and air quality and to develop, implement, and enforce regulations within their borders. States submit implementation plans to the EPA for approval, and if a state's plans are not adequate, the EPA can take control of enforcement. If a region fails to clean up its air, the EPA can prevent it from receiving federal money for transportation projects.

Agencies monitor emissions

State and local agencies monitor and report to the EPA emissions of six major pollutants, profiled below. Across the United States in 2014, human activity polluted the air with 88 million tons of these six monitored pollutants. Carbon monoxide was the most abundant pollutant by mass (FIGURE 17.13).

Carbon monoxide **Carbon monoxide (CO)** is a colorless, odorless gas produced primarily by the incomplete combustion of fuel. Vehicles and engines account for most CO emissions in the United States. Other sources include industrial processes, waste combustion, and residential wood burning. Carbon monoxide is hazardous because it binds to hemoglobin in red blood cells, which in turn prevents the hemoglobin from binding with oxygen. Carbon monoxide poisoning induces nausea, headaches, fatigue, heart and nervous system damage, and potentially death.

Sulfur dioxide **Sulfur dioxide (SO_2)** is a colorless gas with a pungent odor. Most emissions result from the combustion of coal for electricity generation and industry. During combustion, elemental sulfur (S), a contaminant in coal, reacts with oxygen (O_2) to form SO_2. Once in the atmosphere, SO_2 may react to form sulfur trioxide (SO_3) and sulfuric acid (H_2SO_4), which may then settle back to Earth in acid deposition (p. 469).

Nitrogen oxides **Nitrogen oxides (NO_x)** are a family of compounds that include nitric oxide (NO) and nitrogen dioxide (NO_2). Most U.S. emissions of nitrogen oxides result when nitrogen and oxygen from the atmosphere react at high temperatures during combustion in vehicle engines. Fossil

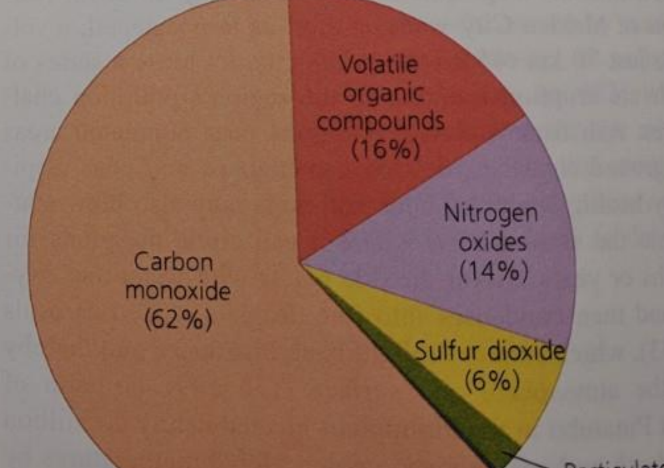


FIGURE 17.13 In 2014, the United States emitted 88 million tons of the six major pollutants whose emissions are monitored by the EPA and state agencies. These figures omit pollutants from dust and wildfires. *Data from U.S. EPA.*

fuel combustion in industry and at electrical utilities accounts for most of the rest. NO_X emissions contribute to smog, acid deposition, and stratospheric ozone depletion.

Volatile organic compounds **Volatile organic compounds (VOCs)** are carbon-containing chemicals emitted by vehicle engines and a wide variety of solvents, industrial processes, household chemicals, and consumer items. Examples range from benzene to acetone to formaldehyde. One common group of VOCs consists of hydrocarbons (p. 27) such as methane (CH_4, the primary component of natural gas), propane (C_3H_8, used as a portable fuel), butane (C_4H_{10}, found in cigarette lighters), and octane (C_8H_{18}, a component of gasoline). Human activities account for about half the VOC emissions in the United States. The remainder comes from natural sources; for example, plants produce isoprene and terpenes, compounds that generate a bluish haze that has given the Blue Ridge Mountains their name. VOCs can react to produce secondary pollutants, as occurs in urban smog.

Particulate matter **Particulate matter** is composed of solid or liquid particles small enough to be suspended in the atmosphere. Particulate matter includes primary pollutants such as dust and soot, as well as secondary pollutants such as sulfates and nitrates. Scientists classify particulate matter by the size of the particles. Smaller particles are more likely to get deep into the lungs and cause respiratory damage and heart problems. PM_{10} pollutants consist of particles less than 10 microns in diameter (one-seventh the width of a human hair), whereas $PM_{2.5}$ pollutants consist of still-finer particles less than 2.5 microns in diameter. Most PM_{10} pollution is from road dust, whereas most $PM_{2.5}$ pollution results from combustion.

Lead **Lead** (Pb) is a heavy metal that enters the atmosphere as a particulate pollutant. The lead-containing compounds tetraethyl lead and tetramethyl lead, when added to gasoline, improve engine performance. However, exhaust from the combustion of leaded gasoline emits airborne lead, which can be inhaled or can be deposited on land and water. When lead enters the food chain, it accumulates in body tissues and can cause central nervous system malfunction and many other ailments (p. 361). Since the 1980s, most developed nations have phased out leaded gasoline (p. 7), and today most developing nations are following suit. In developed nations, the main remaining source of atmospheric lead is industrial metal smelting.

We have reduced pollutant emissions

Since passage of the Clean Air Act of 1970, the United States has reduced emissions of each of the six monitored pollutants substantially (FIGURE 17.14a). These dramatic reductions in emissions have occurred despite significant increases in the nation's population, energy consumption, miles traveled by vehicle, and gross domestic product (FIGURE 17.14b). Likewise, most other industrialized nations have taken their own steps to reduce emissions and have attained similar results.

We have achieved this success in controlling pollution as a result of policy steps and technological developments, each motivated by grassroots social demand for cleaner air. In factories, power plants, and refineries, technologies such as baghouse filters, electrostatic precipitators, and

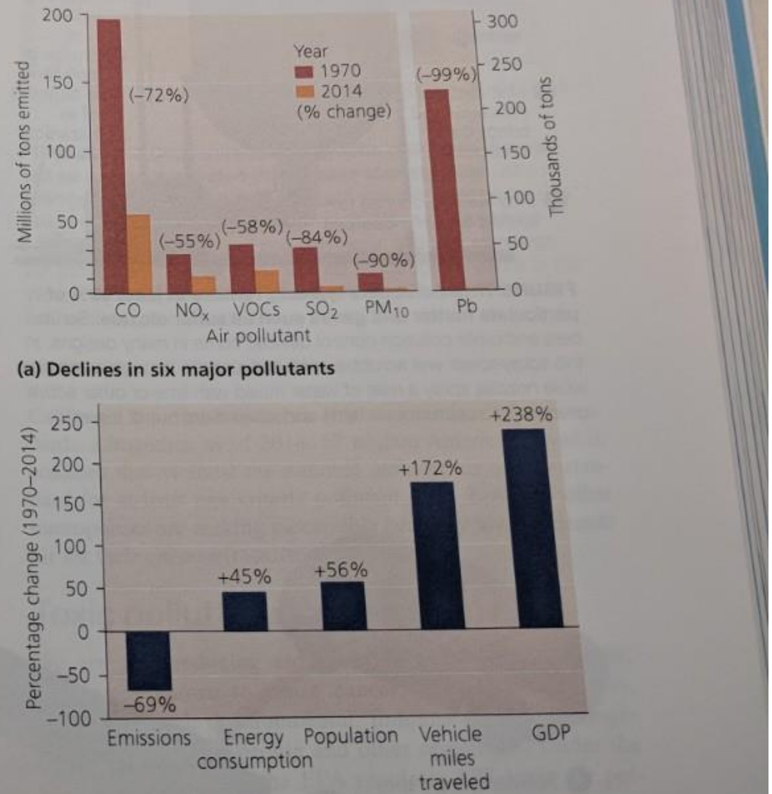


FIGURE 17.14 U.S. emissions have declined sharply since 1970. We have achieved reductions **(a)** in the six major pollutants tracked by the EPA, despite increases **(b)** in U.S. energy consumption, population, vehicle miles traveled, and gross domestic product. *Data from U.S. EPA.*

DATA By what percentage has population increased since 1970? By what percentage have emissions decreased? Using these two amounts, calculate the change in emissions per person.

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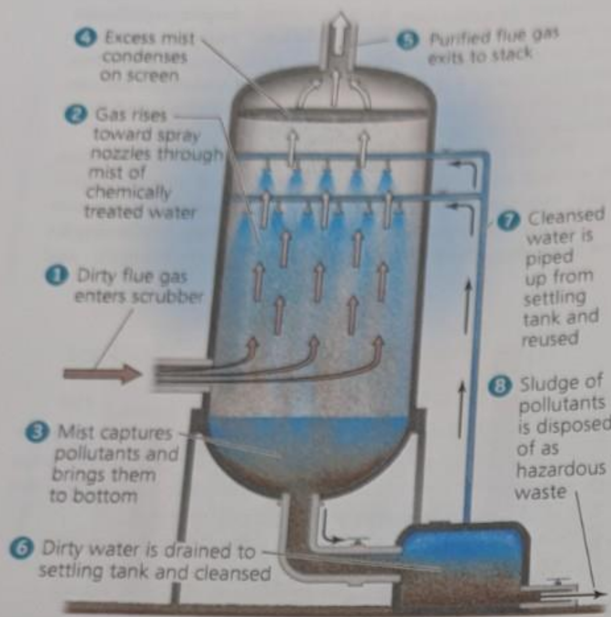

FIGURE 17.15 Scrubbers typically remove at least 90% of particulate matter and gases such as sulfur dioxide. Scrubbers and other pollution control devices come in many designs. In this spray-tower wet scrubber, polluted air rises through a chamber while nozzles spray a mist of water mixed with lime or other active chemicals to capture pollutants and wash them out of the air.

scrubbers (FIGURE 17.15) have been installed to chemically convert or physically remove airborne pollutants before they are emitted from smokestacks. Meanwhile, cleaner-burning motor vehicle engines and automotive technologies such as catalytic converters have cut down on pollution from automobile exhaust. In a **catalytic converter** (FIGURE 17.16), engine exhaust reacts with metals that convert hydrocarbons, CO, and NO_x into carbon dioxide, water vapor, and nitrogen gas. Such pollution control technologies were initially resisted by industry because of added expense, but came to be widely adopted once policy measures were in place encouraging or mandating them. Other policies have been influential, as well. Phaseouts of leaded gasoline caused lead emissions to plummet, and the EPA's Acid Rain Program and its emissions trading system (p. 471), along with clean coal technologies (p. 538), have reduced SO_2 and NO_x emissions.

The reduction of outdoor air pollution in the United States since 1970 has resulted in notably cleaner air throughout the nation and represents one of America's greatest accomplishments in safeguarding human health and environmental quality. It demonstrates how seemingly intractable problems can be tackled and addressed within a democratic system when government and industry are informed by science and are responsive to the public's demands. The EPA estimates that between 1970 and 1990 alone, clean air regulations and the resulting technological advances in pollution control saved the lives of 200,000 Americans. Similar advances in pollution control have been made by most other wealthy nations in recent years.

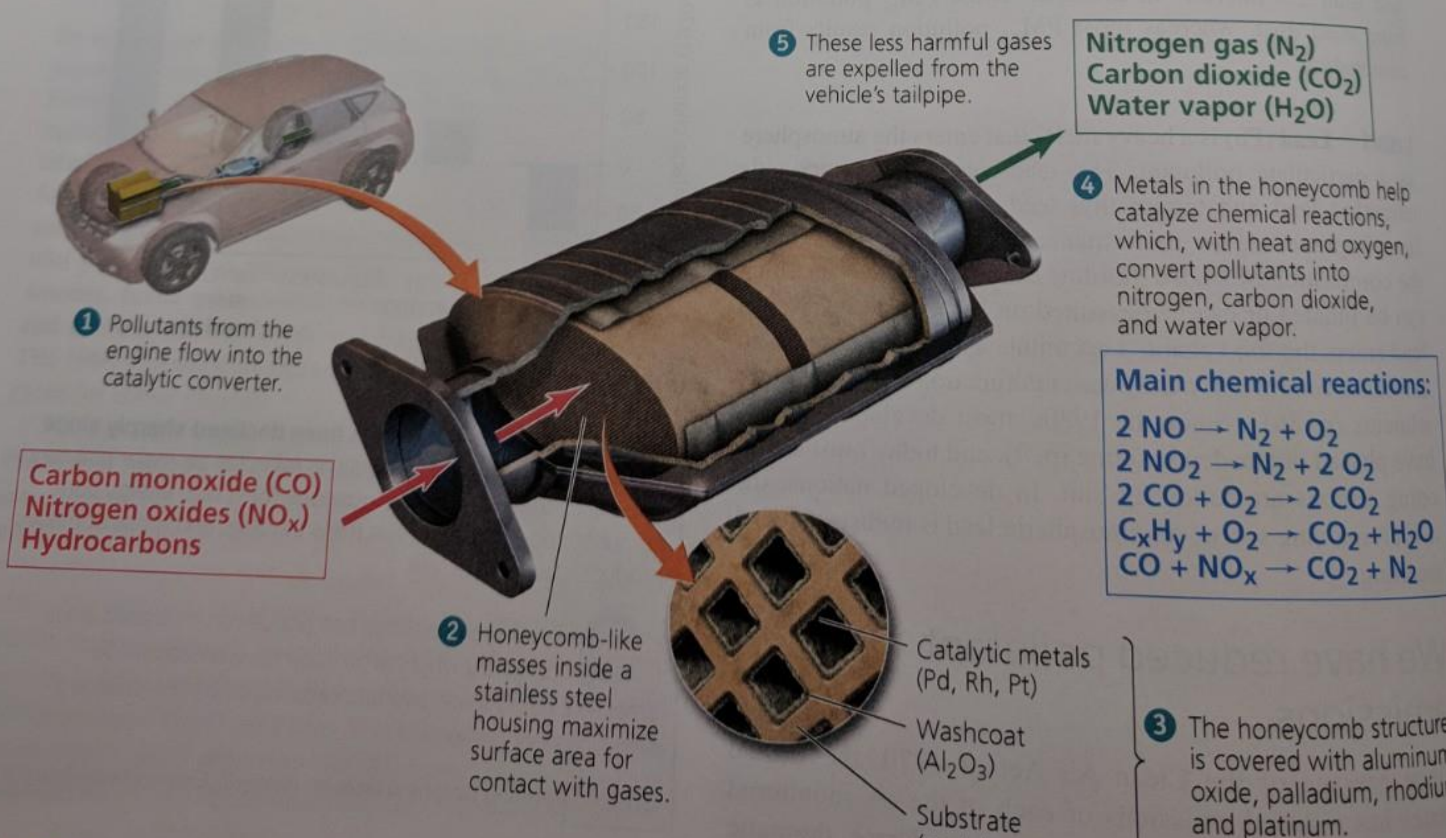

FIGURE 17.16 Catalytic converters improve air quality by filtering pollutants from vehicle exhaust.

