

Chapter 5: Air Pollution



Industrial emissions and global atmospheric circulation: this illustration depicts smoke from factory chimneys contributing to air pollution and greenhouse gas emissions, with arrows around Earth symbolizing the global transport and circulation of pollutants. *Source:* AI generated

Learning Outcomes

At the end of this chapter, students will be able to:

1. Describe the composition and structure of the atmosphere.
2. Explain the importance of the ozone layer, the cause of its depletion, and specific steps taken to address the problem.
3. Distinguish between indoor and outdoor air pollution and how these compare among industrialized and less industrialized countries
4. Identify natural and anthropogenic sources of air pollution
5. Identify point (stationary) and non-point (mobile) sources of air pollution
6. Explain the effects of air pollution on human and ecosystem health
7. Explain air pollution legislation in the United States and describe its outcomes

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5.1 Composition and Structure of the Atmosphere

Atmosphere refers to the layer of gases that surround Earth and held in place by Earth's gravitational attraction (gravity). The mix of gases in the atmosphere forms a complex system organized into layers that together support life on Earth. Although there are numerous gases, as shown in **Table 5.1**, the top four gases make up 99.998 % of the volume of *clean dry air* (unpolluted air that does not contain water vapor). Of this dry composition of the atmosphere **nitrogen**, by far, is the most common (78%). Nitrogen dilutes oxygen and prevents rapid or instantaneous burning on the Earth's surface, as oxygen gas is a necessary reactant of the combustion process. Nitrogen is also needed and used by living things to make proteins, though as nitrogen gas, N_2 , it is unavailable to most living things.

Table 5.1: Average composition of clean dry air in the lower atmosphere

Gas	Symbol	Content
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
Argon	Ar	0.93%
Carbon dioxide	CO_2	0.03%
Neon	Ne	18.20 parts per million
Helium	He	5.20 parts per million
Krypton	Kr	1.10 parts per million
Sulfur dioxide	SO_2	1.00 parts per million
Methane	CH_4	2.00 parts per million
Hydrogen	H_2	0.50 parts per million
Nitrous oxide	N_2O	0.50 parts per million
Xenon	Xe	0.09 parts per million
Ozone	O_3	0.07 parts per million
Nitrogen dioxide	NO_2	0.02 parts per million
Iodine	I_2	0.01 parts per million
Carbon monoxide	CO	Trace
Ammonia	NH_3	Trace

Source: NOAA <https://www.noaa.gov/jetstream/atmosphere>

Oxygen is used by all living things to make molecules that are essential for life. It is also essential for aerobic respiration as well as combustion or burning. **Argon** is a non-reactive gas and we use it in light bulbs, in double-pane windows, and to preserve priceless documents such as the original Declaration of Independence and the Constitution. **Carbon dioxide** is an essential gas used by plants and other organisms to make sugar (food) through photosynthesis. This process is also essential for other organisms because during photosynthesis, water molecules are split apart and their oxygen is released back to the atmosphere. Carbon dioxide also acts as a blanket that prevents the escape of heat into outer space (see more on this in Chapter 6). The atmosphere is rarely, if ever, completely dry. **Water vapor** (water in a 'gas' state) is usually present up to about 4% of the total volume depending on location. In the

Earth's desert regions (30° N/S) when dry winds are blowing, the water vapor contribution to the composition of the atmosphere will be near zero.

Scientists divide the Earth's atmosphere into four distinct layers, each with unique characteristics that influence climate, energy transfer, and the behavior of gases. These layers are classified primarily by thermal properties (how temperature changes with altitude), but also by differences in chemical composition, patterns of air movement, and variations in density (**Figure 5.1**). Understanding these layers helps explain phenomena such as weather patterns, the greenhouse effect, and the distribution of life-supporting gases.

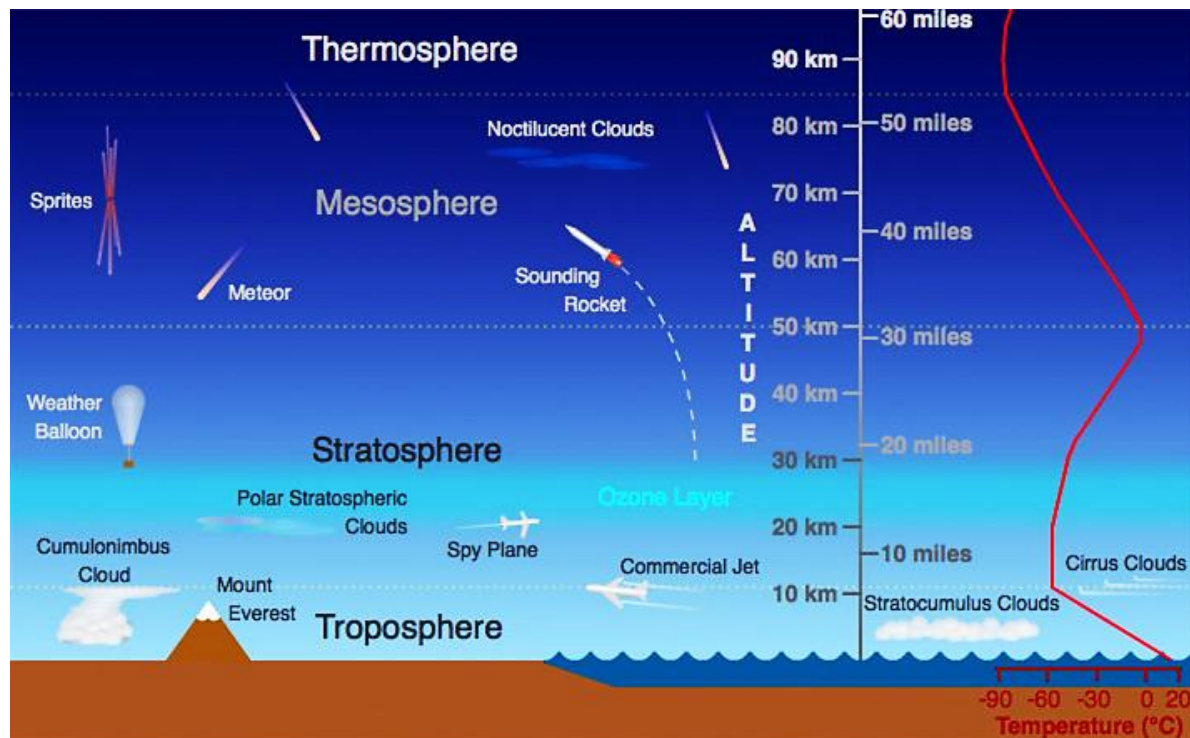


Figure 5.1: Illustration of the atmospheric layers including an average temperature profile (vertical red line on the right). Height (in miles and kilometers) is indicated to show distance of each layer. Only a small part of the thermosphere which extends to 375 miles(600 km) is represented here. (Source: scied.ucar.edu ete.cet.edu.)

5.1.1 Troposphere

The **troposphere** is the lowest layer extending from the surface up to roughly 18 km above the surface depending on location (varies from as low as 6 km to as high as 20 km). There is continuous flow and swirling of air constantly through convection currents redistributing heat and moisture around the globe. This results in the short-lived and local patterns of temperature and moisture that we call **weather**. Because gravity holds most air molecules close to the Earth's surface, the troposphere is the densest of all layers, containing about 75% of the total mass of the atmosphere. The density of the gases in this layer decrease with height so the air becomes thinner. In response, the temperature in the troposphere also decreases with height. As one climbs higher, the temperature drops from an average around 17°C (62°F) at sea level to about -51°C (-60°F) at the **tropopause**, a sharp boundary at the top of the troposphere that limits mixing between the troposphere and the upper layers.

5.1.2 Stratosphere

The **stratosphere** is the layer that extends from the tropopause up to about 50 km to 53 km above the Earth's surface depending on location. The proportions of most gases in this layer are like those in the troposphere with two main exceptions: 1) there is almost no water vapor in the stratosphere, and 2) the stratosphere has nearly 1,000 times more ozone (O₃) than the troposphere. With only about 19% of the total mass of the atmosphere, the density of the stratosphere is significantly lower than the troposphere. However, temperature in this region increases with height because of heat that is produced during the formation of ozone (more on ozone in **section 5.2**). This heat is responsible for temperature increases from an average -51 °C (-60°F) at tropopause to a maximum of about -15°C (5°F) at the top of the stratosphere. This increase in temperature with height means warmer air is located above cooler air. This prevents "convection" as there is no upward vertical movement of the gases. The consequence of this little to no mixing of gases in the stratosphere makes it relatively calm but also means that once substances such as pollutants enter this zone, they can remain suspended for many years. The top of the stratosphere is bound by a boundary known as the **stratopause**.

5.1.3 Mesosphere

Above the stratosphere is the **mesosphere** the third layer of Earth's atmosphere, located above the stratosphere and below the thermosphere. It extends roughly from 50 km to 85 km above Earth's surface. The mesosphere has no ozone molecules and the other gases such as oxygen and nitrogen continue to become less dense with height. As a result, not much ultraviolet and x-ray radiation from the sun is absorbed by molecules in this layer so temperature decreases with altitude, making it the coldest region of the atmosphere, with values dropping to about -90°C near the mesopause, the boundary between the mesosphere and thermosphere. Both the stratosphere and the mesosphere are considered the middle atmosphere.

The mesosphere plays a critical role in atmospheric processes. It is where meteors burn up upon entering Earth's atmosphere due to friction with air molecules. This layer also contains very thin air, too sparse for breathing, and exhibits strong winds and atmospheric tides that influence global circulation. Unlike the stratosphere, the mesosphere lacks a significant ozone concentration, so it does not absorb much solar radiation. Because it lies above the range of aircraft and below the orbit of satellites, the mesosphere is one of the least studied layers of the atmosphere.

5.1.4 Thermosphere

Between about 85 km and 600 km lies the **thermosphere**. This layer is known as the upper atmosphere. Unlike the mesosphere, the gases in this layer readily absorb incoming high energy ultraviolet and x-ray radiation from the sun. Because of this absorption, the temperature in the thermosphere increases with height and can reach as high as 2,000°C (3,600°F) near the top depending on solar activity. However, despite the high temperature, this layer of the atmosphere would still feel very cold to our skin due to the very thin atmosphere. The high temperature indicates the amount of energy absorbed by molecules but with so few in this layer, the total number of molecules is not enough to heat our skin. There's no sharp boundary that marks the end of the atmosphere. Pressure and density simply continue to decrease with distance until they become indistinguishable from the near vacuum of outer space.