Air quality has improved

As a result of emissions reductions, air quality has improved markedly in industrialized nations. In the United States, the EPA and the states monitor outdoor air quality by measuring the concentrations of six **criteria pollutants,** pollutants judged to pose substantial risk to human health. For each of these, the EPA has established *national ambient air quality standards,* which are maximum concentrations allowable in ambient outdoor air. The six criteria pollutants include four of the six pollutants whose emissions are monitored—carbon monoxide, sulfur dioxide, particulate matter, and lead—and also nitrogen dioxide and tropospheric ozone.

Nitrogen dioxide (NO_2) is a highly reactive, reddish brown, foul-smelling gas that contributes to smog and acid deposition. Along with nitric oxide (NO), NO_2 belongs to the family of compounds called nitrogen oxides (NO_x). Nitric oxide reacts readily in the atmosphere to form NO_2, which is both a primary and secondary pollutant.

Although ozone in the stratosphere shields us from the dangers of UV radiation, ozone from human activity accumulates low in the troposphere. **Tropospheric ozone (O_3),** also called *ground-level ozone*, is a secondary pollutant, created by the reaction of nitrogen oxides and volatile carbon-containing chemicals in the presence of sunlight. A major component of photochemical smog (pp. 462–463), this colorless gas poses health risks due to the instability of the O_3 molecule. This triplet of oxygen atoms will readily split into a molecule of oxygen gas (O_2) and a free oxygen atom. The oxygen atom may then participate in reactions that can injure living tissues and cause respiratory problems. Tropospheric ozone is the pollutant that most frequently exceeds its national ambient air quality standard.

Across the United States, more than 4000 monitoring stations take hourly or daily air samples to measure pollutant concentrations. The EPA compiles these data and calculates values on its Air Quality Index (AQI) for each site. Each of six pollutants—CO, SO_2, NO_2, O_3, PM_{10}, and $PM_{2.5}$—receives an AQI value from 0 to 500 that reflects its current concentration. AQI values below 100 indicate satisfactory air conditions, and values above 100 indicate unhealthy conditions. The highest AQI value from the pollutants on a particular day is reported as the overall AQI value for that day, and these values are made available online and reported in weather forecasts.

The actions of scientists, policymakers, industrial leaders, and everyday citizens have made air quality today far better than it was a generation or two ago (FIGURE 17.17). However, there remains plenty of room for improvement. Concerns over new pollutants are emerging, greenhouse gas emissions are altering the climate, and people in low-income communities suffer disproportionately from living near hotspots of pollution. In fact, many Americans live in areas where pollution continues to reach unhealthy levels. Despite enormous improvement over the past two decades, residents of Los Angeles County, for instance, still regularly breathe air that violates national ambient air quality standards for five of the six criteria pollutants. People in four adjacent southern California counties breathe air that violates four of the standards. Altogether, as of 2014, 57 million Americans lived in counties that violated the national ambient air quality standard for at least one criteria pollutant. Still, L.A. and other metropolises are making perceptible headway toward cleaner air for their citizens (FIGURE 17.18, p. 458).

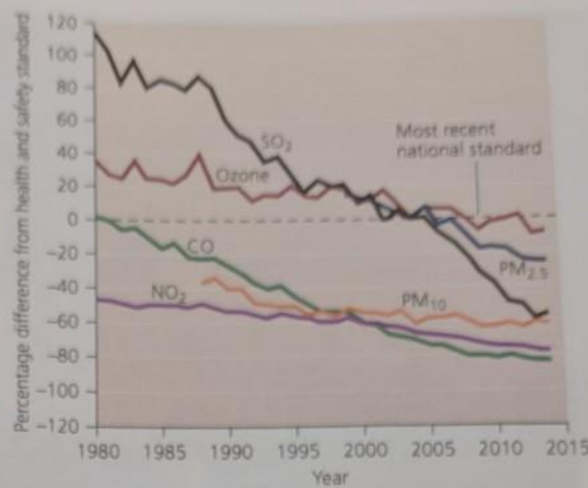

FIGURE 17.17 Concentrations of criteria pollutants in ambient air across the United States have steadily fallen. All now average below their standards for health and safety set by the EPA. Lead (not shown) has plummeted from 900% of its standard in 1980. Still, local hotspots of pollution occur, and U.S. standards are sometimes more lax than those set by European nations or the World Health Organization. These data omit pollutants from dust and wildfires. *Data from U.S. EPA.*

Toxic pollutants pose health risks

We are also reducing emissions of **toxic air pollutants,** substances known to cause cancer; reproductive defects; or neurological, developmental, immune system, or respiratory problems in people and other organisms. Under the 1990 Clean Air Act, the EPA regulates 187 toxic air pollutants produced by a variety of activities, including metal smelting, sewage treatment, and industrial processes. These pollutants range from the heavy metal mercury (from coal-burning power plant emissions and other sources) to VOCs such as benzene (a component of gasoline) and methylene chloride (found in paint stripper). Based on monitoring at 300 sites across the United States, scientists estimate that toxic air pollutants cause cancer in 1 out of every 25,000 Americans (40 cancer cases per 1 million people). Health risks are highest in urban and industrialized areas such as the Los Angeles region, but nationwide the EPA estimates that Clean Air Act regulations on facilities such as chemical plants, waste incinerators, dry cleaners, and coke ovens have helped to reduce emissions of toxic air pollutants since 1990 by more than 42%.

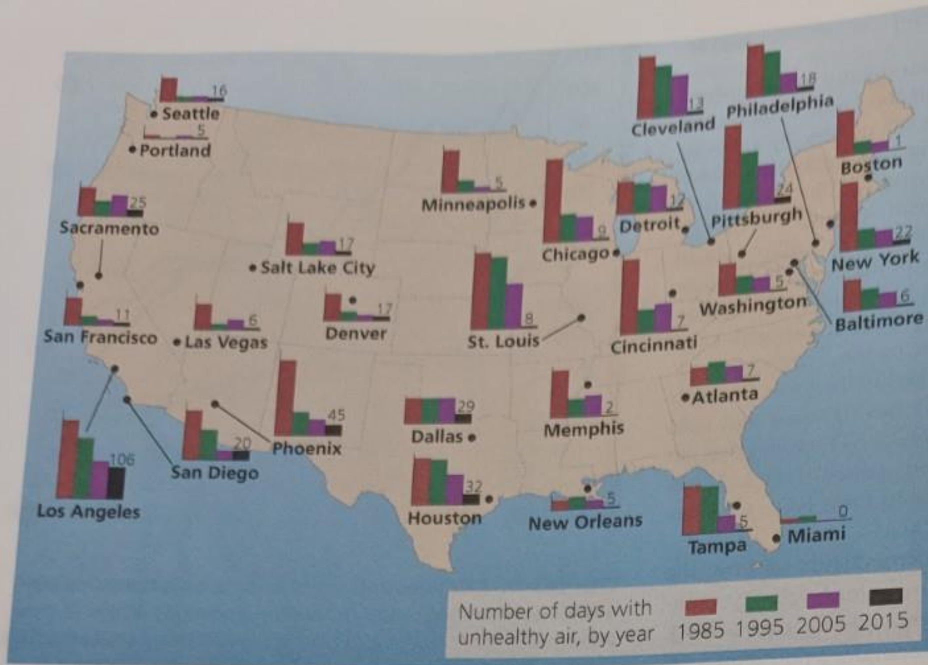

FIGURE 17.18 In most U.S. cities, air is becoming cleaner. This map shows numbers of days with unhealthy air from years spanning four decades for 29 metropolitan areas, according to the Air Quality Index (AQI). The AQI combines data on CO, NO_2, SO_2, O_3, and particulate matter. Days with AQI values over 100, shown here, indicate unhealthy air and national ambient air quality standard violations. *Data from U.S. EPA.*

DATA Locate where you live on the map. How does your city or the nearest major city to you compare to others in its air quality? Has it improved its air quality in recent years? Now explore one of the EPA websites that lets you browse information on the air you breathe: www.airnow.gov, www3.epa.gov/aircompare, or www3.epa.gov/air/emissions/where.htm. What factors do you think influence the quality of your region's air? Propose three steps for reducing air pollution in your region.

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Rural areas also confront pollution challenges

Although we tend to focus on pollution in cities, air quality is also a rural issue. In rural areas, people suffer from drift of airborne pesticides from farms, as well as industrial pollutants that drift far from cities, factories, and power plants. Air pollution also emanates from feedlots (p. 241) where cattle, hogs, or chickens are raised. The huge numbers of animals densely concentrated at feedlots and the voluminous amounts of waste they produce generate methane, hydrogen sulfide, and ammonia. These gases create objectionable odors, and ammonia contributes to nitrogen deposition. Studies show that people working at and living near feedlots have high rates of respiratory illness.

Indeed, some of the worst air quality in the United States occurs in certain rural regions, including California's Central Valley (the nation's agricultural fruit basket) and areas near natural gas extraction sites, where fumes from extraction pollute the air.

Air pollution remains severe in industrializing nations

Although the United States and other industrialized nations have improved their air quality, outdoor air pollution is worsening in many industrializing countries. In these societies, proliferating factories and power plants are emitting more pollutants as governments encourage economic growth. Additionally, more citizens own and drive automobiles. At the same time, many people continue to burn traditional sources of fuel, such as wood, charcoal, and coal, for cooking and home heating. As a result, only one person out of eight who live in cities that report on their air quality enjoys air that meets the health guidelines of the World Health Organization (WHO). Half the world's urban population breathes air polluted at levels at least 2.5 times beyond the WHO's standards.

Mexico embodies these trends, and despite the progress in its capital, residents of Mexico City and many other Mexican cities and towns continue to suffer a variety of health impacts from polluted air (see **THE SCIENCE BEHIND THE STORY**, pp. 460–461).

Currently, people in the vast sprawling cities of India, China, and other Asian nations suffer the world's worst air quality. Most Asian nations have fueled their rapid industrial development with coal, the most-polluting fossil fuel. Power plants and factories often use outdated, inefficient, heavily polluting technology because it is cheaper and quicker to build. In addition, car ownership is skyrocketing. Urban air quality is nearly as bad in eastern European nations such as Poland and Bulgaria, where old Soviet-era factories still pollute the air and where many people burn coal for home heating. In countless cities in these regions of the world, the haze often becomes thick enough to obscure the sun.

In China's capital of Beijing in winter 2013, pollution became so severe that airplane flights were cancelled and people wore face masks to breathe (**FIGURE 17.19**). Levels of particulate matter were literally off the charts; a monitor atop the U.S. Embassy designed to measure the Air Quality Index detected record-breaking readings beyond the maximum value of 500, up to 755. During this "airpocalypse," a fire at a factory went unnoticed for three hours because the pollution was so thick

FIGURE 17.19 At Tiananmen Square in Beijing, China, children wear face masks during an "airpocalypse" gripping the city.

FIGURE 17.20 Delhi, India, was rated by the World Health Organization as having the poorest air quality in the world.

that no one could see the smoke! Thousands of people suffered ill health as the pollution soared 30 times past the WHO's safe limits. In 2014 and in 2015, Beijing's "airmageddon" returned, and conditions became so bad that the national government and the official state media were finally forced to admit the problem and begin a public discussion about solutions.

In many Chinese cities, air pollution is worse than in Beijing, and across China, the health impacts of air pollution are enormous. A 2013 international research report blamed outdoor air pollution for 1.2 million premature deaths in China each year. Another 2013 study found that residents of polluted northern China die, on average, five years earlier than residents of southern China, where the air is cleaner. Moreover, prevailing westerly winds carry some of China's pollution across the Pacific Ocean to North America! A 2014 study quantified Chinese pollution reaching the U.S. West Coast and estimated that it adds at least one extra smoggy day per year to Los Angeles's total.