Test your knowledge...

1. What are the four most abundant gases in Earth's atmosphere, and what percentage of clean dry air does each contribute?
2. Explain the importance of nitrogen, oxygen, and carbon dioxide gases for life on Earth.
3. Which layer of the atmosphere contains most of the weather phenomena?
4. Why does temperature increase with altitude in the stratosphere?
5. Which statement about the thermosphere is **correct**?
 - A) It is the densest layer of the atmosphere
 - B) It contains most of the ozone
 - C) It absorbs high-energy UV and X-ray radiation
 - D) It is where most weather occurs

5.2 Ozone

Ozone (O_3) is a molecule in which three atoms of oxygen are bonded together. The oxygen gas in the air we breathe has two oxygen atoms bonded together (O_2). Ozone is relatively unstable and releases its third oxygen atom readily so it **oxidizes** and burns things more readily than oxygen gas. This characteristic makes ozone in the troposphere (ground-level ozone) an air pollutant (see **section 5.3**) but in the stratosphere, ozone is essential for protecting life on Earth. Ozone in the stratosphere is formed when an oxygen molecule (O_2) is broken apart into two separate oxygen atoms (O) by high-energy **ultra violet (UV) solar radiation**. Each of the resulting oxygen atoms (O) in turn reacts with an oxygen molecule (O_2) creating ozone (O_3) (**Figure 5.2**). Once produced, ozone can absorb UV radiation breaking the molecule to regenerate an oxygen molecule and a single oxygen atom. So, while ozone is continually being replenished, it is also continually being destroyed. If the rate of ozone creation is equal to the rate of destruction, the total amount will remain the same. Because there is so much oxygen in our atmosphere, this “**ozone-oxygen cycle**” is continuously absorbing UV radiation.

5.2.1 The Ozone Layer

Ozone makes up a very small proportion of the gases in our atmosphere and most of it is concentrated in a portion of the stratosphere roughly 17 – 30 km above the surface. This region, called the **ozone layer**, acts as a protective shield that protects life on the surface of the Earth by absorbing most of the harmful portions of the high-energy UV radiation coming from the sun. UV is subdivided into three types namely **UV-A**, **UV-B**, and **UV-C** (**Figure 5.3**). Of these three types, UV-A is the least energetic and least harmful but can cause some damage to living cells, resulting in sunburns and skin damage. UV-A is also not absorbed by

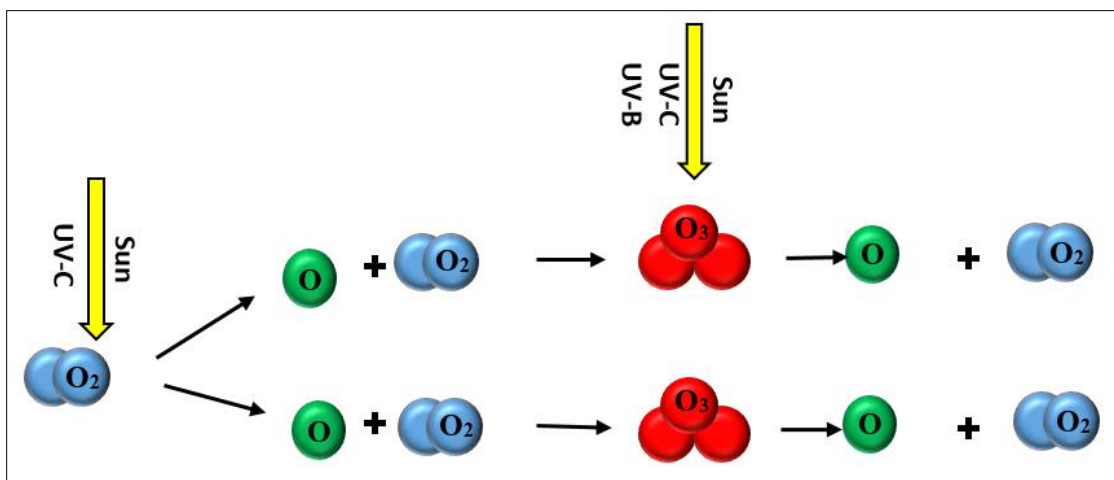


Figure 5.2: The “ozone-oxygen cycle” showing the natural formation and breaking of ozone (O_3) in the stratosphere

ozone in the stratosphere and is therefore transmitted through the atmosphere to the surface of the Earth. UV-C is the most harmful and most energetic of all UV, but is strongly absorbed in both the thermosphere and the stratosphere and does not make it to the Earth’s surface. UV-C is the one responsible for the splitting of oxygen molecules in the stratosphere that leads to the formation of ozone. When ozone absorbs UV it regenerates oxygen atoms and releases heat which warms the upper part of the stratosphere. Since UV-C does not make it to the Earth’s surface, the most harmful form of UV radiation that reaches the surface is UV-B. However, the amount of UV-B that reaches Earth’s surface is significantly reduced because most of it is absorbed by ozone in the stratosphere. Ozone is the only known gas that absorbs UV-B.

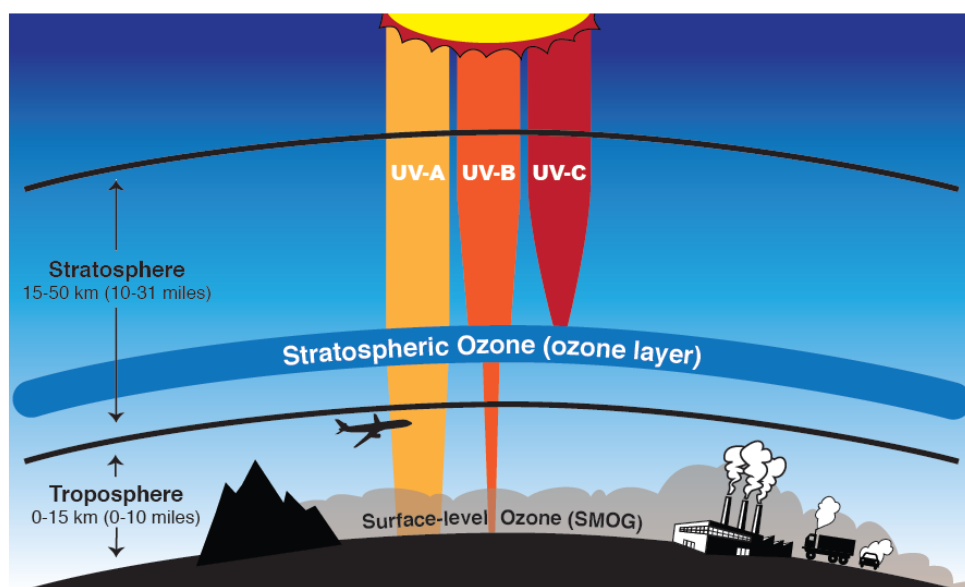


Figure 5.3: Ozone is “good” in the stratosphere because it absorbs most ultraviolet radiation. Ozone is “bad” in the troposphere because it is harmful to breathe and is the primary component of smog in summer. *Source:* [NASA](#)

Natural conditions in the stratosphere sustain a dynamic balance between the creation and destruction of ozone which helps to ensure the continued existence of the ozone layer. Any disruption of this balance that results in a higher rate of ozone destruction than ozone creation would result in depletion of ozone. Ozone depletion, consequently, leads to significant increase in the amount of harmful UV-B radiation that reaches the Earth's surface and this what we are talking about when we discuss the ozone problem.

5.2.2 The Ozone Hole

The **Ozone Hole** is not really a “hole” but rather an area where the thickness of the ozone layer is greatly reduced. This hole is a result of ozone depletion that occurs every year during the Antarctic spring (**Figure 5.4**) and was first reported to the public by the British Antarctic Survey in 1985. The thickness of the ozone layer above the Antarctic continued to decline while the geographic area covered by the ozone hole continued to increase, reaching its lowest concentration (thickness) in 1994 and largest geographic area in 2000. Recent data shows that ozone concentration globally and in the Arctic and Antarctic is no longer declining.

During the long winter months of darkness over the Antarctic, atmospheric temperatures drop, creating unique conditions for chemical reactions that are not found anywhere else in the atmosphere. During this time, the Antarctic air mass is isolated from the rest of the atmosphere and circulates around the pole in what is known as the *polar vortex*. This isolation allows temperatures to drop low enough to create ice crystals at high altitudes. Ozone, nitric acid, sulfuric acid and some chlorine containing molecules are absorbed on the surfaces of these ice particles. When the sun rises over the Antarctic in the southern spring (October), light rapidly releases free chlorine atoms into the stratosphere. The chlorine atoms react with ozone breaking it down to molecular oxygen and an oxygen atom. The polar vortex keeps the ozone-depleted air inside the vortex from mixing with the undepleted air outside the vortex, hence the formation of an ozone hole.

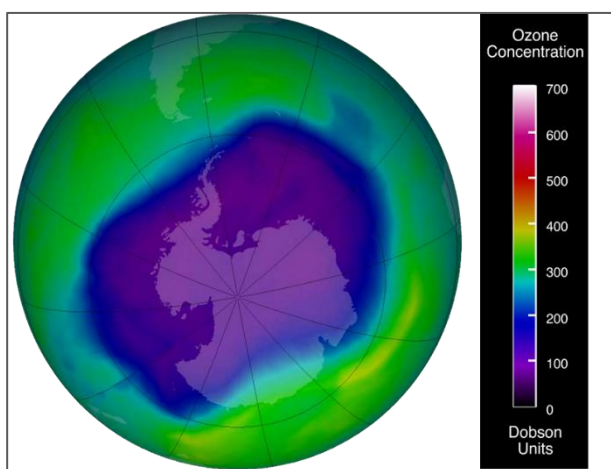


Figure 5.4. Ozone concentration over Antarctica during the austral spring. Colors indicate total column ozone in Dobson Units (DU). The blue and purple colors are where there is the least ozone, and the greens, yellows, and

5.2.3 Ozone Depletion

Global ozone concentrations change periodically with regular natural cycles such as changing seasons, winds, and long-time scale sun variations. Concentrations of ozone in the atmosphere are measured in **parts per billion** (ppb). Scientists have been measuring ozone since the 1920's using ground-based instruments that look skyward. Satellite measurements of concentrations of atmospheric ozone began in 1970 and continue today. Ozone depletion occurs when the rate at which ozone is broken down is greater than the rate of its creation,

interfering with the dynamic balance between creation and destruction that maintains the ozone layer. When this happens, the amount of harmful UV-B radiation that reaches the Earth's surface increases. Ozone depletion was first identified over the Antarctic. Scientists suggested that reactions involving man-made chlorine-containing compounds were responsible for depleting ozone in the stratosphere. This hypothesis was based mostly on the physical and chemical properties of these compounds and knowledge about atmospheric conditions.

Chlorofluorocarbons

(CFCs) are man-made compounds made up of chlorine, fluorine and carbon (**Figure 5.5**). These compounds were commonly used as propellants in everyday products such as shaving cream, hair spray, deodorants, paints and insecticides and as coolants in refrigerators and air conditioners. CFCs are extremely stable molecules and do not react with other chemicals in the lower atmosphere, part of the reason why they were considered a safe choice. Their stability means that they tend to remain in the atmosphere for a very long time. With the constant movement of

air in the lower atmosphere, CFCs eventually make their way into the stratosphere. Exposure to ultraviolet radiation in the stratosphere breaks them apart, releasing chlorine atoms. Free chlorine (Cl) atoms then react with ozone molecules, taking one oxygen atom to form chlorine monoxide (ClO) and leaving an oxygen molecule (O₂) (**Figure 5.5**). The ClO reacts with other atoms freeing up the Cl making it available to react with another ozone molecule, repeating the cycle over and over resulting in ozone depletion.

If each chlorine atom released from a CFC molecule destroyed only one ozone molecule, CFCs would pose very little threat to the ozone layer. However, when a chlorine monoxide molecule encounters a free atom of oxygen, the oxygen atom breaks up the chlorine monoxide, stealing the oxygen atom and releasing the chlorine atom back into the stratosphere to destroy another ozone molecule. These two reactions happen over and over again, so that a single atom of chlorine, acting as a **catalyst**, destroys many molecules (about 100,000) of ozone.

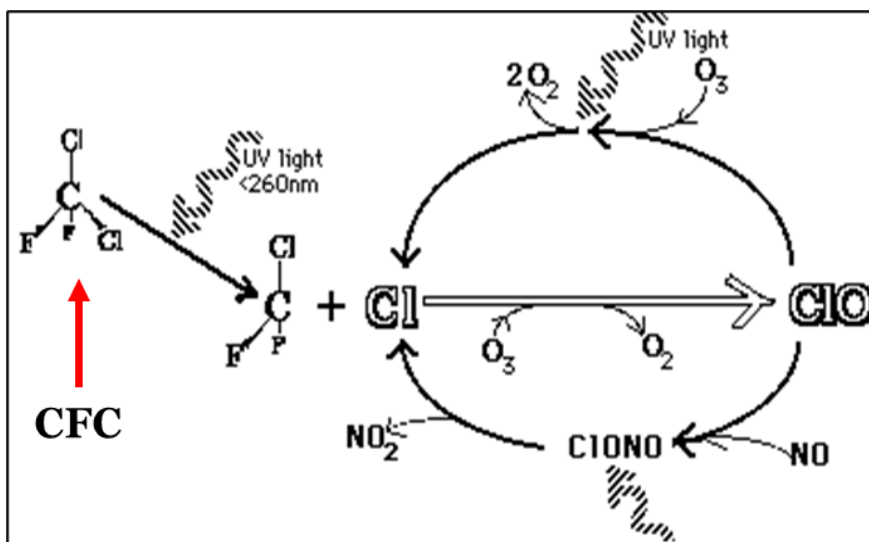


Figure 5.5: The process of ozone destruction. Ultraviolet (UV) radiation breaks a chlorine (Cl) atom off a CFC molecule. The free Cl atom reacts with an ozone (O₃) molecule, forming chlorine monoxide (ClO) and oxygen gas (O₂). The ClO then reacts with another ozone molecule, producing two more oxygen gas molecules and releasing the Cl atom. The freed Cl atom can repeat this cycle many times, continually destroying ozone. Image by Brien Sparling

The consequence of stratospheric ozone depletion is increased levels of UV-B radiation reaching the Earth's surface, posing a threat to human health and the environment. **Figure 5.6** shows a lower than average amount of stratospheric ozone over North America in 1997 when it was abnormally cold compared to 1984, which was warmer than average, showing that ozone depletion does not exclusively affect just the South Pole (Antarctic).

5.2.4 The Montreal Protocol

International policy efforts to restrict production of ozone depleting CFCs culminated in the 1987 treaty known as the **Montreal Protocol** in which signing nations agreed to cut CFC

production in half by 1998. At least five follow-up agreements since then helped to deepen the cuts, advanced timetables for compliance, and addressed additional ozone-depleting substances such as halons, methyl chloroform, carbon tetrachloride, and **hydrochlorofluorocarbons** (HCFCs). Most countries around the world have phased out production of the substances covered by the agreements and industry has been able to shift to safer alternative chemicals. As a result, there's evidence that the Antarctic ozone hole has stopped growing worse, although complete recovery is not expected anytime soon. **Figure 5.7** shows ozone depletion through time. Phasing out CFCs and HCFCs is also beneficial in protecting the earth's climate, as these substances are also very damaging **greenhouse gases**.

As part of the United States' commitment to implementing the Montreal Protocol, the U.S. Congress amended the **Clean Air Act (section 5.7)**, adding provisions for protection of the ozone layer. Most importantly, the amended Act required the gradual end to the production of chemicals that deplete the ozone layer. The Clean Air Act amendments passed by Congress requires the **Environmental Protection Agency** (EPA) to develop and implement regulations for the responsible management of ozone-depleting substances in the United States. Under the Clean Air Act, EPA has created several regulatory programs to address numerous issues, including:

- ending the production of ozone-depleting substances,
- ensuring that refrigerants and halon fire extinguishing agents are recycled properly,
- identifying safe and effective alternatives to ozone-depleting substances,
- banning the release of ozone-depleting refrigerants during the service, maintenance, and disposal of air conditioners and other refrigeration equipment,
- requiring that manufacturers label products either containing or made with the most harmful ozone depleting substances.

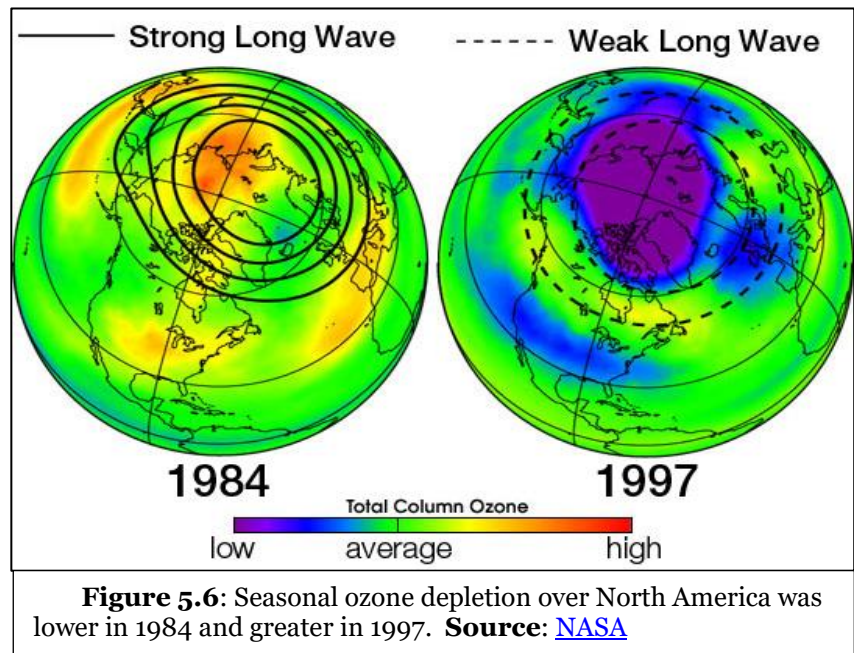


Figure 5.6: Seasonal ozone depletion over North America was lower in 1984 and greater in 1997. **Source:** [NASA](#)

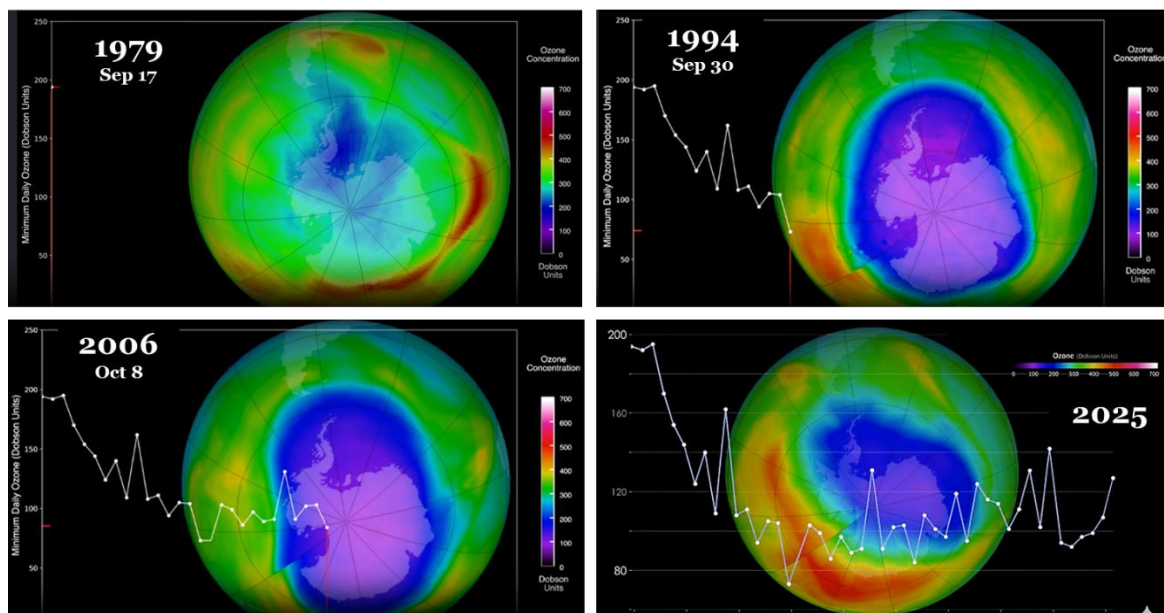


Figure 5.7: Evolution of the Antarctic ozone hole from 1979 to 2025. Satellite images show the size and intensity of ozone depletion over Antarctica during the spring – top left 1979 (pre-hole era), top right 1994 (rapid expansion), bottom left 2006 (near-maximum extent), and bottom right 2025 (partial recovery following international mitigation efforts such as the Montreal Protocol). Source: www.nasa.gov Visit [NASA Ozone Watch: Latest status of ozone](https://www.nasa.gov/monitoring-our-planets-ozone/)

5.2.5 Trends and Current Status

Figure 5.8 illustrates two key metrics related to the Antarctic ozone hole: average ozone hole area (top panel) and minimum ozone concentration (bottom panel) during the austral spring. The ozone hole area is calculated for the period 7 September–13 October, while minimum ozone values are averaged over 21 September–16 October. In 1979, the ozone hole was virtually absent, with an average area of **0 million km²** and a minimum ozone concentration of 225 Dobson Units (DU). Over the following decades, the ozone hole expanded dramatically, peaking in **2006** at an average area of **27 million km²**. Similarly, the lowest recorded ozone concentration occurred in **1994**, dropping to **92 DU**, a level far below the threshold considered healthy for the stratosphere.