In 2015, China's citizens were transfixed by an online video that went viral, titled *Under the Dome*. This powerful 104-minute documentary, produced and narrated by a well-known Chinese investigative reporter, Chai Jing, confirmed for China's people what they already know: They spend their daily lives trapped under a dome of dangerously polluted air. The Chinese government sent mixed messages, banning the video while also proclaiming a commitment to fighting pollution. Many commentators drew a parallel with *Silent Spring*, Rachel Carson's 1962 book on DDT that galvanized the grassroots environmental movement in the United States (p. 170).

China's government is now striving to reduce pollution. It has closed down some heavily polluting factories and mines, phased out some subsidies for polluting industries, and installed pollution controls in power plants. It subsidizes efficient electric heaters for homes to replace dirty, inefficient coal stoves. It has mandated cleaner formulations for gasoline and diesel and has raised standards for fuel efficiency and emissions for cars above what the United States requires. In Beijing, mass transit is being expanded, many buses run on natural gas, and heavily polluting vehicles are kept out of the central city. China is also aggressively developing cleaner wind, solar, and nuclear power to substitute for coal-fired power.

As bad as air pollution is in China, it is even worse in India's cities, and sometimes in other Asian metropolises such as Karachi, Jakarta, Bangkok, and Singapore. Delhi, India, has the world's worst air quality (**FIGURE 17.20**), according to 2014 WHO data for $PM_{2.5}$ pollutants. In this WHO survey, 13 of the 20 most polluted cities on Earth were in India. Because India's cities struggle with many challenges of urban poverty, there have been few efforts to tackle air pollution, despite an estimated toll of 1.5 million premature deaths each year.

Across India, China, and other industrializing nations of Asia, pollution from autos, industry, agriculture, and wood-burning stoves has resulted in a persistent 2-mile-thick layer of pollution that hangs over southern Asia throughout the dry season each December through April. Dubbed the Asian Brown Cloud, or Atmospheric Brown Cloud, this massive layer of brownish haze is estimated to reduce the sunlight reaching Earth's surface in southern Asia by 10–20%; promote flooding in some areas and drought in others by altering the monsoon; decrease rice yields by 5–10%; speed the melting of Himalayan glaciers by depositing dark soot that absorbs sunlight; and contribute to many thousands of deaths each year.

Smog poses health risks

Now let's take a closer look at one of the most prevalent types of air pollution: smog. As we saw in our Central Case Study, **smog** is a general term for a mixture of air pollutants that can accumulate as a result of fossil fuel combustion, generally over industrial regions or urban areas with heavy automobile traffic.

What Are the Health Impacts of Mexico City's Air Pollution?

Dr. Lilian Calderón-Garcidueñas

"I know I'm inhaling poison," a 38-year-old candy vendor named Guadalupe told a reporter amid the fumes of a traffic-choked intersection in Mexico City. "But there is nothing I can do."

For as long as we have polluted our air, people have felt effects on their health. But identifying and quantifying those impacts poses a challenge for scientists. For researchers wanting to understand pollution's health impacts—and to design solutions for people like Guadalupe—what better place to go than Mexico City, long home to some of the world's worst air pollution?

A key first step is to determine what's actually in the air. One researcher who has led the way is Mario Molina, the Nobel Prize–winning chemist who helped discover the cause of stratospheric ozone depletion and who appears in this chapter's other **Science behind the Story** feature (pp. 466–467). Molina stepped away from scholarly work at U.S. universities to return to his hometown of Mexico City and help address its pollution issues. In 2003 and 2006, Molina organized intensive air-sampling projects in Mexico City involving hundreds of scientists.

Nearly 200 research publications later, these efforts have larified many aspects of the city's pollution. One study used achines that could identify and record individual particles in al time. Its data indicated that metal-rich particulates from ish incinerators were peaking in the morning, whereas smoke m fires outside the city blew in during the afternoon. Other earchers discovered that volatile organic carbons control the ount of tropospheric ozone formed in smog (not nitrogen es, as was expected). City officials responded by targeting emissions for reduction, while also taking steps to discourautomobile traffic (**FIGURE 1**).

ew people today understand Mexico City's air pollution in detail than Armando Retama, the city's director of atmoc monitoring. But he may grasp its impacts best when he town. "I can breathe better. I'm not all dry. My eyes aren't l. My skin doesn't crack," he says. "We have chronic ms that we aren't aware of."

t health impacts of urban pollution affect the respiratory At high altitudes like Mexico City's, the "thin air" forces people to breathe deeply to obtain enough oxygen. This means they pull more air pollutants into their lungs than people at lower elevations. As result, respiratory problems are commonplace. Many studies have confirmed that Mexico City residents show reduced lung function in comparison with people from less-polluted areas and that respiratory problems become worse and emergency room visits become more numerous when pollution is severe.

Most studies have looked at short-term exposure, but in 2007 a research team led by Isabelle Romieu of Mexico's National Institute of Public Health examined the effects of growing up amid polluted air. Her team measured lung function in 3170 eight-year-old children from 39 Mexico City schools across 3 years and correlated this with their exposure to tropospheric ozone, nitrogen dioxide, and particulate matter. The children's ability to inhale and exhale deeply improved as they matured, but children from more-polluted areas lagged behind those from cleaner areas, indicating smaller, weaker lungs.

Romieu and her colleagues also showed in a series of studies that the city's pollution worsens asthma in children, particularly those with certain genetic profiles. In 2008 her team analyzed data from 200 asthmatic and healthy children and found that children in areas with more traffic and pollutants coughed, wheezed, and used respiratory medication more often.

FIGURE 1 During a resurgence of smog in March, 2016, Mexico City commuters wore face masks to guard against air pollutants and took advantage of free mass transit when authorities restricted car traffic.

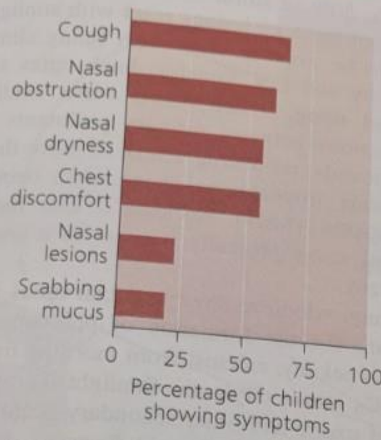


FIGURE 2 Mexico City children show respiratory symptoms from air pollution. These data are from 174 Mexico City children. Of 27 similar children from less-polluted areas outside Mexico City, none showed any of these conditions. *Data from Calderón-Garcidueñas, L., et al., 2003. Respiratory damage in children exposed to urban pollution. Pediatric Pulmonology 36: 148–161.*

Another Mexican researcher, Lilian Calderón-Garcidueñas, has led several studies comparing chest X-ray films and medical records of Mexico City children with those of similar children from nonpolluted locations. Her team found hyperinflation (chronic overexpansion) and other problems with the lungs of the Mexico City youth. Mexico City children also reported many respiratory problems, whereas rural children did not (**FIGURE 2**).

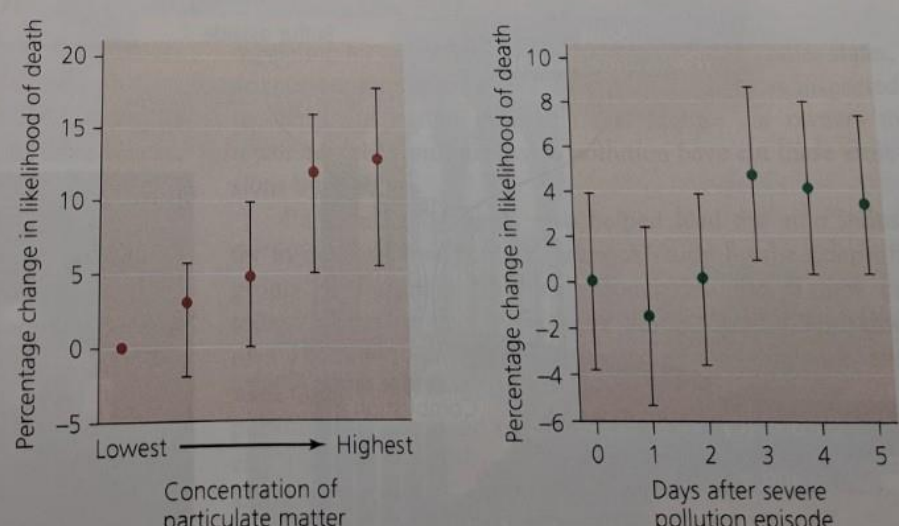
Air pollution harms the heart and the cardiovascular system, too. Multiple studies reveal that pollution can affect heart rate, blood pressure, blood clotting, blood vessels, and atherosclerosis. Epidemiological studies (p. 370) show that pollution correlates with emergency room admissions for heart attacks, chest pain, and heart failure, as well as death from heart-related causes.

Part of the reason smog affects the cardiovascular system is that tiny particulates can work their way into the bloodstream, causing the heart to reduce blood flow or go out of rhythm. The heart mounts an inflammatory response against pollutant particles laden with dead bacteria in the blood, but because the pollution is persistent, the inflammation becomes chronic and stresses the heart, even from an early age. Even young people are at risk. One Mexican research team analyzed the hearts of 21 people from Mexico City who had died at an early age, and found that pollution exacts a toll before age 18.

Besides affecting the heart and lungs, air pollution can affect the brain. Recent research shows it can damage children's brain tissue in ways similar to Alzheimer's disease. In one study, Calderón-Garcidueñas and her colleagues used brain scans and found that 56% of youth in Mexico City had lesions on the prefrontal cortex, whereas fewer than 8% did in a region with clean air. In another study, they compared 20 children aged 7–8 from Mexico City with 10 similar children from a Mexican city with clean air, measuring their cognitive skills and scanning their brains with magnetic resonance imaging (MRI). Results showed that the Mexico City children performed more poorly on most tests of reasoning, knowledge, and memory. The differences in cognition were consistent with differences in the volume of white matter in key portions of the brain, as revealed by the MRIs.

All these impacts can lead to higher rates of death. Studies by a U.S. and Mexican research team in Mexico City in the late 1990s confirmed this by comparing death certificate records against air pollution measurements. The team found that death rates rose on the day of and the day after severe pollution episodes, especially in response to particulate matter (**FIGURE 3a**). They also found that infant mortality was significantly higher in the days following strong pollution episodes (**FIGURE 3b**).

The extensive research showing a diversity of health impacts from air pollution in Mexico City has caught the attention of city leaders. These scientific findings have helped motivate them to work hard to clean up their city's air.



(a) Death rates increase with pollution intensity

(b) Infant mortality rates are higher after a pollution episode

FIGURE 3 Rates of (a) death and (b) infant mortality each increase in Mexico City with exposure to air pollution. *Data from (a) Borja-Aburto, V., et al., 1997. Ozone, suspended particulates, and daily mortality in Mexico City. American Journal of Epidemiology 145: 258–268; and (b) Loomis, D., et al., 1999. Air pollution and infant mortality in Mexico City. Epidemiology 10: 118–123.*

Since the onset of the industrial revolution, cities have suffered a type of smog known as **industrial smog** (FIGURE 17.21a). When coal or oil is burned, some portion is completely combusted, forming CO_2; some is partially combusted, producing CO; and some remains unburned and is released as soot (particles of carbon). Moreover, coal contains contaminants such as mercury and sulfur. Sulfur reacts with oxygen to form sulfur dioxide, which can undergo a series of reactions to form sulfuric acid and other compounds. These substances, along with soot, are the main components of industrial smog.

America's most severe industrial smog event occurred in the small town of Donora, Pennsylvania, in 1948 (FIGURE 17.21b). Donora is located in a mountain valley, and one day after air had cooled during the night, the morning sun did not reach the valley floor to warm and disperse the cold air. The resulting temperature inversion trapped smog containing particulate matter emissions from a steel and wire factory. Twenty-one people died, and more than 6000 people—nearly half the town—became ill.