Since the early 2000s, both metrics show signs of recovery, largely attributed to international efforts such as the **Montreal**

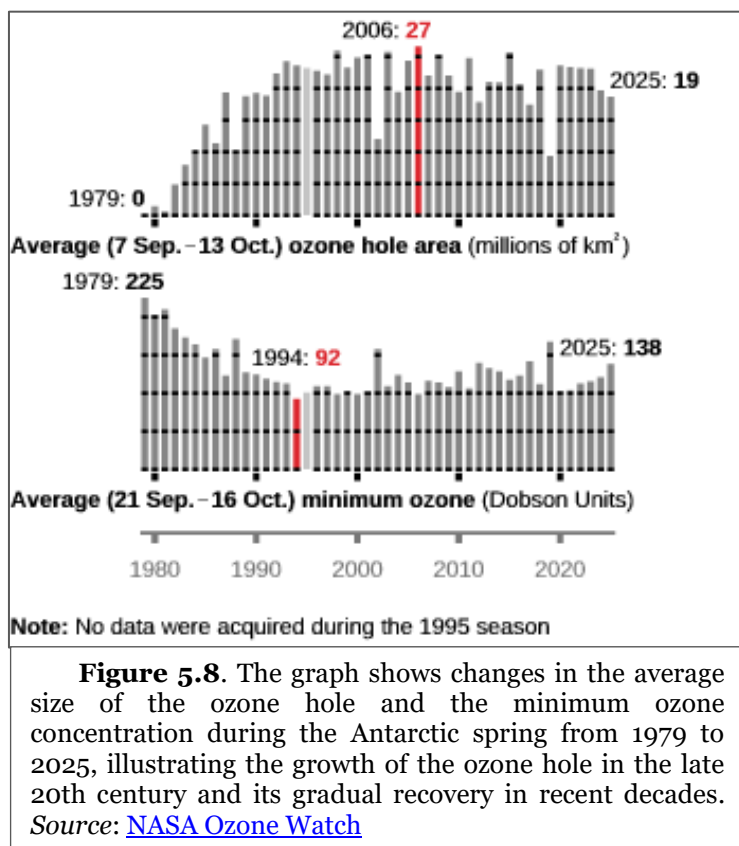


Figure 5.8. The graph shows changes in the average size of the ozone hole and the minimum ozone concentration during the Antarctic spring from 1979 to 2025, illustrating the growth of the ozone hole in the late 20th century and its gradual recovery in recent decades. Source: [NASA Ozone Watch](https://www.nasa.gov/monitoring-our-planets-ozone/)

Protocol, which phased out ozone-depleting substances. By **2025**, the average ozone hole area has declined to **19 million km²**, and the minimum ozone concentration has risen to **138 DU**, indicating gradual healing of the ozone layer. However, the data also reveal year-to-year variability, influenced by factors such as stratospheric temperature and atmospheric circulation.



Test your knowledge...

1. Ozone gas is made up of ____ oxygen atoms
2. Good ozone is located in the ____ and ____ are the pollutants that cause ozone layer depletion.
3. Our main concern when ozone is depleted is harmful UV__
4. The international agreement aimed at reducing ozone depletion is ____
5. Where is the ozone hole most commonly observed?
a. Arctic b) Equator c) North America d) Antarctic
6. According to the data presented, the ozone hole is
a. Completed recovered
b. Still getting bigger
c. Showing some recovery, though small

5.3 Outdoor Air Pollution

Air pollution refers to the introduction, into the atmosphere, of substances that have harmful effects on humans, other living organisms, and the environment either as solid particles, liquid droplets or gases. Air pollution can result from natural processes such as dust storms, forest fires, and volcanic eruptions, or from human activities such as biomass burning, vehicular emissions, mining, agriculture, and industrial processes. Improved technology and government policies have helped reduce most types of outdoor air pollution in many industrialized countries including the United States, in recent decades. However, outdoor air quality is still a problem in less industrialized nations, especially in megacities of rapidly industrializing nations such as China and India.

Outdoor pollutants can come from **stationary (point)** sources or **mobile (nonpoint)** sources (**Figure 5.9**). Stationary sources have a fixed location, for example power plant smokestacks, burning, construction sites, farmlands and surface mines among others. Mobile sources of air pollutants move from place to place while emitting pollutants. Examples of mobile sources include vehicles, aircrafts, ships, and trains.

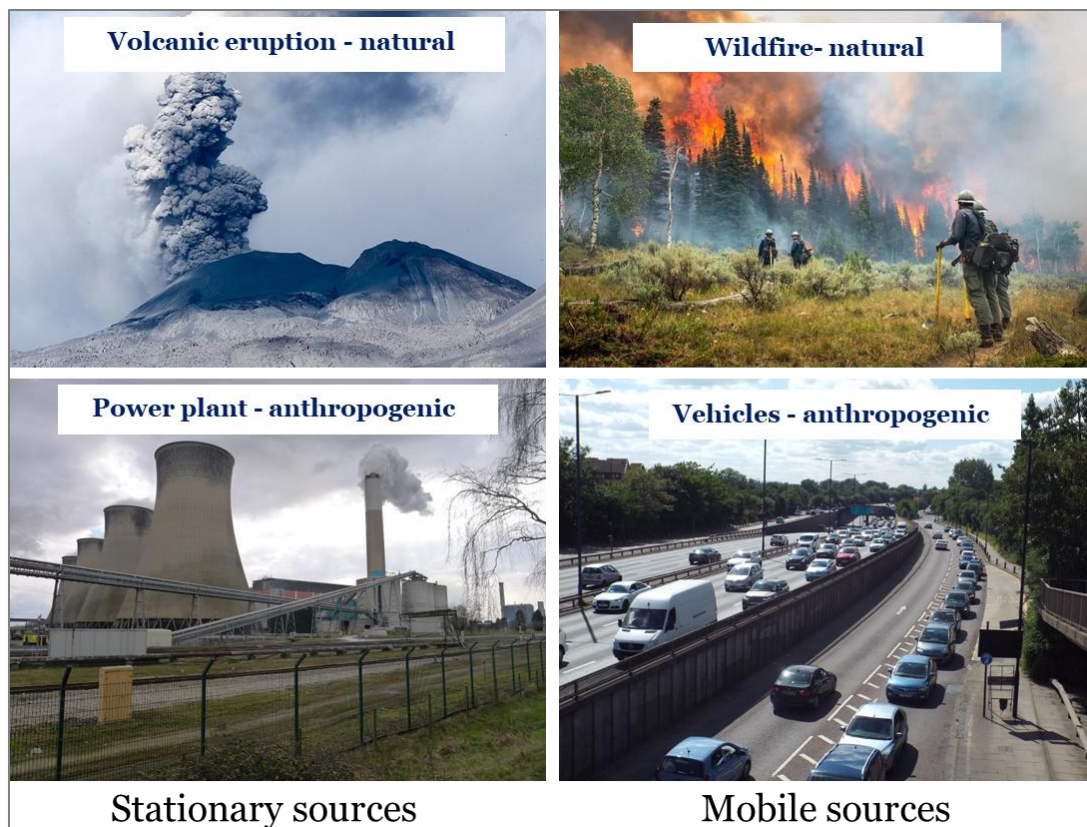


Figure 5.9: Images showing various sources of air pollution: topl left is volcanic eruption (source: [Galeria del Ministerio de Defensa del Perú](#)), bottom left is a coal power plant (source: [Tim Heaton](#)), top right is a natural wildfire (source: [unknown author](#)), bottom right is vehicles (source: [Malc McDonald](#))

Pollutants are categorized into two major types based on how they originated namely primary and secondary pollutants. **Primary pollutants** are those released directly from the source into the air in a harmful form. The primary pollutants that account for nearly all air pollution problems are carbon monoxide (58%), volatile organic compounds (VOCs, 11%), nitrogen oxides (15%), sulfur dioxides (13%), and particulate material (3%). **Secondary pollutants** are not released directly into the air. Instead, they form when primary pollutants (the ones that come straight from sources like cars, factories, or volcanoes) react with other substances in the atmosphere. For example, ground-level ozone (bad ozone) forms over urban areas when gases from car exhaust and other atmospheric gases such as VOCs mix and react in sunlight.

5.3.1 Criteria pollutants

Under the Clean Air Act (see **section 5.7.1**), the Environmental Protection Agency (EPA) establishes **air quality standards** to protect public health and the environment. EPA has set national air quality **standards** for six common air pollutants namely: 1) carbon monoxide; 2) ground-level ozone; 3) nitrogen dioxide; 4) Sulfur dioxide; 5) lead; and 6) particulate matter (also known as particle pollution). Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or

environmentally-based criteria (science-based guidelines) for setting permissible levels. The set of limits based on human health is called primary standards. Another set of limits intended to prevent environmental and property damage is called secondary standards.