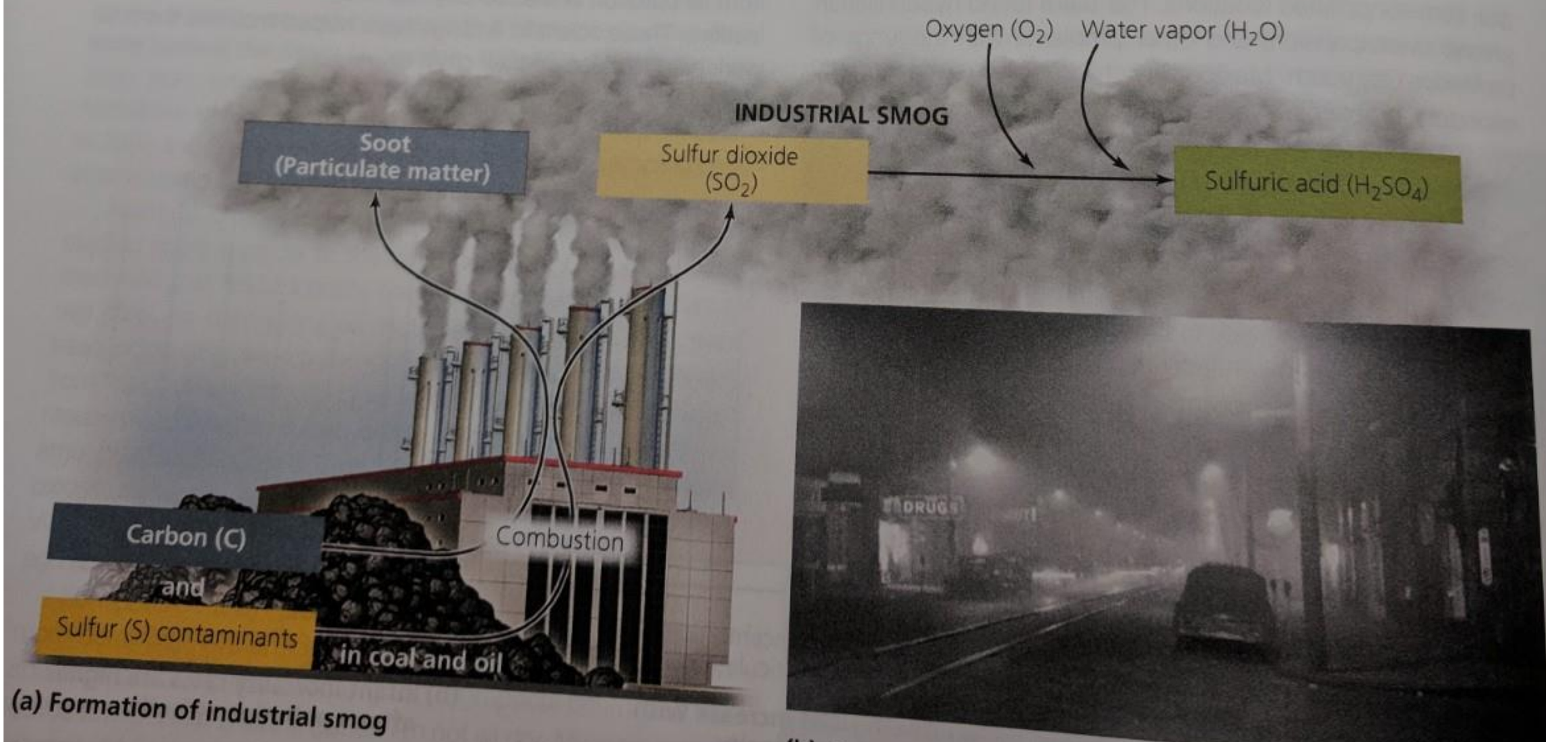
The world's worst industrial smog crisis was even more catastrophic: In 1952, in London, England, a high-pressure system settled over the city for several days, trapping sulfur dioxide and particulate matter emitted from factories and coal-burning stoves and creating foul conditions that killed 4000 people—and by some estimates up to 12,000. In the wake of "killer smog" episodes such as those in London and Donora, governments of developed nations began regulating industrial emissions and greatly reduced industrial smog. However, in industrializing regions such as China, India, and eastern Europe, coal burning and lax pollution control continue to result in industrial smog that poses significant health risks.

Most smog pollution in urban areas today results largely from automobile exhaust. In Mexico City, vehicles contribute 31% of VOCs, 50% of sulfur dioxide, and 82% of nitrogen oxides. Some of these emissions react with sunlight, so pollution tends to be worst in cities with sunny climates, such as Mexico City and Los Angeles. Such cities suffer from **photochemical smog**, which forms when sunlight drives chemical reactions between primary pollutants and atmospheric compounds, producing a mix of more than 100 different chemicals, tropospheric ozone often being the most abundant (FIGURE 17.22a). Because it also includes NO_2, photochemical smog generally appears as a brownish haze (FIGURE 17.22b).

Hot, sunny, windless days in urban areas provide perfect conditions for the formation of photochemical smog. On a typical weekday, exhaust from morning traffic releases NO and VOCs into a city's air. Sunlight then promotes the production of ozone and other secondary pollutants, leading pollution typically to peak in midafternoon. Photochemical smog irritates people's eyes, noses, and throats, and over time can lead to asthma, lung damage, heart problems, decreased resistance to infection, and even cancer.

We can take steps to reduce smog

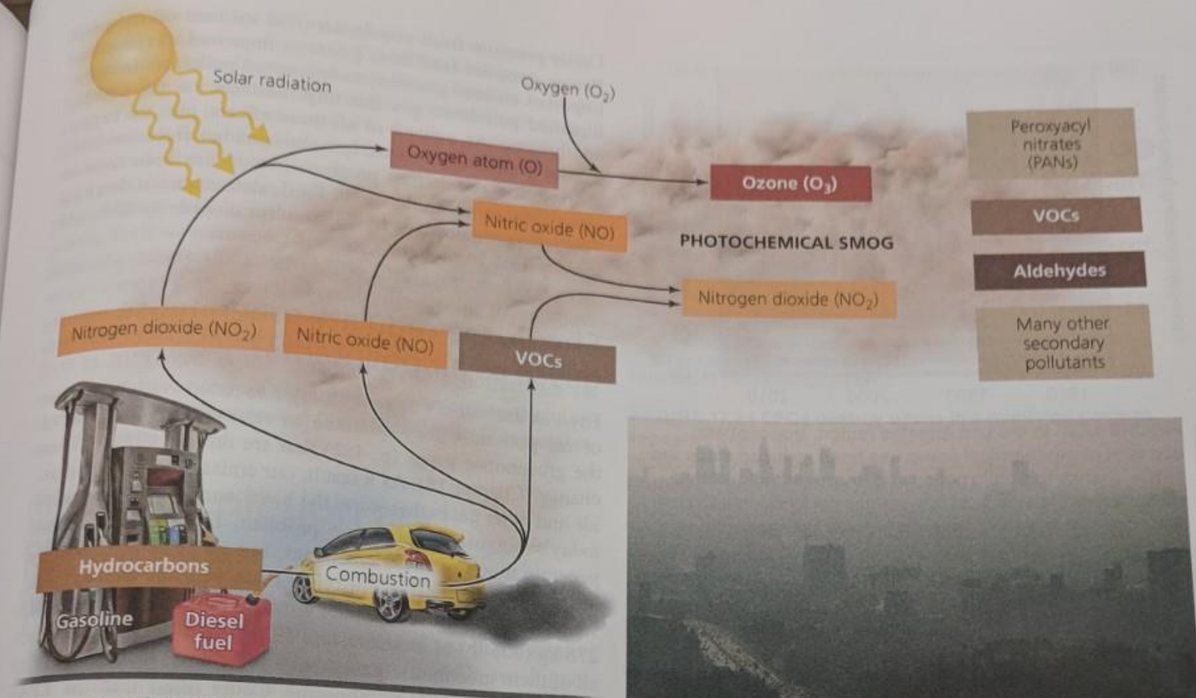
Smog afflicts countless American cities and suburbs, from Atlanta to Newark to Baltimore to Houston to Salt Lake



(a) Formation of industrial smog

(b) Donora, Pennsylvania, at midday in its 1948 smog event

FIGURE 17.21 Industrial smog results from fossil fuel combustion. When coal or oil is burned in a power plant or factory, soot (particulate matter of carbon) is released, and sulfur contaminants give rise to sulfur diox-de, which may react with atmospheric gases to produce further compounds **(a)**. Carbon monoxide and carbon ioxide are also emitted. Under certain weather conditions, industrial smog can blanket whole regions, as it did Donora, Pennsylvania **(b)**, shown in the daytime during its deadly 1948 smog episode.



(a) Formation of photochemical smog

(b) Photochemical smog over Los Angeles

FIGURE 17.22 Photochemical smog results when pollutants from automobile exhaust react amid exposure to sunlight. Nitrogen dioxide, nitric oxide, and VOCs initiate a series of chemical reactions **(a)** that produce a toxic brew of secondary pollutants, including ozone, peroxyacyl nitrates (PANs), aldehydes, and others. Photochemical smog is common over many urban areas, especially those with hilly topography or frequent inversions, such as **(b)** Los Angeles.

City. Mayors, city councils, and state and federal regulators everywhere are trying to devise ways to clear their air. Los Angeles's struggle with air pollution began in 1943, when the city's first major smog episode cut visibility to three blocks. With the city's then-predominant image as a clean and beautiful coastal haven at risk, civic leaders confronted the problem head-on. In fact, Los Angeles's quest to understand and solve its smog problem spurred much of the original research into how photochemical smog forms and how automobiles might burn fuel more cleanly.

Los Angeles's city and county officials began their air pollution control efforts by passing ordinances restricting emissions from power plants, oil refineries, and the petrochemical industry, then continued with efforts to cut emissions from motor vehicles. Because air pollution spreads from place to place, responsibility for pollution control soon moved from the city and county levels to the state and federal levels.

California took the lead among U.S. states in adopting pollution control technology and setting emissions standards for vehicles. In 1967 state leaders established the California Air Resources Board, the first state agency focused on regulating air quality. Today in California and 33 other states, drivers are required to have their vehicle exhaust inspected regularly. Inspection programs that require car owners to repair cars that emit excessive pollution have cut these emissions by 30%.

California's demands also helped lead the auto industry to develop less-polluting cars. A study by the nonprofit group Environment California concluded that a new car today generates just 1% of the smog-forming emissions of a 1960s-era car. For this reason, the air is cleaner, even with many more vehicles on the road. In Los Angeles, VOC pollution has declined by 98% since 1960, even though the city's drivers now burn 2.7 times more gasoline. L.A.'s peak smog levels have also decreased substantially since 1980 (**FIGURE 17.23**, p. 464).

Despite its progress, Los Angeles still suffers the worst tropospheric ozone pollution of any U.S. metropolitan area, according to 2016 rankings by the American Lung Association. L.A. residents breathe air exceeding California's health standard for ozone on more than 90 days per year. One recent study calculated that air pollution in the L.A. basin and the nearby San Joaquin Valley each year causes nearly 3900 premature

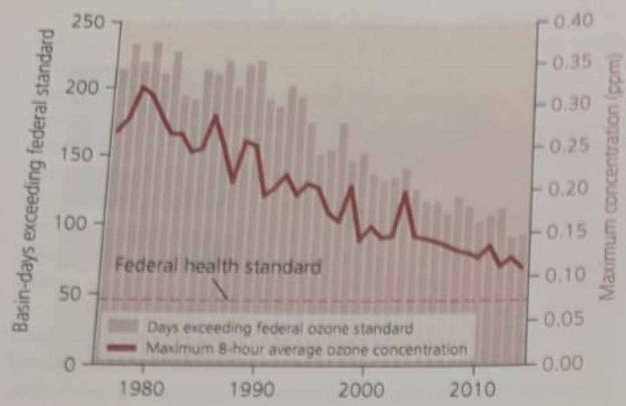


FIGURE 17.23 In the Los Angeles region, tropospheric ozone in photochemical smog has been reduced since the 1970s, thanks to public policy and improved automotive technology. Ozone pollution still violates the federal health standard, however. *Data from South Coast Air Quality Management District.*

DATA By roughly what percentage has Los Angeles reduced its ozone pollution since the late 1970s? Calculate changes in each data set shown. Do the two data sets show similar patterns?

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deaths and costs society $28 billion (due to hospital admissions, lost workdays, etc.).

Across the world, many cities struggle with photochemical smog and are working to develop solutions. One example is Tehran, the capital of Iran. Here, city leaders now require vehicle inspections, regulate traffic into the city center, and pay drivers to trade in old polluting cars for newer cleaner ones. Over the past decade or two, sulfur was reduced in diesel fuel, lead was removed from gasoline, and buses running on (cleaner-burning) natural gas hit the roads. To raise public awareness, 22 electronic billboards were installed around the city, displaying current pollutant levels. All these efforts helped reduce pollution, yet so many people continued to stream into the city and buy cars that pollution soon grew worse again. In response, officials lowered gasoline subsidies, rationed fuel, and began expanding the subway system.

weighing the ISSUES

Smog-Busting Solutions

Does the city you live in, or the nearest major city to you, suffer from photochemical smog or other air pollution? How is this city responding? What policies do you think it should pursue? What benefits might your city enjoy from such policies? Would they bring any problems?

Of all the world's cities, Mexico City is gaining attention today for its success in reducing smog—once the world's worst—even as its population, cars, and economic activity continue to grow. Regulations now require cars to have catalytic converters and get emissions tests. Some industrial facilities were forced to clean up their operations. Under pressure from city leaders, the national oil company Pemex removed lead from gasoline, improved its refineries, imported cleaner gasoline, and removed pollutants from the liquefied petroleum gas that city residents use for cooking and heating. As a result of all these efforts, plus the expansion of the subway system, low-emission bus fleet, and bike-sharing and car-sharing programs, smog has been reduced since 1990 by more than half. Particulate matter is down by 70%, carbon monoxide by 74%, sulfur dioxide by 86%, and lead by 95%.

Should we regulate greenhouse gases as air pollutants?

Even as the world's nations struggle to reduce various sources of air pollution, they continue to release vast quantities of the greenhouse gases (p. 482) that are driving global climate change (Chapter 18). As a result, our emission of carbon dioxide and other gases that warm the lower atmosphere is arguably today's biggest air pollution problem. Industry and utilities generate much of these emissions, but all of us contribute by living carbon-intensive lifestyles. Each year the average U.S. vehicle driver releases close to 6 metric tons of carbon dioxide, 275 kg (605 lb) of methane, and 19 kg (41 lb) of nitrous oxide, all of them greenhouse gases that drive climate change.