1. **Carbon Monoxide (CO):** is a colorless, odorless gas emitted from combustion processes, specifically, the incomplete combustion of fuel. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.
2. **Ground-level ozone (O₃):** is a colorless gas with a slightly sweet odor that is not emitted directly into the air, but is created by the interaction of sunlight, heat, oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). Ozone is likely to reach unhealthy levels on hot sunny days in urban environments. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NO_x and VOCs.
3. **Nitrogen dioxide (NO₂):** is one of a group of highly reactive gasses known as "oxides of nitrogen," or "**nitrogen oxides** (NO_x).\" Other nitrogen oxides include nitrous acid and nitric acid. NO₂ is a yellowish-brown to reddish-brown foul-smelling gas that is a major contributor to smog and acid rain. Nitrogen oxides result when atmospheric nitrogen and oxygen react at the high temperatures created by combustion engines. Most emissions in the U.S. result from combustion in vehicle engines, electrical utility, and industrial combustion.
4. **Sulfur dioxide (SO₂):** Sulfur dioxide is one of a group of highly reactive gasses known as "oxides of sulfur.\" The largest sources of SO₂ emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO₂ emissions include industrial processes such as extracting metals from their ores, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment.
5. **Particulate material (PM),** sometimes known simply as "**particulates**" refers to solid particles and liquid droplets suspended in the air we breathe. Particulate pollution is made up of a variety of components, including acids (nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (pollen and mold spores). The size of the particles is directly linked to their potential for causing health problems. Particles that are 10 micrometers in diameter or smaller generally pass through the throat and nose and enter the lungs. EPA groups these into two types: "**inhalable coarse particles**," with diameters larger than 2.5 micrometers and smaller than 10 micrometers and "**fine particles**," with diameters that are 2.5 micrometers and smaller. How small is 2.5 micrometers? Think about a single hair from your head. The average human hair is about 70 micrometers in diameter – making it 30 times larger than the largest fine particle (**Figure 5.10**). Our respiratory systems are equipped to filter larger particles out of the air once it is inhaled. However, the lungs are vulnerable to both coarse particles (PM₁₀), and fine particles (PM_{2.5}). These can slip past the respiratory system's natural defenses and get deep into the lungs and some may even get

into the bloodstream. Coarse particles come from road dust while fine particles come from combustion processes.

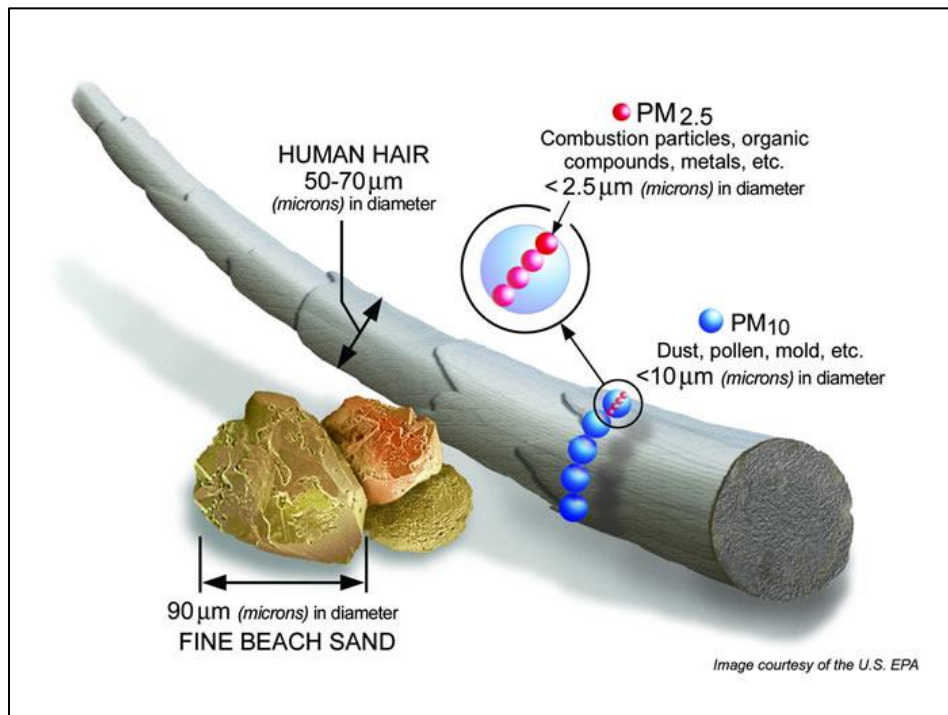


Figure 5.10: Graphic showing size comparison of particulate material (PM₁₀ and PM_{2.5}) compared to fine beach sand and human hair. **Source:** US EPA [Particulate Matter \(PM\) Basics | US EPA](#)

6. **Lead (Pb):** is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in motor vehicles (such as cars and trucks) and industrial sources. As a result of EPA's regulatory efforts to remove lead from gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent during that time period. The major sources of lead emissions today are ore and metal processing and piston-engine aircraft operating on leaded aviation gasoline. Today, the highest levels of lead in air are usually found near lead smelters.

5.3.2 Volatile Organic Compounds

Volatile organic compounds (VOCs) are carbon-containing chemicals emitted as gases from natural and human-made sources. Natural sources of VOCs include plants, the largest source, and bacteria in the guts of termites and ruminant animals. These compounds are generally oxidized to carbon monoxide and carbon dioxide in the atmosphere. VOCs are of great concern because they are precursors for the formation of ozone, a secondary air pollutant.

A large number of synthetic organic chemicals such as benzene, toluene, formaldehyde, vinyl chloride, chloroform, and phenols are widely used as ingredients in countless household

products. Paints, paint strippers, varnishes, many cleaning, disinfecting, cosmetic, degreasing, and hobby products all contain VOCs. Fuels are also made up of organic chemicals. All of these products can release organic compounds while you are using them, and, to some degree, when they are stored. The “new car smell” characteristic of new cars is from a complex mix of dozens of VOC. Also, concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. They are often held responsible for sick building syndrome, an illness resulting from indoor pollution in which the specific cause is not identified.

5.3.3 Smog

Smog is a mixture of air pollutants (sulfur dioxide, nitrogen oxides, ozone, and particulates) that often form over urban areas as a result of fossil fuel combustion. The term was coined from the terms “smoke” and “fog” referring to a brownish haze that pollutes the air, greatly reducing visibility and making it difficult for some people to breathe (**Figure 5.11**). There are two main types of smog: industrial and photochemical smog. **Industrial smog** is produced primarily by the burning of fossil fuels which produces carbon dioxide (from complete combustion), carbon monoxides (from partial combustion), sulfur, and mercury. The sulfur reacts with other chemicals in the atmosphere producing several sulfur compounds including sulfur dioxide. These compounds along with particulate material make up industrial smog. **Photochemical smog** is formed when sunlight drives chemical reactions between primary pollutants from automobiles and normal atmospheric compounds. The product is a mix of over 100 different chemicals with the most abundant being ground-level ozone.



Figure 5.11. Images compare smog conditions in two metropolitan areas, illustrating the impact of industrial emissions, vehicle exhaust, and atmospheric conditions on air quality. Such pollution reduces visibility and poses significant health risks. *Source:* Left photo by Igors Jefimovs [Wikicommons](#). Right image German [Wikipedia](#)

5.3.4 Toxic pollutants

Toxic air pollutants, also known as hazardous air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Examples of toxic air pollutants include benzene, which is found in gasoline; perchloroethylene, which is emitted from some dry cleaning facilities; methylene chloride, which is used as a solvent and paint stripper by a

number of industries; and others such as dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds.

Most air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents). Some air toxics are also released from natural sources such as volcanic eruptions and forest fires. Exposure to air toxics is mainly through breathing but some toxic air pollutants such as mercury can deposit onto soils or surface waters, where they are taken up by plants and ingested by animals and are eventually magnified up through the food chain. Like humans, animals may experience health problems if exposed to sufficiently high quantities of air toxics over time.



Test your knowledge...

1. *Differentiate between primary and secondary pollutants with examples.*
2. *Why is ground-level ozone harmful while stratospheric ozone is beneficial?*
3. *What are criteria pollutants? Name the six criteria pollutants.*

5.4 Indoor Air Pollution

In both developed and developing nations, indoor air pollution poses a greater health risk than outdoor air pollution. According to the **World Health Organization** (WHO) and other agencies such as the Environmental Protection Agency (EPA), indoor air generally contains higher concentrations of toxic pollutants than outdoor air. Additionally, people generally spend more time indoors than outdoors, hence, the health effects from indoor air pollution in workplaces, schools, and homes are far greater than outdoor. Indoor pollution sources that release gases or particles into the air are the primary cause of indoor air quality problems in homes. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the home.

Outdoor air enters and leaves a building by infiltration, natural ventilation, and mechanical ventilation. In infiltration, outdoor air flows into the house through openings, joints, and cracks in walls, floors, and ceilings, and around windows and doors. In natural ventilation, air moves through opened windows and doors. Air movement associated with infiltration and natural ventilation is caused by air temperature differences between indoors and outdoors and by wind. Finally, there are a number of mechanical ventilation devices, from outdoor-vented fans that intermittently remove air from a single room, such as bathrooms and kitchen, to air handling systems that use fans and duct work to continuously remove indoor air and distribute filtered and conditioned outdoor air to strategic points throughout the house. The rate at which outdoor air replaces indoor air is described as the air exchange rate. When there is little infiltration, natural ventilation, or mechanical ventilation, the air exchange rate is low and pollutant levels can increase. High temperature and humidity levels can also increase concentrations of some pollutants.

There are many sources of indoor air pollution in any home (**Figure 5.12**). These include combustion sources such as oil, gas, kerosene, coal, wood, and tobacco products; building materials and furnishings as diverse as deteriorated, asbestos-containing insulation, wet or damp carpet, and cabinetry or furniture made of certain pressed wood products; products for household cleaning and maintenance, personal care, or hobbies; central heating and cooling systems and humidification devices. Pollutants causing indoor air pollution can also originate from outside sources such as radon, pesticides, and outdoor air pollution. **Radon** is a naturally occurring radioactive gas produced from the decay of uranium in rock. If a building/home is constructed in an area with uranium containing rock, the gas can seep through the foundations and accumulate in basements. Exposure to radon can cause lung cancer.

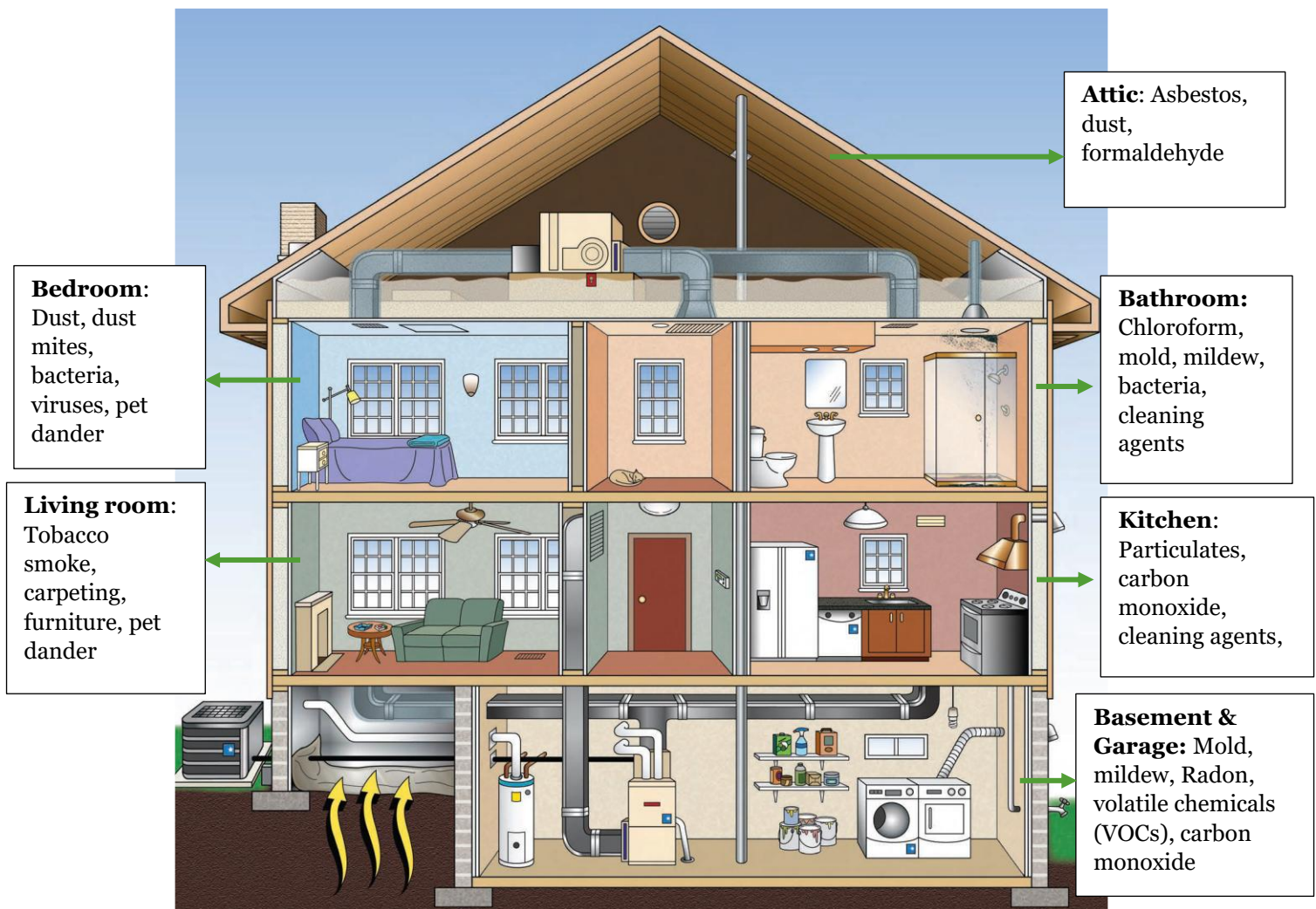


Figure 5.12: Sources of indoor air pollution. Image source: EPA [careforyourair.pdf](https://www.epa.gov/careforyourair)

The relative importance of any single source depends on how much of a given pollutant it emits and how hazardous those emissions are. In some cases, factors such as how old the source is and whether it is properly maintained are significant. For example, an improperly adjusted gas stove can emit significantly more carbon monoxide than one that is properly

adjusted. Some sources, such as building materials, furnishings, and household products like air fresheners, release pollutants more or less continuously. Other sources, related to activities carried out in the home, release pollutants intermittently. These include smoking, the use of unvented or malfunctioning stoves, furnaces, or space heaters, the use of solvents in cleaning and hobby activities, the use of paint strippers in redecorating activities, and the use of cleaning products and pesticides in house-keeping. High pollutant concentrations can remain in the air for long periods after some of these activities.

Risks from indoor air pollution differ between less industrialized and industrialized nations. Indoor pollution has a greater impact in less industrialized nations where many people use cheaper sources of fuel such as wood, charcoal, and crop waste among others for cooking and heating, often with little or no ventilation. The most significant indoor pollutant, therefore, is soot and carbon monoxide. In industrialized nations, the primary indoor air health risks are cigarette smoke and radon.



Test your knowledge...

1. *Why can indoor air be worse than outdoor (2–5×) and what makes VOCs particularly problematic (up to 10× higher indoors)?*
2. *What is the source of radon and what's its impact?*
3. *Which indoor pollutants are most significant in industrialized versus industrializing countries?*

5.5 Effects of Air Pollution on Human Health

The World Health Organization (WHO) and other international agencies recognize air pollution as a major threat to human health. Numerous scientific studies have linked air pollution to a variety of health problems (**Table 5.2**) including: aggravation of respiratory and cardiovascular diseases; decreased lung function; increased frequency and severity of respiratory symptoms such as difficulty breathing and coughing; increased susceptibility to respiratory infections; effects on the nervous system, including the brain, such as IQ loss and impacts on learning, memory, and behavior; cancer; and premature death. Immediate effects of air pollution may show up after a single exposure or repeated exposures. Other health effects may show up either years after exposure has occurred or only after long or repeated periods of exposure.

Immediate effects of air pollution include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Such immediate effects are usually short-term and treatable. Sometimes the treatment is simply eliminating the person's exposure to the source of the pollution, if it can be identified. Symptoms of some diseases, including asthma, hypersensitivity pneumonitis, and humidifier fever, may also show up soon after exposure to some indoor air pollutants.

The likelihood of immediate reactions to air pollutants depends on several factors. Age and preexisting medical conditions are two important influences. Some sensitive individuals appear to be at greater risk for air pollution-related health effects, for example, those with pre-existing heart and lung diseases (e.g., heart failure/ischemic heart disease, asthma, emphysema, and chronic bronchitis), diabetics, older adults, and children. In other cases, whether a person reacts to a pollutant depends on individual sensitivity, which varies tremendously from person to person. Some people can become sensitized to biological pollutants after repeated exposures, and it appears that some people can become sensitized to chemical pollutants as well.

Table 5.2: Sources and health effects of criteria pollutants

Pollutant	Sources	Health Effects
Ground-level Ozone (O₃)	Secondary pollutant typically formed by chemical reaction of volatile organic compounds (VOCs) and NO _x in the presence of sunlight.	Decreases lung function and causes respiratory symptoms, such as coughing and shortness of breath; aggravates asthma and other lung diseases leading to increased medication use, hospital admissions, emergency department (ED) visits, and premature mortality.
Particulate Matter (PM)	Emitted or formed through chemical reactions; fuel combustion (e.g., burning coal, wood, diesel); industrial processes; agriculture (plowing, field burning); and unpaved roads.	Short-term exposures can aggravate heart or lung diseases leading to respiratory symptoms, increased medication use, hospital admissions, ED visits, and premature mortality; long-term exposures can lead to the development of heart or lung disease and premature mortality.
Lead	Smelters (metal refineries) and other metal industries; combustion of leaded gasoline in piston engine aircraft; waste incinerators; and battery manufacturing.	Damages the developing nervous system, resulting in IQ loss and impacts on learning, memory, and behavior in children. Cardiovascular and renal effects in adults and early effects related to anemia.
Oxides of Nitrogen (NO_x)	Fuel combustion (e.g., electric utilities, industrial boilers, and vehicles) and wood burning.	Aggravate lung diseases leading to respiratory symptoms, hospital admissions, and ED visits; increased susceptibility to respiratory infection.
Carbon Monoxide (CO)	Fuel combustion (especially vehicles), industrial processes, fires, waste combustion, and residential wood burning.	Reduces the amount of oxygen reaching the body's organs and tissues; aggravates heart disease, resulting in chest pain and other symptoms leading to hospital admissions and ED visits.
Sulfur Dioxide (SO₂)	Fuel combustion (especially high-sulfur coal); electric utilities and industrial processes; and natural sources such as volcanoes.	Aggravates asthma and increased respiratory symptoms. Contributes to particle formation with associated health effects.

Source: [Criteria Air Pollutants | US EPA](#)



Test your knowledge...

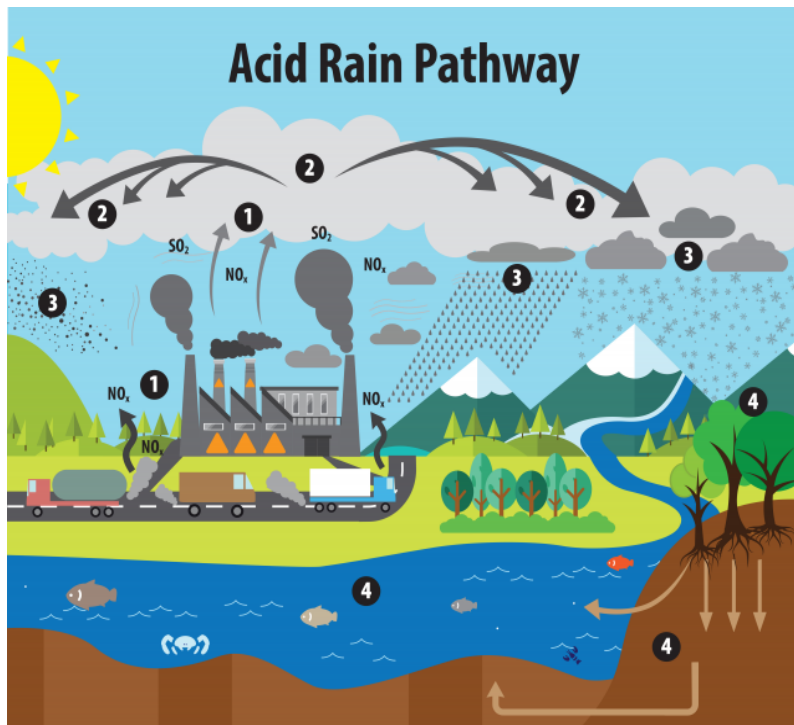
1. Which health effect is the most common among many of the criterial pollutants?
2. What is the most common source of many of the criteria pollutants?
3. What distinguishes ground-level ozone from the other criteria pollutants?
4. In wildfire smoke waves, what makes health impacts comparable to years of progress on PM/O₃ control?

5.6 Acid Rain

Pure rainfall is slightly acidic, pH 5.6, because water reacts with atmospheric carbon dioxide to produce weak carbonic acid. When higher than normal amounts of nitric and sulfuric acid occur in the atmosphere, the result is precipitation with a pH below 5.6 which is referred to as **acid rain**. Acid rain includes both wet deposition (rainfall, snow, fog) and dry deposition (particulates). Acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO₂) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. In the United States, roughly $\frac{2}{3}$ of all SO₂ and $\frac{1}{4}$ of all NO_x come from electric power generation that relies on burning fossil fuels, like coal. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds (**Figure 5.13**). The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles. Regions of greatest acidification tend to be downwind from heavily industrialized source areas of pollution.