In 2007 the U.S. Supreme Court ruled that the EPA has legal authority under the Clean Air Act to regulate carbon dioxide and other greenhouse gases as air pollutants. President Barack Obama urged Congress to address greenhouse gas emissions through bipartisan legislation. When Congress failed to do so, Obama instructed the EPA to develop regulations for these emissions. In 2011, the EPA introduced moderate carbon emission standards for cars and light trucks, and in 2012 it announced that it would limit carbon emissions for new coal-fired power plants and cement factories (but not existing ones). The EPA decided to phase in regulations gradually, beginning with the largest emitters.

The coal-mining and petrochemical industries objected, and these industries and several states sued to stop the regulations. A court of appeals unanimously upheld the EPA regulations in 2012. The automotive industry supported the EPA's regulations. U.S. automakers had begun investing in fuel-efficient vehicles, and preferred to have one set of federal emissions standards so as not to have to worry about meeting many differing state standards. The public also voiced strong support; 2.1 million Americans sent comments to the EPA in favor of its actions—a record number of public comments for any federal regulation.

In 2015, the EPA finalized and launched a regulatory plan for existing power plants, the Clean Power Plan. Under the plan, states would be allowed to choose how to reduce their plants' emissions—by upgrading technology, switching from coal to natural gas, enhancing efficiency, promoting renewable energy, or through carbon taxes or cap-and-trade programs. The plan aims to cut carbon dioxide emissions from power plants by 32% below 2005 levels by the year 2030. The EPA also estimates that SO_2 and NO_X will be reduced by 20% and that cleaner air will save 3600 lives. All told, the

EPA estimates that by 2030 the plan will bring total public health and climate benefits worth $54 billion each year.

A number of industries and states soon lined up to challenge the plan in court, and in 2016 the Supreme Court issued a stay of the plan in a controversial 5–4 ruling, preventing the EPA from enforcing the plan's requirements until the lawsuits are resolved. The EPA will no doubt continue to face formidable political opposition from emitting industries and from policymakers who fear that regulations will hamper economic growth. Yet if we were able to reduce emissions of other major pollutants sharply since 1970 while advancing our economy, we can hope to achieve similar results in reducing greenhouse gas emissions. Indeed, although U.S. carbon dioxide emissions rose by 51% from 1970 to 2005, they fell by 12% from 2005 to 2015 even as the economy grew. This decrease in emissions resulted from a shift from coal to cleaner-burning natural gas and from improved fuel efficiency in automobiles and other technologies.

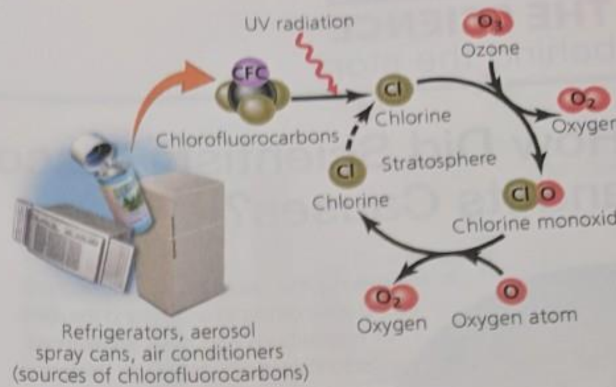


FIGURE 17.24 CFCs destroy ozone in a multistep process, repeated many times. A chlorine atom released from a CFC molecule in the presence of UV radiation reacts with an ozone molecule, forming one molecule of oxygen gas and one chlorine monoxide (ClO) molecule. The oxygen atom of the ClO molecule then binds with a stray oxygen atom to form oxygen gas, leaving the chlorine atom to begin the destructive cycle anew.

Ozone Depletion and Recovery

Although ozone in the troposphere is a pollutant in photochemical smog, ozone is a highly beneficial gas in the stratosphere, where it forms the ozone layer (p. 447; see Figure 17.2). In this region of the stratosphere, concentrations of ozone reach only about 12 parts per million, but ozone molecules are so effective at absorbing the sun's ultraviolet radiation that even this diffuse concentration helps to protect life on Earth's surface from UV radiation's damaging impacts on tissues and DNA.

A generation ago, scientists discovered that our planet's stratospheric ozone was being depleted, posing a major threat to human health and the environment. Years of dynamic research by hundreds of scientists (see **THE SCIENCE BEHIND THE STORY**, pp. 466–467) revealed that certain airborne chemicals destroy ozone and that most of these **ozone-depleting substances** are human-made. Our subsequent campaign to halt degradation of the ozone layer stands as one of society's most successful efforts to address a major environmental problem.

Synthetic chemicals deplete stratospheric ozone

Researchers identifying ozone-depleting substances pinpointed primarily **halocarbons**—human-made compounds derived from simple hydrocarbons (p. 27) in which hydrogen atoms are replaced by halogen atoms, such as chlorine, bromine, or fluorine. In the 1970s, industry was producing more than 1 million tons per year of one type of halocarbon, **chlorofluorocarbons (CFCs).** CFCs were useful as refrigerants, as fire extinguishers, as propellants for aerosol spray cans, as cleaners for electronics, and for making polystyrene foam. Because CFCs rarely reacted with other chemicals, scientists surmised that they would be harmless to people and the environment.

Unfortunately, the nonreactive qualities that made CFCs ideal for industrial purposes were having disastrous consequences for the ozone layer. Whereas reactive chemicals are broken down quickly in the troposphere, CFCs reach the stratosphere unchanged and can linger there for a century or more. In the stratosphere, intense UV radiation from the sun eventually breaks CFCs into their constituent chlorine and carbon atoms. In a two-step chemical reaction (**FIGURE 17.24**), each newly freed chlorine atom can split an ozone molecule and then ready itself to split more. During its long residence time in the stratosphere, each free chlorine atom can catalyze the destruction of as many as 100,000 ozone molecules!

The ozone hole appears each year

In 1985, researchers shocked the world when they announced that stratospheric ozone levels over Antarctica in the southern springtime had declined by nearly half during just the previous decade, leaving a thinned ozone concentration that was soon named the **ozone hole** (**FIGURE 17.25**, p. 468). During each Southern Hemisphere spring since then, ozone concentrations over this immense region have dipped to roughly half their historic levels.

Extensive scientific detective work has revealed why seasonal ozone depletion is so severe over Antarctica (and, to a lesser extent, the Arctic). During the dark and frigid Antarctic winter (June to August), temperatures in the stratosphere dip below −80°C (−112°F), enabling unusual high-altitude *polar stratospheric clouds* to form. Many of these icy clouds contain condensed nitric acid, which splits chlorine atoms off from compounds such as CFCs. The freed chlorine atoms accumulate in the clouds, trapped over Antarctica by wind currents that swirl in a circular *polar vortex* that prevents air from mixing with the rest of Earth's atmosphere.

How Did Scientists Discover Ozone Depletion and Its Causes?

Releasing a high-altitude balloon equipped to measure stratospheric ozone

In discovering the depletion of stratospheric ozone and coming to understand the roles of halocarbons and other substances, scientists have relied on historical records, field observations, laboratory experiments, computer models, and satellite technology.

The story starts back in 1924, when British scientist G.M.B. Dobson built an instrument that measured atmospheric ozone concentrations by sampling sunlight at ground level and comparing the intensities of wavelengths that ozone does and does not absorb. By the 1970s, the Dobson ozone spectrophotometer was being used by a global network of observation stations.

Meanwhile, atmospheric chemists were learning how stratospheric ozone is created and destroyed. Ozone and oxygen exist in a natural balance, with one occasionally reacting to form the other, and oxygen being far more abundant. Researchers found that certain chemicals naturally present in the atmosphere, such as hydroxyl (OH) and nitric oxide (NO), destroy ozone, making the ozone layer thinner than it would otherwise be. And nitrous oxide (N_2O) produced by soil bacteria can make its way to the stratosphere and produce NO, Dutch meteorologist Paul Crutzen reported in 1970. This last observation was important, because some human activities, such as fertilizer application, were increasing emissions of N_2O.

Following Crutzen's report, American scientists Richard Stolarski and Ralph Cicerone showed in 1973 that chlorine atoms can catalyze the destruction of ozone even more effectively than N_2O can. And two years earlier, British scientist James Lovelock had developed an instrument to measure trace amounts of atmospheric gases and found that virtually all the chlorofluorocarbons (CFCs) humanity had produced in the past four decades were still aloft, accumulating in the stratosphere.

This set the stage for the key insight. In 1974, American chemist F. Sherwood Rowland and his Mexican postdoctoral associate Mario Molina took note of all the preceding research and realized that CFCs were rising into the stratosphere, being broken down by UV radiation, and releasing chlorine atoms that ravaged the ozone layer (see Figure 17.24, p. 465). Molina and Rowland's analysis, published in the journal *Nature*, earned them the 1995 Nobel prize in chemistry jointly with Crutzen.

The paper also sparked discussion about setting limits on CFC emissions. Industry leaders attacked the research; DuPont's chairman of the board reportedly called it "a science fiction tale . . . a load of rubbish . . . utter nonsense." But measurements in the lab and in the stratosphere by numerous researchers soon confirmed that CFCs and other halocarbons were indeed depleting ozone. In response, the United States and several other nations banned the use of CFCs in aerosol spray cans in 1978. Other uses continued, however, and by the early 1980s global production of CFCs was again on the rise.

Then, a shocking new finding spurred the international community to take action. In 1985, Joseph Farman and colleagues

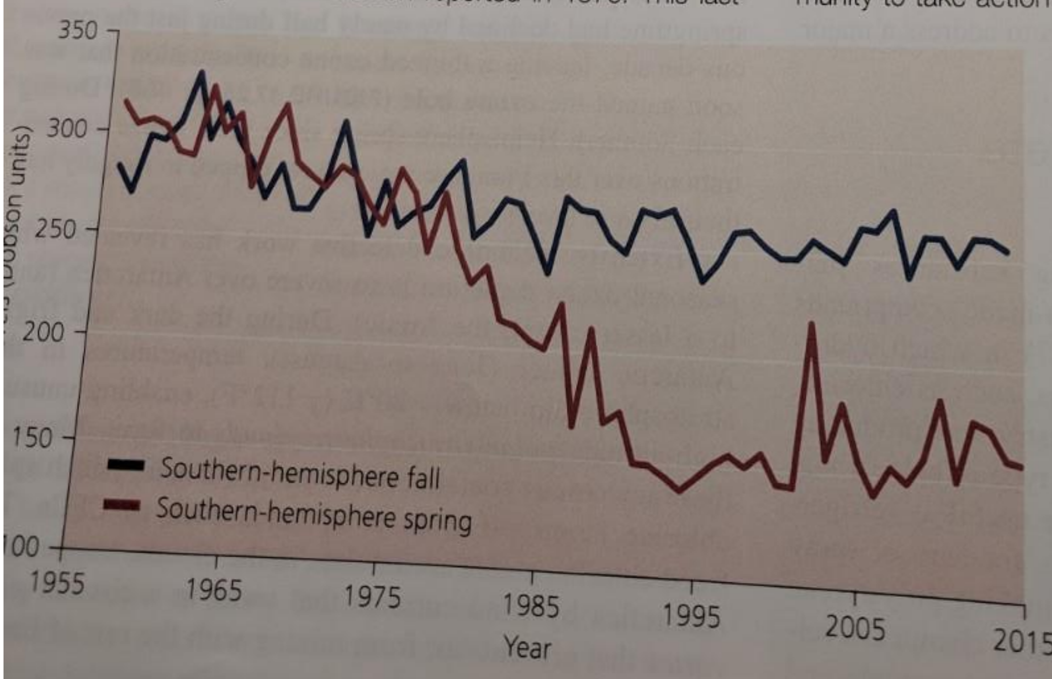


FIGURE 1 Data from Halley, Antarctica, show a decrease in springtime stratospheric ozone concentrations from the 1950s to 1990. Once ozone-depleting substances began to be phased out, ozone concentrations stopped declining. *Data from British Antarctic Survey.*

Because of this time lag and the long residence times of many halocarbons, we can expect many years to pass before our policies have the desired result.

One challenge in restoring the ozone layer is that nations can plead for some ozone-depleting substances to be exempt from the ban. For instance, the United States was allowed to continue using methyl bromide, a fumigant used to control pests on strawberries. Yet despite the remaining challenges, the Montreal Protocol and its follow-up amendments are widely considered our biggest success story in addressing a global environmental problem. The success has been attributed to several factors:

1. Informative scientific research developed rapidly, facilitated by new and evolving technologies.
2. Policymakers engaged industry in helping to solve the problem. Industry became willing to develop replacement chemicals in part because patents on CFCs were running out and firms wanted to position themselves to profit from next-generation chemicals.
3. Implementation of the Montreal Protocol after 1987 followed an adaptive management approach (p. 309), adjusting strategies in response to new scientific information, technological advances, and economic data.

Because of its success in addressing ozone depletion, the Montreal Protocol is widely viewed as a model for international cooperation to resolve other pressing global problems, from biodiversity loss (p. 291) to persistent organic pollutants (p. 379) to climate change (p. 506).

Addressing Acid Deposition

Just as stratospheric ozone depletion crosses political boundaries, so does another atmospheric pollution concern—**acid deposition,** the deposition of acidic (p. 26) or acid-forming pollutants from the atmosphere onto Earth's surface. As with ozone depletion, we are enjoying some success in addressing this challenge.

Fossil fuel combustion spreads acidic pollutants far and wide

Acid deposition often takes place by precipitation (commonly referred to as **acid rain**) but also may occur by fog, gases, or the deposition of dry particles. Acid deposition is one type of **atmospheric deposition,** which refers more broadly to the wet or dry deposition onto land of a wide variety of pollutants, including mercury, nitrates, organochlorines, and others.