Acid rain is a serious environmental problem that is particularly damaging to lakes, streams, and forests and the plants and animals that live in these ecosystems, as well as to infrastructure. Some of the impacts include:

- Leaching of soil nutrients such as calcium, magnesium, and potassium out of the topsoil, altering soil chemistry and harming plants and soil organisms.
- Acid rain causes the release of substances that are toxic to trees and other plants, such as aluminum, into the soil. Scientists hypothesize that this combination of loss of soil nutrients and increase of toxic aluminum may be one way that acid rain harms trees (**Figure 5.14a**). Such substances also wash away in the **runoff** and are carried into streams, rivers, and lakes.
- Damage to automotive paints and other coatings. The reported damage typically occurs on horizontal surfaces and appears as irregularly shaped, permanently etched areas.
- Acidic particles contribute to the **corrosion** of metals (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects



This image illustrates the pathway for acid rain in our environment:

(1) Emissions of SO_2 and NO_x are released into the air mainly from fossil fuel combustion.

(2) Pollutants in the air are transformed into acid particles that may be transported long distances in the atmosphere.

(3) These acid particles then fall to the earth as wet and dry deposition (dust, rain, snow, etc.) = acid rain

(4) The acid rain may cause harmful effects on soil, forests, streams, and lakes.

Figure 5.13: Formation of acid rain from both natural and anthropogenic pollutants. **Source:** US EPA [What is Acid Rain? | US EPA](https://www.epa.gov/acidrain/what-is-acid-rain)

- significantly reduce the societal value of buildings, bridges, cultural objects (such as statues, monuments, and tombstones) (**Figure 5.14b**).
- Sulfates and nitrates that form in the atmosphere contribute to visibility impairment, meaning we cannot see as far or as clearly through the air. Sulfate particles account for 50 to 70 percent of the visibility reduction in the eastern part of the U.S., affecting our enjoyment of national parks, such as the Shenandoah and the Great Smoky Mountains

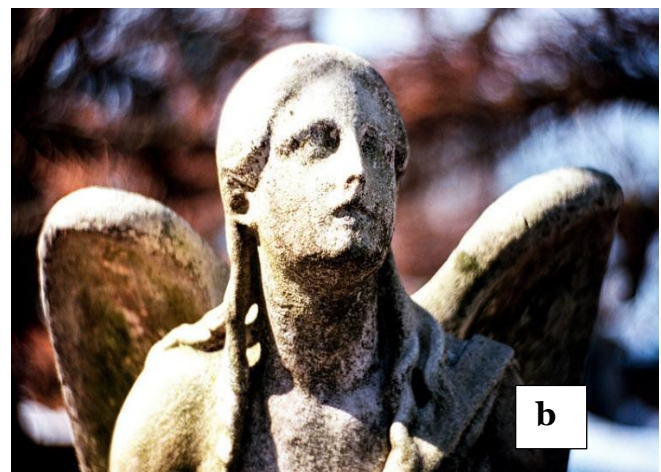


Figure 5.14: **a)** Effects of acid rain on trees, Jizera Mountains, Czech Republic. Image from [Wikimedia commons](https://commons.wikimedia.org/wiki/File:Dead_trees_in_Jizera_Mountains.jpg), Public Domain. **b)** Effects of acid rain on a monument in Greenwood cemetery, Brooklyn New York. Photo by James P. Fischer ([Source](https://www.fischerphoto.com/)).



Test your knowledge...

1. *What is the pH of acid rain versus pure rain?*
2. *Which pollutants contribute greatly to acid rain?*
3. *How does particulate matter affect human health?*
4. *Explain the link between acid rain and forest decline.*

5.7 Air Pollution Legislation in the United States

In 1930, 63 people died and 1000 were sickened in Belgium when a phenomenon referred to as temperature inversion caused pollutants to be trapped near the surface, leading to a sudden spike in atmospheric sulfur levels. In October 1948, a thick cloud of air pollution formed above the industrial town of Donora, Pennsylvania. The cloud which lingered for five days, killed 20 people and caused sickness in 6,000 of the town's 14,000 people. In 1952, the infamous London fog in which acid aerosols were trapped in the lower atmosphere killed 4000 people. Events like these alerted us to the dangers that air pollution poses to public health. In this section, we focus on how air pollution regulation is structured and implemented in the United States. While the specific laws and agencies differ, most other industrialized countries use comparable regulatory frameworks to address air pollution and protect the public.

5.7.1 Clean Air Act

In the United States, several federal and state laws were passed, including the original Clean Air Act of 1963, which established funding for the study and cleanup of air pollution. But there was no comprehensive federal response to address air pollution until Congress passed a much stronger **Clean Air Act in 1970**. That same year Congress created the Environmental Protection Agency (EPA) and gave it the primary role in carrying out the law. Since 1970, EPA has been responsible for a variety of Clean Air Act programs to reduce air pollution nationwide. The Clean Air Act is a federal law covering the entire country. However, states, tribes and local governments do a lot of the work to meet the Act's requirements. For example, representatives from these agencies work with companies to reduce air pollution. They also review and approve permit applications for industries or chemical processes.

5.7.2 EPA's Role

EPA's mission is basic health and environmental protection from air pollution for all Americans. To achieve this mission, EPA implements a variety of programs under the Clean Air Act that focus on:

- reducing outdoor, or ambient, concentrations of air pollutants that cause smog, haze, acid rain, and other problems;
- reducing emissions of toxic air pollutants that are known to, or are suspected of, causing cancer or other serious health effects; and
- phasing out production and use of chemicals that destroy stratospheric ozone.

Under the Clean Air Act, EPA sets limits on certain air pollutants, including setting limits on how much can be in the air anywhere in the United States. The Clean Air Act also gives EPA the authority to limit emissions of air pollutants coming from sources like chemical plants, utilities, and steel mills. Individual states or tribes may have stronger air pollution laws, but they may not have weaker pollution limits than those set by EPA. EPA must approve state, tribal, and local agency plans for reducing air pollution. If a plan does not meet the necessary requirements, EPA can issue sanctions against the state and, if necessary, take over enforcing the Clean Air Act in that area. EPA assists state, tribal, and local agencies by providing research, expert studies, engineering designs, and funding to support clean air progress. Since 1970, Congress and the EPA have provided several billion dollars to the states, local agencies, and tribal nations to accomplish this.

5.7.3 State and Local Governments' Roles

It makes sense for state and local air pollution agencies to take the lead in carrying out the Clean Air Act. They are able to develop solutions for pollution problems that require special understanding of local industries, geography, housing, and travel patterns, as well as other factors. State, local, and tribal governments also monitor air quality, inspect facilities under their jurisdictions and enforce Clean Air Act regulations. States have to develop **State Implementation Plans** (SIPs) that outline how each state will control air pollution under the Clean Air Act. A SIP is a collection of the regulations, programs and policies that a state will use to clean up polluted areas. The states must involve the public and industries through hearings and opportunities to comment on the development of each state plan.

5.7.4 Outcomes of the Clean Air Act

For more than forty years, the Clean Air Act has cut pollution as the U.S. economy has grown. The combined emissions of the six criteria pollutants have continued to decrease while population, gross domestic product, energy consumption, and vehicle miles travelled have all continued to increase (**Figure 5.15**). The following is a summary of some of the accomplishments of the Clean Air Act:

- Clean Air Act programs have lowered levels of the six criteria pollutants - particulates, ozone, lead, carbon monoxide, nitrogen dioxide and sulfur dioxide - as well as numerous toxic pollutants.
- From 1970 to 2023, aggregate national emissions of the six common pollutants alone dropped an average of 78 percent while gross domestic product grew by 321 percent (**Figure 5.15**). This progress reflects efforts by state, local and tribal governments; EPA; private sector companies; environmental groups and others.
- The emissions reductions have led to dramatic improvements in the quality of the air that we breathe.
- These air quality improvements have enabled many areas of the country to meet national air quality standards set to protect public health and the environment. For example, all of the 41 areas that had unhealthy levels of carbon monoxide in 1991 now have levels that meet the health-based national air quality standard. A key reason is that the motor vehicle fleet is much cleaner because of Clean Air Act emissions standards for new motor vehicles.