Acid deposition originates primarily with the emission of sulfur dioxide and nitrogen oxides, largely through fossil fuel combustion by automobiles, electric utilities, and industrial facilities. Once airborne, these pollutants react with water, oxygen, and oxidants to produce compounds of low pH (p. 27), primarily sulfuric acid and nitric acid. Suspended in the troposphere, droplets of these acids may travel days or weeks for hundreds of kilometers (**FIGURE 17.28**). Depending on climate, 20–80% of all acidic compounds emitted into the atmosphere may fall in precipitation, with the remainder falling as dry deposition.

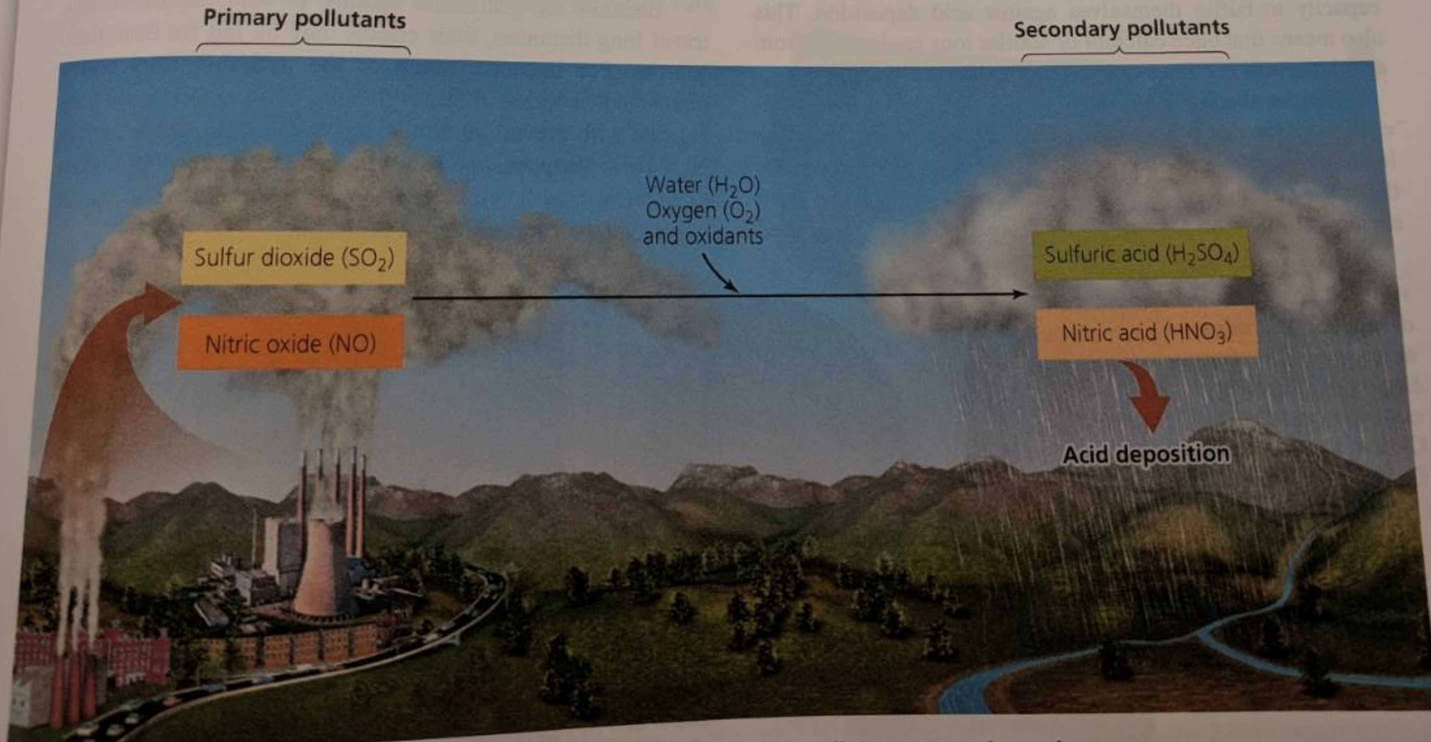


FIGURE 17.28 Acid deposition has impacts far downwind from where pollutants are released. Sulfur dioxide and nitric oxide emitted by industries, utilities, and vehicles react in the atmosphere to form sulfuric acid and nitric acid. These acidic compounds descend to Earth's surface in rain, snow, fog, and dry deposition.

Acid deposition has many impacts

Acid deposition has wide-ranging detrimental effects on ecosystems (TABLE 17.1). Acids leach nutrients such as calcium, magnesium, and potassium ions out of the topsoil, altering soil chemistry and harming plants and soil organisms. This occurs because hydrogen ions from acid precipitation take the place of calcium, magnesium, and potassium ions in soil compounds, and these valuable nutrients leach into the subsoil, where they become inaccessible to plant roots.

Acid precipitation also "mobilizes" toxic metal ions such as aluminum, zinc, mercury, and copper by chemically converting them from insoluble forms to soluble forms. Elevated soil concentrations of metal ions such as aluminum damage the root tissues of plants, hindering their uptake of water and nutrients. In some areas, acid fog with a pH of 2.3 (equivalent to vinegar, and more than 1000 times more acidic than normal rainwater) has enveloped forests for extended periods, killing trees. Animals are affected by acid deposition, too; populations of snails and other invertebrates typically decline, and this reduces the food supply for birds.

When acidic water runs off from land, it affects streams, rivers, and lakes. Thousands of lakes in Canada, Europe, the United States, and elsewhere have lost their fish because acid precipitation leaches aluminum ions out of soil and rock and into waterways. These ions damage the gills of fish and disrupt their salt balance, water balance, breathing, and circulation.

The severity of all these effects depends not only on the pH of the deposition but also on the acid-neutralizing capacity of the soil, rock, or water that receives the acidic input. Substrates differ naturally in their chemistry and pH, and regions with more alkaline soil, rock, or water have a greater capacity to buffer themselves against acid deposition. This also means that once calcium or similar ions are leached from a soil, the soil becomes more sensitive to acidification.

Besides altering natural ecosystems, acid precipitation damages crops, erodes stone buildings, and corrodes vehicles, causing billions of dollars in damage. And as acid precipitation erases the writing from tombstones and dissolves away features from ancient cathedrals in Europe, sacred temples in Asia, and revered monuments in Washington, D.C., it hastens the loss of cultural amenities that are beyond monetary value (FIGURE 17.29).

Because the pollutants leading to acid deposition can travel long distances, their effects may be felt far from their sources. For instance, much of the pollution from power plants and factories in Pennsylvania, Ohio, and Illinois travels east with prevailing winds and falls out in states such as New York, Vermont, and New Hampshire. As a result, regions of greatest acidification tend to be downwind from heavily industrialized source areas of pollution.

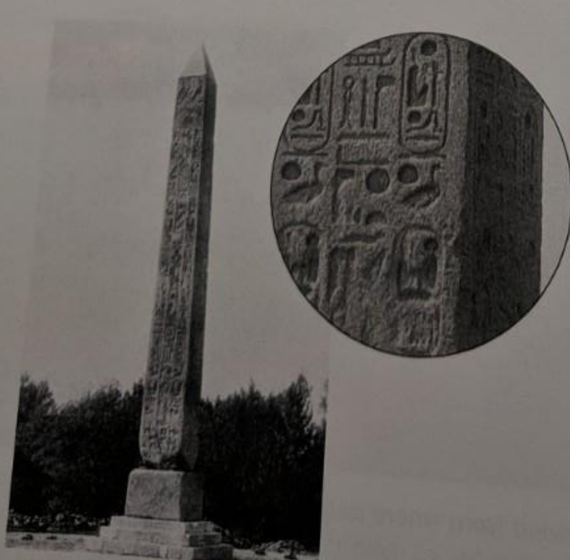
TABLE 17.1 Ecological Impacts of Acid Deposition

ACID DEPOSITION IN NORTHEASTERN FORESTS HAS . . .

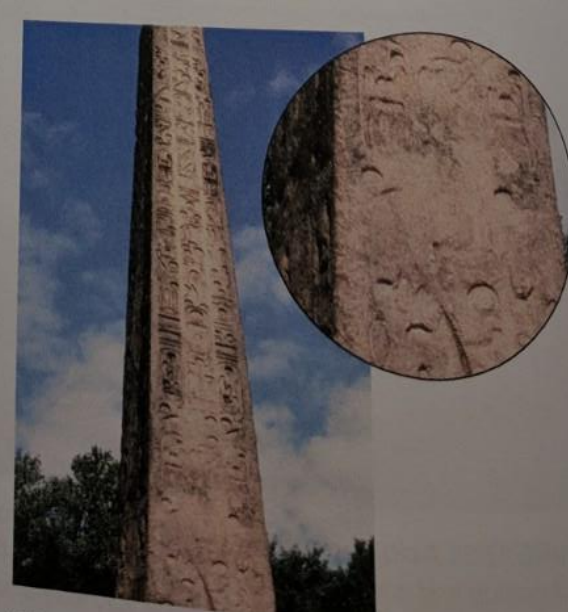
- Accelerated leaching of base cations (ions such as Ca^{2+}, Mg^{2+}, NA^{+}, and K^{+}, which counteract acid deposition) from soil
- Allowed sulfur and nitrogen to accumulate in soil, where excess N can overfertilize native plants and encourage weeds
- Increased dissolved inorganic aluminum in soil, hindering plant uptake of water and nutrients
- Leached calcium from needles of red spruce, causing trees to die from wintertime freezing
- Increased mortality of sugar maples due to leaching of base cations from soil and leaves
- Acidified 41% of Adirondack, New York, lakes and 15% of New England lakes
- Diminished lakes' capacity to neutralize further acids
- Elevated aluminum levels in surface waters
- Reduced species diversity and abundance of aquatic life, affecting entire food webs

Adapted from Driscoll, C.T., et al., 2001. *Acid rain revisited*. Hubbard Brook Research Foundation.

FIGURE 17.29 Acid deposition corrodes statues and buildings. *Shown is an Egyptian obelisk known as Cleopatra's Needle, in Central Park, New York City, **(a)** before and **(b)** after significant acid deposition.*



(a) Before acid rain damage



(b) After acid rain damage

We are addressing acid deposition

The Acid Rain Program established under the Clean Air Act of 1990 has helped fight acid deposition in the United States. This program set up an emissions trading system (p. 179) for sulfur dioxide. Coal-fired power plants were allocated permits for emitting SO_2 and could buy, sell, or trade these allowances. Each year the overall amounts of allowed pollution were decreased. (See p. 509 for further explanation of how such a system works.) The economic incentives created by this cap-and-trade program encouraged polluters to switch to low-sulfur coal, invest in technologies such as scrubbers, and devise other ways to become cleaner and more efficient. During the course of the cap-and-trade program, SO_2 emissions across the United States fell by 67% (**FIGURE 17.30**). As a result, average sulfate loads in precipitation across the eastern United States were 51% lower in 2008–2010 than in 1989–1991.

The Acid Rain Program also required power plants to reduce nitrogen oxide emissions, with the EPA allowing plants flexibility in how they implemented the reductions. Emissions of NO_X fell significantly as a result, and wet nitrogen deposition declined, as well. Thanks to the declines in SO_2 and NO_X, air and water quality improved throughout the eastern United States (**FIGURE 17.31**). This market-based program spawned similar cap-and-trade programs for other pollutants, including greenhouse gases (p. 482). The Los Angeles region adopted its own cap-and-trade program in 1994. The RECLAIM (Regional Clean Air Incentives Market) program has helped the L.A. basin reduce emissions of sulfur oxides and nitrogen oxides by more than 70%.

Many have attributed the success in reducing acid deposition at the national level to the Acid Rain Program, and the EPA has calculated that the program's economic benefits (in health care expenses avoided, for instance) outweighed its costs by 40 to 1. However, some experts maintain that pollution declined because cleaner fuels became less expensive and because simultaneous conventional regulation mandated emissions cuts. Indeed, during this time period European nations using command-and-control regulation (p. 177) instead of emissions trading reduced their SO_2 emissions by even more than the United States did. In 2011, emissions trading ended once the EPA issued its Cross-State Air Pollution Rule, which aimed to limit pollution drifting from upwind states into downwind states.