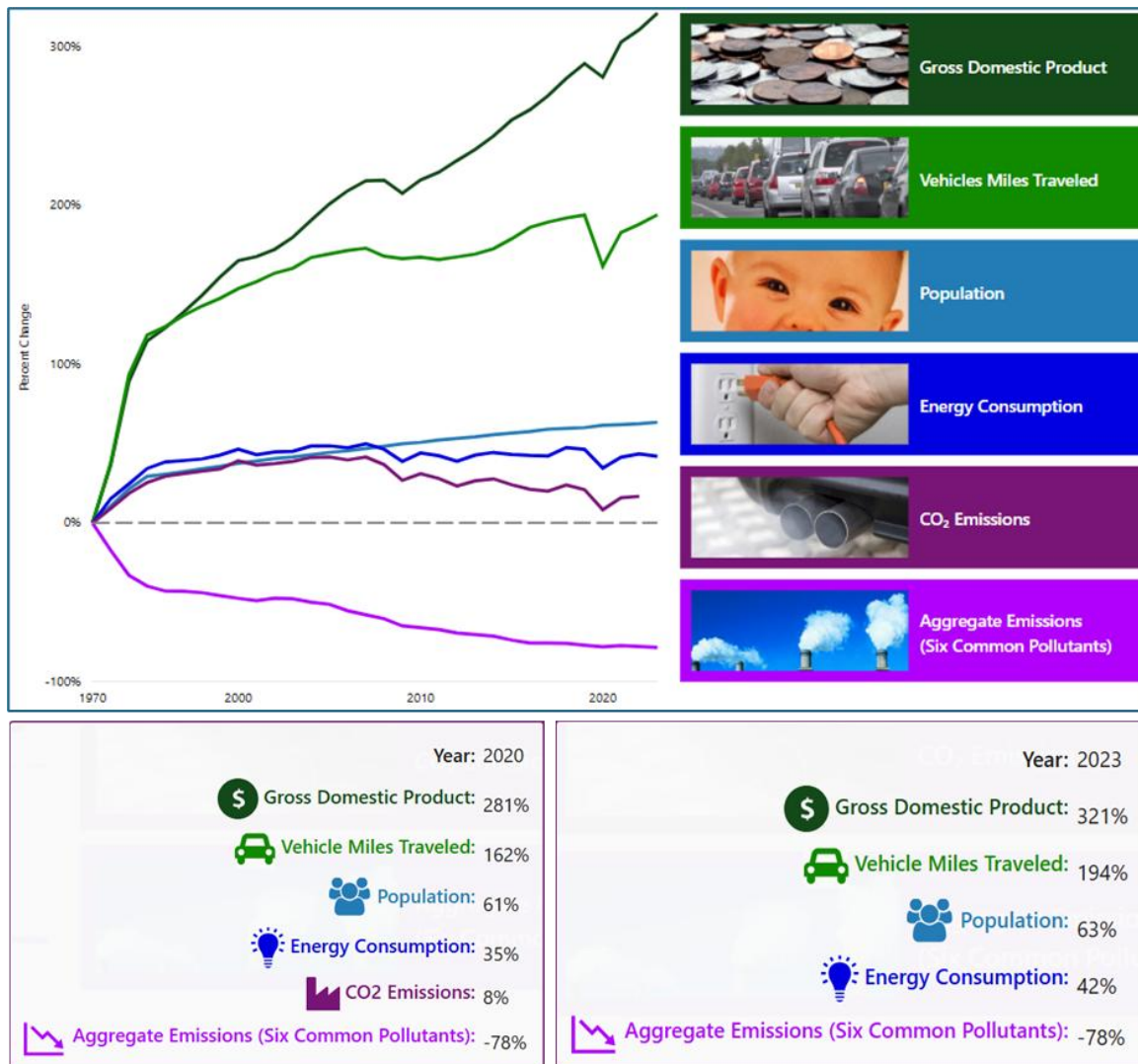


Figure 5.15: Showing a decrease in the combined emissions for the six criterial pollutants since the passing of the Clean Air Act. Meanwhile, population, energy consumption, vehicle miles travelled, and gross domestic product have all increased. **Source:** US EPA [Our Nation's Air 2024](#)

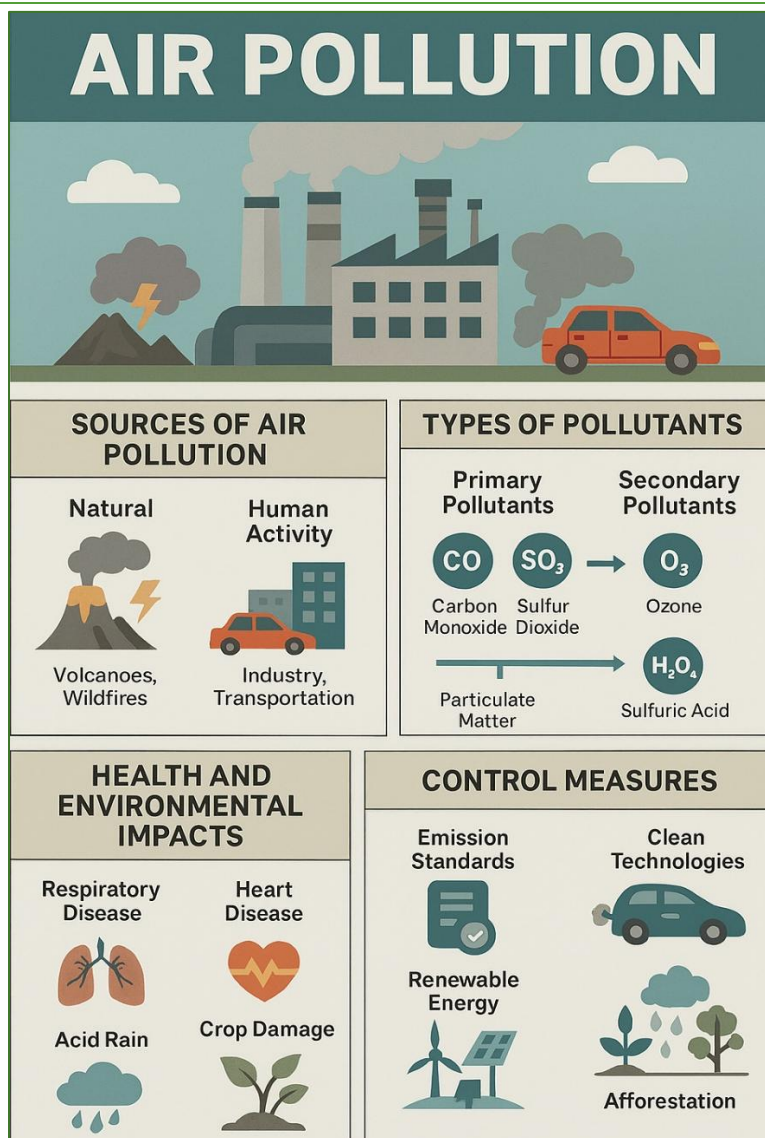
- Airborne lead pollution, a widespread health concern before EPA phased out lead in motor vehicle gasoline under Clean Air Act authority, now meets national air quality standards in most areas of the country.



Test your knowledge...

1. How did the original Clean Air Act of 1963 differ in its achievements from the revised Clean Air Act of 1970?
2. What are the key provisions of the Clean Air Act?
3. What evidence demonstrates that air pollution regulations in the United States have successfully improved air quality?

5.8 Chapter Summary in Graphic Form



5.9 Chapter Activities

1. Activity: **Debate**

Policy Debate: “Should stricter emission standards be enforced globally?”

Design Challenge: Propose an air pollution reduction plan for your campus.

2. Activity: **Analysis**

Analyze your local AQI objective: Understand real-time air quality data.

Instructions:

1. Visit AirNow.gov (<https://www.airnow.gov/>) or use an AQI app.
2. Record today's AQI and main pollutant.
3. Identify the health category and precautions.

Extension: Track AQI for 7 days and graph the trend.

3. Activity: **Case Study**

Spend a few minutes and research the London Smog case study and then answer the questions below.

The London Smog of 1952 Background: A severe smog event caused by coal burning and stagnant weather.

Key Facts:

- Location: London, UK
- Main pollutants: SO₂, PM
- Impact: ~4,000 deaths in 5 days
- [London's Great Smog 1952 & Air Pollution - Population Education](#)
- [The Great Smog of London: Air pollution pt. 1 - American Chemical Society](#)

- 1) Policy Impact: What did this event lead to in terms of Policy Response?
- 2) Discussion Question: How might similar conditions occur today despite modern technology?

End of Chapter Review

1. Describe the importance and unique characteristics of each layer of our atmosphere. How might pollution in each of these layers impact humans or the environment differently?
2. For each of the criteria pollutants, identify: a) natural and anthropogenic sources, b) environmental effects, and c) human health effects. What steps can we take to reduce the concentration of each of these pollutants?
3. How do outdoor and indoor air quality differ in less- and more-industrialized countries? Can you extrapolate this to differences in outdoor and indoor air quality in urban, rural, and industrial areas of these countries?
4. Where in our atmosphere does the ozone layer reside, and what benefit does it provide humans and the environment? What causes ozone depletion, and how is this problem being addressed?
5. Compare and contrast acid rain with the concept of acid mine drainage (see Chapter 3). How are these similar and different in terms of sources, environmental impact, and remediation?
6. What is the role of local and national governments in regulating air quality? Identify the major pieces of legislation outlined in this chapter, and describe their impacts on local air quality. What role do international agencies have in regulating air quality?
7. What have been the results of the Clean Air Act in terms of human and environmental health?
8. Are there any categories of anthropogenic emissions that are not specifically covered by the Clean Air Act (hint: look ahead to Chapter 6)?
9. Which gas makes up the largest proportion of Earth's atmosphere?

A) Oxygen	C) Nitrogen
B) Carbon dioxide	D) Argon

10. What is the primary role of nitrogen in the atmosphere?
 - A) It absorbs UV radiation
 - B) It dilutes oxygen to prevent rapid combustion
 - C) It forms ozone in the stratosphere
 - D) It acts as a greenhouse gas
11. What causes the ozone hole over Antarctica during the Austral spring?
 - A) Increased volcanic activity
 - B) Chlorine atoms from CFCs reacting with ozone
 - C) Excessive UV radiation from the sun
 - D) High concentrations of greenhouse gases
12. Which type of UV radiation is most harmful but does NOT reach Earth's surface?
 - A) UV-A
 - B) UV-B
 - C) UV-C
 - D) UV-D
13. Which international agreement aimed to phase out ozone-depleting substances?
 - A) Kyoto Protocol
 - B) Paris Agreement
 - C) Montreal Protocol
 - D) Geneva Convention
14. What is the main consequence of stratospheric ozone depletion?
 - A) Increased acid rain
 - B) Increased UV-B radiation reaching Earth's surface
 - C) Increased greenhouse effect
 - D) Increased tropospheric ozone
15. Why is ozone in the stratosphere considered "good"?
 - A) It prevents acid rain
 - B) It absorbs harmful UV radiation
 - C) It reduces greenhouse gases
 - D) It improves air quality at ground level
16. Which of the following is a primary pollutant?
 - A) Ozone (O₃)
 - B) Sulfur dioxide (SO₂)
 - C) Acid rain
 - D) Smog

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- National Weather Service <http://www.srh.noaa.gov/jetstream/atmos/layers.htm>
- US EPA Our Nations Air <https://gispub.epa.gov/air/trendsreport/2024/#home>
- NASA – Historical ozone video, follow the following link
svs.gsfc.nasa.gov/vis/a010000/a014400/a014449/14449_2023_Ozone_Horizontal.mp4

Terms

Acid rain	Parts per million (ppm)
Air pollution	Photochemical smog
Air quality	Point source
Argon	Primary pollutant
Atmosphere	Radiation
Carbon dioxide	Radon
Carbon monoxide	Runoff
Catalyst	Secondary pollutant
Chlorofluorocarbons (CFCs)	Standards
Clean Air Act	State implementation plan (SIP)
Corrosion	Stationary source
Environmental Protection Agency (EPA)	Stratopause
Greenhouse gas	Stratosphere
Ground-level ozone	Sulfur dioxides
Hydrochlorofluorocarbons (HCFCs)	Thermosphere
Industrial smog	Tropopause
Lead	Troposphere
Mesosphere	Ultra violet (UV)
Mobile source	UV-A
Montreal Protocol	UV-B
Nitrogen	UV-C
Nitrogen dioxide	Volatile organic compounds (VOCs)
Nitrogen oxides	Water vapor
Nonpoint source	Weather
Oxidize	World Health Organization
Oxygen	
Ozone	
Ozone hole	
Ozone layer	
Ozone-oxygen cycle	
Particulate material	
Parts per billion (ppb)	