As with recovery of the ozone layer, there is a time lag before the positive consequences of emissions cuts kick in, so it will take years for acidified ecosystems to recover. Research indicates that soils across the northeastern United States are showing signs of recovery, but that they remain degraded and vulnerable. Scientists also point out that further

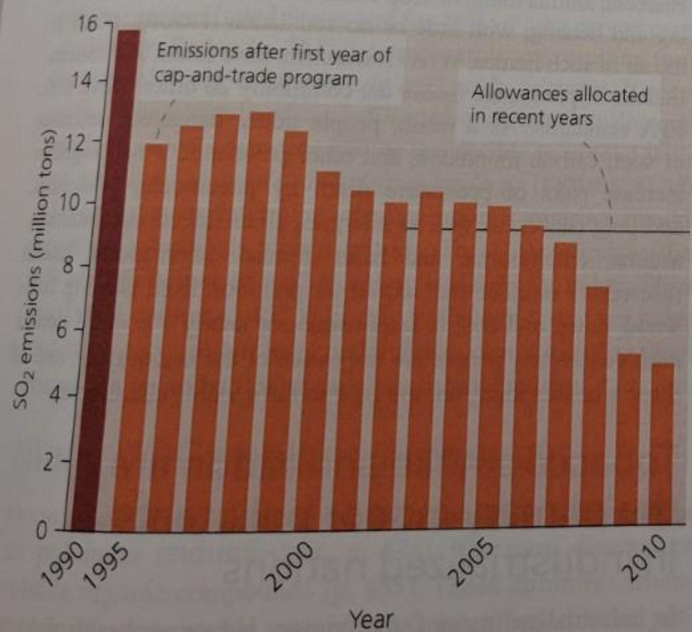
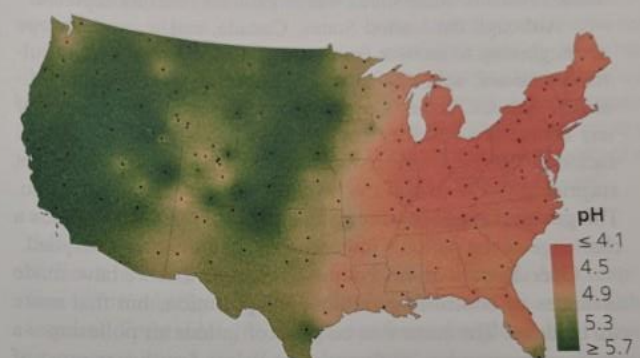


FIGURE 17.30 Sulfur dioxide emissions fell 67% in the wake of an emissions trading system. By 2010, emissions from U.S. power plants participating in this EPA program mandated by the 1990 Clean Air Act had dropped well below the amount allocated in permits (**black line**). *Data from U.S. EPA.*



(a) pH of precipitation in 1990

(b) pH of precipitation in 2014

FIGURE 17.31 Precipitation has become less acidic as air quality has improved under the Clean Air Act. Average pH values for precipitation rose between **(a)** 1990 and **(b)** 2014. Precipitation remains most acidic in regions near and downwind from areas of heavy industry. *Data from the National Atmospheric Deposition Program.*

DATA Q In the area where you live, how did the pH of precipitation change between 1990 and 2014? Has precipitation become more acidic or less acidic?

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pollution reductions are needed if we are to fully restore ecosystems in the Northeast and prevent further damage to property and infrastructure.

In the meantime, some researchers are jump-starting the process of ecosystem recovery. At Hubbard Brook Experimental Forest in New Hampshire, where scientists first studied acid deposition's effects in the United States, scientists used a helicopter to distribute 50 tons of a calcium-containing mineral called wollastonite over one watershed. Within three years of this experimental application, topsoil pH rose from 3.9 to 4.2. Sugar maples (one of the forest's key tree species that had been declining because of acid deposition) began producing healthier foliage, thicker root growth, more seeds, and more surviving seedlings. Over the next 50 years, scientists plan to evaluate the impact of calcium addition on the watershed's soil, water, and life, and compare these results to watersheds where calcium remains depleted.

Although the United States, Canada, and western Europe are beginning to recover from acid deposition after cutting sulfur emissions, acid deposition is becoming worse in industrializing nations. Today China emits the most sulfur dioxide of any nation as a result of coal combustion in power plants and factories that lack effective pollution control equipment. Not surprisingly, China has the world's worst acid rain problem. The government is beginning to tackle the issue, but it faces a challenge as the nation's industrial sector continues to expand.

Overall, data on acid deposition show that we have made advances in controlling outdoor air pollution, but that more can be done. The same can be said for indoor air pollution—a source of human health threats that is less familiar to most of us but statistically more dangerous.

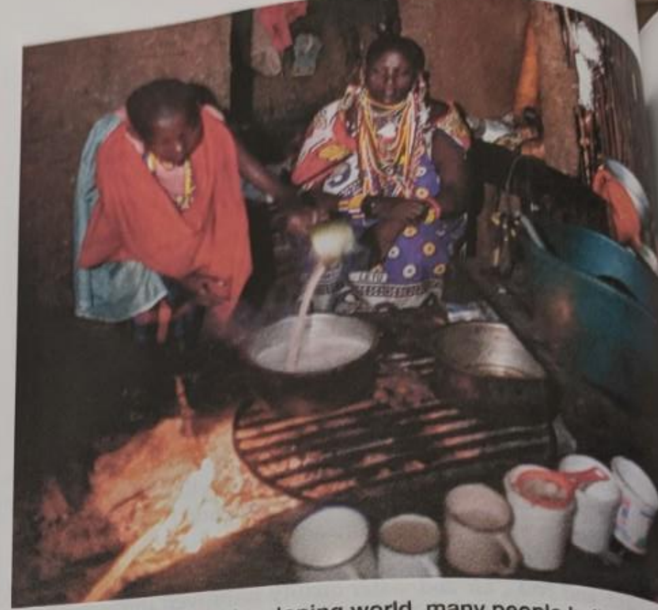


FIGURE 17.32 In the developing world, many people build fires indoors for cooking and heating, as in this Maasai home in Kenya. Indoor fires expose people to severe pollution from particulate matter and carbon monoxide.

Indoor Air Quality

Indoor air generally contains higher concentrations of pollutants than does outdoor air. As a result, the health impacts from **indoor air pollution** in workplaces, schools, and homes outweigh those from outdoor air pollution. The World Health Organization (WHO) attributes nearly 3.5 million premature deaths each year to indoor air pollution (compared with 3.3 million for outdoor air pollution). Indoor air pollution takes nearly 10,000 lives each day.

If this seems surprising, consider that the average American spends at least 90% of his or her time indoors. Then consider the dizzying array of consumer products in our homes and offices that play major roles in our daily lives. Many of these products are made of synthetic materials, and novel synthetic substances are not comprehensively tested for health effects before being brought to market (Chapter 14). Furniture, carpeting, cleaning fluids, insecticides, and plastics all exude volatile chemicals into the air.

Ironically, some attempts to be environmentally prudent during the energy crises of the 1970s (p. 540) worsened indoor air quality. To improve energy efficiency by reducing heat loss, building managers sealed off ventilation in buildings, and designers constructed new buildings with limited ventilation and with windows that did not open. These steps saved energy, but they also trapped stable, unmixed air—and pollutants—inside.

Burning fuel causes indoor pollution in the developing world

Indoor air pollution has by far the greatest impact in the developing world, where poverty forces millions of people to burn wood, charcoal, animal dung, or crop waste inside their homes for cooking and heating, with little or no ventilation (FIGURE 17.32). In the air of such homes, WHO researchers have found that concentrations of particulate matter are commonly 20 times above U.S. EPA standards. As a result, people inhale dangerous amounts of soot, carbon monoxide, and other pollutants, which together increase risks of premature death by pneumonia, bronchitis, and lung cancer, as well as allergies, sinus infections, cataracts, asthma, emphysema, and heart disease. International health researchers estimate that indoor air pollution from burning fuelwood, dung, and coal is responsible for nearly 7% of all deaths each year. Many people are not aware of the health risks, and of those who are, many are too poor to have viable alternatives.

Tobacco smoke and radon are the primary indoor pollutants in industrialized nations

In industrialized nations, the primary indoor air health risks are cigarette smoke and radon (a naturally occurring radioactive gas). Smoking cigarettes irritates the eyes, nose, and throat; worsens asthma and other respiratory ailments; and greatly increases the risk of lung cancer and heart disease. Inhaling secondhand smoke (smoke inhaled by a nonsmoker who is nearby or shares

FIGURE 17.33 One's risk from radon depends largely on underground geology. This map shows levels of risk across the United States. *Data from U.S. Geological Survey, 1993. Generalized geologic radon potential of the United States.*

an enclosed airspace with a smoker) causes many of the same problems. This hardly seems surprising when one considers that tobacco smoke is a brew of more than 4000 chemical compounds, over 250 of which are known or suspected to be toxic or carcinogenic. Smoking has become less prevalent in developed nations in recent years as a result of public education campaigns, and many public and private venues now ban smoking. Still, smoking is estimated in the United States alone to cause 160,000 lung cancer deaths per year, and secondhand smoke to cause 3000.

Radon is the second-leading cause of lung cancer in the developed world, responsible for an estimated 21,000 deaths per year in the United States and for 15% of lung cancer cases worldwide. Radon (p. 361) is a radioactive gas resulting from the natural decay of uranium in soil, rock, or water. It seeps up from the ground and can infiltrate buildings. Colorless and odorless, radon's presence can be impossible to predict without knowing an area's underlying geology (**FIGURE 17.33**). The only way to determine whether radon is entering a building is to sample air with a test kit. The EPA estimates that 6% of U.S. homes exceed its safety standard for radon. Since the 1980s, millions of U.S. homes have been tested for radon and close to a million have undergone radon mitigation. New homes are being built with radon-resistant features.

Many VOCs pollute indoor air

In our daily lives at home, we are exposed to many indoor air pollutants (**FIGURE 17.34**, p. 474). The most diverse are volatile organic compounds (p. 455). These airborne carbon-containing compounds are released by plastics, oils, perfumes, paints, cleaning fluids, adhesives, and pesticides. VOCs evaporate from furnishings, building materials, color film, carpets, laser printers, fax machines, and sheets of paper. Some products, such as chemically treated furniture, release large amounts of VOCs when new and progressively less as they age. Other items, such as photocopying machines, emit VOCs each time they are used.

Although we are surrounded by products that emit VOCs, they are released in very small amounts. Studies find concentrations of VOCs in buildings to be nearly always less than 1 part per 10 million. This is, however, a much greater concentration than is found outdoors. Moreover, we experience instances of high exposure. The "new car smell" that fills the interiors of new automobiles comes from a complex mix of dozens of VOCs as they outgas from the newly manufactured plastic, metal, and leather components of the car. The smell diminishes with time, but some scientific studies warn of health risks from this mix and recommend that you keep a new car well ventilated.

The implications for human health of chronic exposure to VOCs are far from clear. Because they generally exist in low concentrations and because individuals regularly are exposed to mixtures of many different types, it is extremely difficult to study the effects of any one pollutant. An exception is formaldehyde, a VOC that has clear and known health impacts. Formaldehyde off-gasses from the glues and resins in pressed wood (such as plywood), insulation, and other products. It can irritate mucous membranes, can induce skin allergies, and is considered a likely carcinogen.

weighing the ISSUES

How Safe Is Your Indoor Environment?

Think about the amount of time you spend indoors. Name some potential indoor air quality hazards in your home, work, or school environment. Are these spaces well ventilated? What could you do to improve the safety of the indoor spaces you use?

Living organisms can pollute

The most widespread source of indoor air pollution in the developed world may be living organisms. Tiny dust mites can worsen asthma and cause allergies, as can dander (skin flakes) from pets. The airborne spores of some fungi, molds, and mildews can cause allergies, asthma, and other respiratory ailments. Some airborne bacteria can cause infectious disease, including legionnaires' disease. Of the estimated 10,000–15,000 annual U.S. cases of legionnaires' disease, 5–15% are fatal. Heating and cooling systems in buildings make ideal breeding grounds for microbes, providing moisture, dust, and foam insulation as substrates, along with air currents to carry the organisms aloft.

Microbes that induce allergic responses are thought to be a major cause of building-related illness, a sickness produced by indoor pollution. When the cause of such an illness is a mystery, and when symptoms are general and nonspecific, the illness is often called **sick building syndrome.** The U.S. Occupational Safety and Health Administration (OSHA) estimates that 30–70 million Americans have suffered ailments related to the building in which they live. We can reduce the prevalence of sick building syndrome by using low-toxicity construction materials and ensuring that buildings are well ventilated.

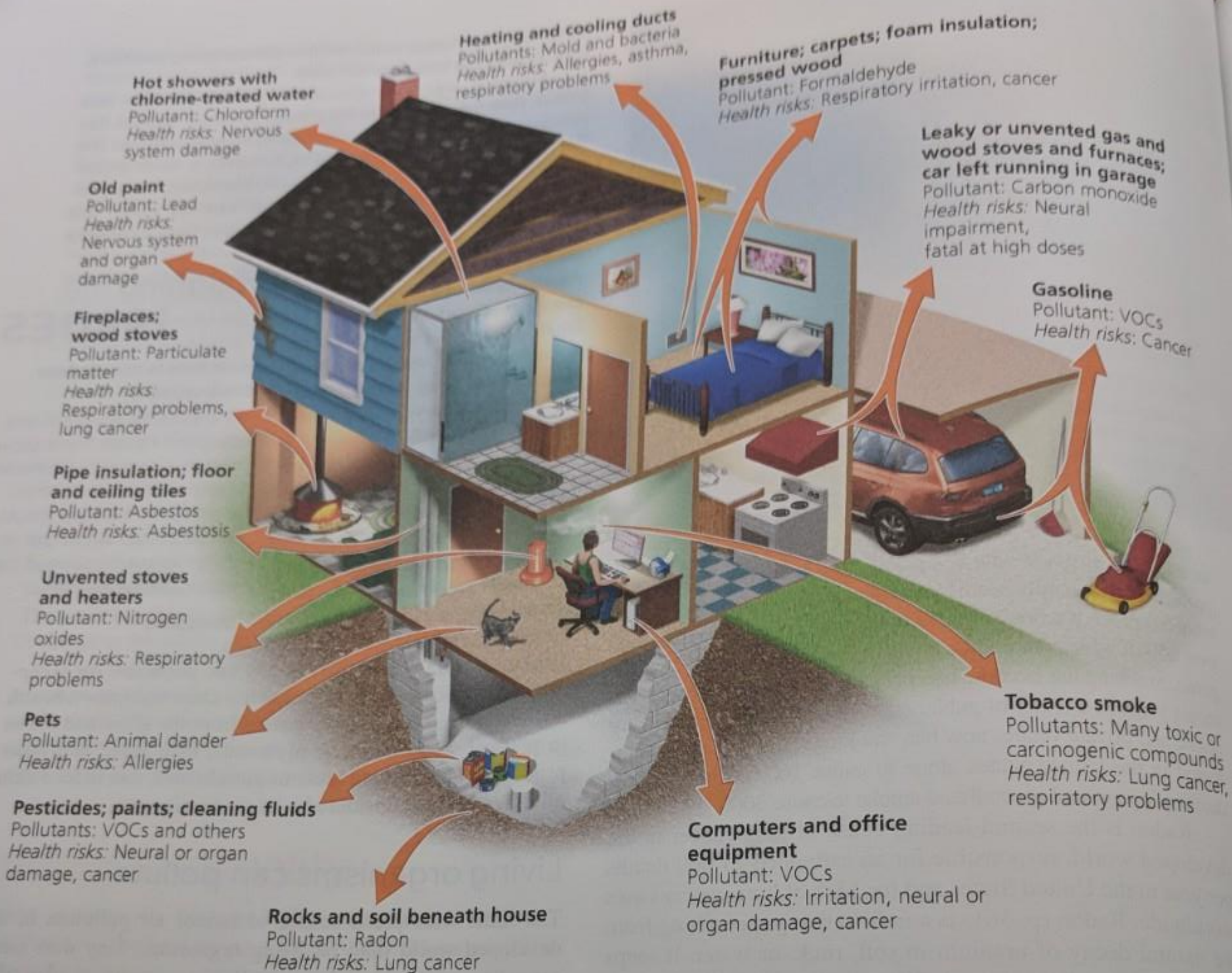


FIGURE 17.34 The typical home contains many sources of indoor air pollution. Shown are common sources, the major pollutants they emit, and some of the health risks they pose.

We can enhance indoor air quality

Using low-toxicity materials, monitoring air quality, keeping rooms clean, and providing adequate ventilation are the keys to alleviating indoor air pollution in most situations. Remedies for fuelwood pollution in the developing world include drying wood before burning (which reduces the amount of smoke produced), cooking outside, shifting to less-polluting fuels (such as natural gas), and replacing inefficient fires with cleaner stoves that burn fuel more efficiently. Installing hoods, chimneys, or cooking windows can increase ventilation for little cost, alleviating most indoor smoke pollution.

In the industrialized world, we can try to avoid cigarette smoke, limit our exposure to new plastics and treated wood, and restrict our contact with pesticides, cleaning fluids, and other toxic substances by keeping them in garages or outdoor sheds. The EPA recommends that we test our homes and offices for radon, mold, and carbon monoxide. Because carbon monoxide is so deadly and so hard to detect, most U.S. states now require new homes to be equipped with alarms that sound if they detect dangerous levels of CO. In addition, keeping rooms and air ducts clean and free of mildew and other biological pollutants will reduce potential irritants and allergens. Most of all, keeping our indoor spaces well ventilated will minimize concentrations of the pollutants among which we live.

Progress is being made worldwide in alleviating the health toll of indoor air pollution. Researchers calculate that rates of premature death from indoor air pollution dropped nearly 40 percent from 1990 to 2010. With continued efforts, we should see additional progress in safeguarding people's health.

closing THE LOOP

Air quality is vitally important for our health both indoors and outdoors, in cities and rural areas, and in developed and developing nations. Los Angeles was among the first cities to confront severe air pollution and take major steps to alleviate the problem. Many other cities and national governments of developed nations subsequently achieved cleaner air through public policy and technological advances. Now many cities of developing nations are following suit and taking steps to clean up their air. Mexico City has been a pioneer, and its success is making it a model for others. Urban areas in China, India, and elsewhere have a long way to go but are beginning to make progress in tackling outdoor air pollution, while in all nations the growing awareness of indoor air pollution is encouraging action and solutions.

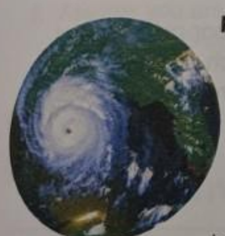
Outdoor air pollution in any location is influenced not only by our emissions but also by natural sources of pollution and by atmospheric conditions. The more we understand about the science of the atmosphere, the better we can protect our health against pollution. Likewise, science has proven crucial to gaining a solid understanding of two other major air quality issues, ozone depletion and acid deposition. Policymakers responded quickly to scientific findings on stratospheric ozone depletion, and as a result, our global society appears to have dodged a bullet; today our planet's ozone layer is gradually on the mend. With acid deposition, we reacted to scientific research by launching policies and economic programs to reduce emissions of the acidic pollutants that lead to the problem, and ecosystems are now beginning to recover. As the world's less-wealthy nations industrialize, continued integration of science, policy, economics, and technology should help us achieve even cleaner air in the future.

REVIEWING Objectives

You should now be able to:

Describe the composition, structure, and function of Earth's atmosphere

The atmosphere consists of 78% nitrogen gas, 21% oxygen gas, and various other gases in minute concentrations. It includes four layers, across which temperature and other attributes vary. Ozone is concentrated in the stratosphere. The atmosphere moderates climate, provides oxygen, conducts and absorbs solar radiation, and transports and recycles nutrients and waste. (pp. 446–448)



Relate weather and climate to atmospheric conditions

The sun's energy heats the atmosphere; drives air circulation; and influences weather, climate, and the seasons. Weather is a short-term phenomenon, whereas climate is a long-term phenomenon. Fronts, pressure systems, and the interactions among air masses influence weather. Global convective cells create latitudinal climate zones. (pp. 448–452)

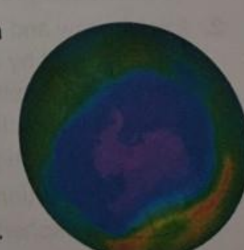
Identify major outdoor air pollutants and outline the scope of air pollution

Natural sources such as fires, volcanoes, and windblown dust pollute the atmosphere, and human activity can worsen some of their impacts. Most pollution is caused by people, however, and we emit pollutants from point and non-point sources. Major pollutants include carbon monoxide, sulfur dioxide, nitrogen oxides, VOCs, particulate matter, lead, nitrogen dioxide, and tropospheric ozone. Photochemical smog, created by chemical reactions of pollutants in the presence of sunlight, impairs visibility and human health widely in urban areas, whereas industrial smog from fossil fuel combustion remains a problem in urban and industrial areas of many developing nations. Today industrializing nations such as China and India are experiencing the world's worst air pollution. (pp. 452–463)

Assess strategies and solutions for control of outdoor air pollution

Thanks to public policy (such as the U.S. Clean Air Act) and to pollution control technologies (such as scrubbers and catalytic converters), pollutant emissions in the United States and many other wealthy nations have decreased substantially since 1970, and ambient air quality has improved in most respects. Today the U.S. EPA is taking early steps toward regulating greenhouse gases as pollutants because they drive climate change. Throughout the world, cities such as Los Angeles and Mexico City have taken bold steps to address photochemical smog. Governments of industrializing nations such as China are beginning to combat air pollution, as well. (pp. 454–465)

Explain stratospheric ozone depletion and identify steps taken to address it



CFCs and other persistent human-made compounds destroy ozone in the stratosphere; ozone depletion is most severe over Antarctica, where an "ozone hole" appears each spring. Thinning ozone concentrations pose dangers to life because they allow more ultraviolet radiation to reach Earth's surface. Fortunately, the

Montreal Protocol and its follow-up agreements have proven remarkably successful in reducing emissions of ozone-depleting substances. However, the long residence time of CFCs in the atmosphere accounts for a time lag between the protocol and full restoration of stratospheric ozone. (pp. 465–469)

Describe acid deposition, discuss its consequences, and explain how we are addressing it

Acid deposition results when pollutants such as SO_2 and NO react in the atmosphere to produce acids that are deposited on Earth's surface. Acid deposition may be wet or dry, and may occur a long distance from the source of pollution. Acid deposition damages soils, water bodies, plants, animals, ecosystems, and human property and infrastructure. Regulation, cap-and-trade programs, and technology have all helped to reduce acid deposition in North America, and industrializing nations are beginning to tackle the problem, as well. (pp. 469–472)

Characterize the scope of indoor air pollution and assess solutions

Indoor air pollution causes more deaths and health problems worldwide than outdoor air pollution. Indoor burning of fuelwood is the developing world's primary indoor air pollution risk, whereas tobacco smoke and radon are the worst indoor pollutants in the developed world. VOCs and living organisms commonly pollute indoor air. Using low-toxicity materials, keeping spaces clean, monitoring air quality, and maximizing ventilation all help to enhance indoor air quality. (pp. 472–474)

TESTING Your Comprehension

1. About how thick is Earth's atmosphere? Name one characteristic of the troposphere and one characteristic of the stratosphere.
2. Where is the "ozone layer" located? Describe how and why stratospheric ozone is beneficial for people, whereas tropospheric ozone is harmful.
3. How does solar energy influence weather and climate? Describe how Hadley, Ferrel, and polar cells help to determine climate patterns and the location of biomes.
4. Describe a temperature inversion. Explain how inversions contribute to severe smog episodes such as the ones in London and in Donora, Pennsylvania.
5. How does a primary pollutant differ from a secondary pollutant? Give an example of each.
6. What has happened with the emissions of major pollutants in the United States in recent decades? What has happened with concentrations of "criteria pollutants" in U.S. ambient air in recent decades? Name one health risk from toxic air pollutants.
7. How does photochemical smog differ from industrial smog? Give three examples of the health risks posed by the outdoor air pollutants in smog.
8. Explain how chlorofluorocarbons (CFCs) deplete stratospheric ozone. Why is this depletion considered a long-term international problem? What was done to address this problem?
9. Why are the effects of acid deposition often felt in areas far from where the primary pollutants are produced? List three impacts of acid deposition.
10. Name three common sources of indoor pollution and their associated health risks. For each pollution source, describe one way to reduce exposure to the source.

SEEKING Solutions

1. Name one type of natural air pollution, and discuss how human activity can sometimes worsen it. What potential solutions can you think of to minimize this human impact?
2. Explain how and why emissions of major pollutants have been reduced by well over 50% in the United States since 1970, despite increases in population, energy use, and economic activity. Describe at least two ways you think air quality might be further improved.
3. International action through a treaty has helped to halt further stratospheric ozone depletion, but other transboundary pollution issues, including acid deposition, have not yet been addressed as effectively. What types of actions do you feel are appropriate for pollutants that cross political boundaries?
4. **CASE STUDY CONNECTION** Describe five ways in which Los Angeles or Mexico City has responded to its pollution challenges. What impacts have each of these responses had? Now consider a major city that is near where you live. Describe at least one approach used by L.A. or Mexico City that you feel would help address air pollution in your city, and explain why.
5. **THINK IT THROUGH** Suppose that you are the head of your county health department, and the EPA informs you that your county has failed to meet the national ambient

air quality standards for ozone, sulfur dioxide, and nitrogen dioxide. Your county is partly rural but is home to a city of 200,000 people and 10 sprawling suburbs. There are several large and aging coal-fired power plants, a number of factories with advanced pollution control technology, and no public transportation system. Describe at least three steps you would urge the county government to take to meet the air quality standards. Explain specifically what effects you would expect each of these steps to have, and why.

6. **THINK IT THROUGH** You have just taken a job at a medical clinic in your hometown. The nursing staff has asked you to develop a brochure for patients featuring tips on how to minimize health impacts from air pollution (both indoor and outdoor) in their daily lives. List the top five tips you will feature, and explain for each why you will include it in your brochure.

CALCULATING Ecological Footprints

"While only some motorists contribute to traffic fatalities, all motorists contribute to air pollution fatalities." So stated a writer for the Earth Policy Institute, pointing out that air pollution kills far more people than vehicle accidents. According to EPA data, emissions of nitrogen oxides in the United States in 2014 totaled 12.2 million tons. Nitrogen oxides come from fuel combustion in motor vehicles, power plants, and other industrial, commercial, and residential sources, but fully 7.2 million tons of the 2014 total came from vehicles. The U.S. Census Bureau estimates the nation's population to have been 318.9 million in 2014 and projects that it will reach 359.4 million in 2030. Considering these data, calculate the missing values in the table to the right (1 ton = 2000 lb).

	TOTAL NO_x EMISSIONS (lb)	NO_x EMISSIONS FROM VEHICLES (lb)
You		
Your class		
Your state		
United States	24.4 billion	14.4 billion

Data from U.S. EPA.

1. By what percentage is the U.S. population projected to increase between 2014 and 2030? Do you think that NO_x emissions will increase, decrease, or remain the same over that period of time? Why? (You may want to refer to Figure 17.14.)
2. Assume you are an average American driver. Using the 2014 emissions totals, how many pounds of NO_x emissions are you responsible for creating? How many pounds would you prevent if you were to reduce by half the vehicle miles you travel? What percentage of your total NO_x emissions would that be?
3. How might you reduce your vehicle miles traveled by 50%? What other steps could you take to reduce the NO_x emissions for which you are responsible?

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