# 17 The Changing Atmosphere

## Learning Goals

After studying this chapter, students should be able to:

1. list the major air pollutants and their main sources (pp. 443–445);
2. describe how atmospheric conditions can influence air quality (pp. 445–449);
3. outline the causes of the depletion of the ozone layer (pp. 451–459);
4. explain how human activities are influencing Earth's climate (pp. 459– 468);
5. list and account for the consequences of anthropogenic climate change (pp. 468–474); and
6. *outline* and *evaluate* action taken to curb anthropogenic climate change (pp. 474–478).

# Summary

1. **Air pollutants** are substances present in the atmosphere at high enough concentrations to be harmful. They can be in gaseous, liquid, or solid form. Some pollutants are emitted directly into the atmosphere, while others form in the atmosphere. Primary gaseous pollutants include carbon monoxide, nitrogen oxides, and sulphur dioxide. Liquid or solid pollutants are collectively known as **particulate matter**. **Volatile organic compounds** can be primary or secondary pollutants; they can also be in gaseous, liquid, or solid form. Ozone, a secondary gaseous pollutant, is the main component of **photochemical smog**. This smog forms when sunlight reacts with nitric oxide and volatile organic compounds from motor vehicle exhaust. Air pollution concentrations often reach their highest levels under anticyclonic conditions.

2. The ozone layer, which protects life from harmful ultraviolet radiation, is being threatened by certain gases associated with human activity. The most serious threat comes from CFCs. These gases are stable until they reach the stratosphere. There they are broken down, releasing chlorine. In turn, chlorine destroys ozone, thinning the ozone layer. Proof that CFCs were destroying the ozone layer came in the mid-1980s, when the **ozone hole** was discovered and studied. Research showed that the ozone hole is a result of very complex chemistry involving polar stratospheric clouds (PSCs). Nitric oxide and bromine also destroy stratospheric ozone. The source of nitric oxide is mostly nitrous oxide from fertilizer use, but a minor source is the exhaust of supersonic jets. Bromine comes from artificially produced **halons**. The Montreal Protocol of 1987 eventually led to the ban of most ozone-depleting substances.

3. Human activities have created a positive radiative forcing on climate; this forcing is responsible for the observed increase in temperature of close to 1°C relative to pre-industrial time. The highest contribution to this positive forcing comes from increases in greenhouse gas concentrations. The burning of fossil fuels, deforestation, and land degradation are the processes most responsible for the increases in carbon dioxide, while agriculture is responsible for most of the increases in methane and nitrous oxide. Aerosol concentrations have also been increasing, mostly due to the burning of fossil fuels. The negative forcing contributed by aerosols partially offsets the positive forcing due to greenhouse gases. The increase in surface albedo, caused mostly by deforestation, also contributes a small negative forcing.

4. Our ability to make predictions about anthropogenic climate change is complicated by feedback effects. The radiative feedback is an important negative feedback that works to stabilize temperature when an energy imbalance occurs. Temperature will continue to change until an energy balance is restored. Two of the most important, and best understood, positive feedbacks are the water vapour feedback and the ice-albedo feedback. Although it seems likely that clouds will also produce a positive feedback, this is not certain. The above feedbacks have a direct effect on temperature; other feedbacks impact greenhouse gas concentrations.

5. There are signs that Earth's climate is changing. Over roughly the last century up until 2011, Earth's temperature has increased about 0.85°C and sea level has risen 19 cm (IPCC, 2014). Glaciers around the world are losing mass, and the September extent of Arctic sea ice has decreased about 30 per cent since the 1970s. With more carbon dioxide in the atmosphere, more carbon dioxide is dissolving in the oceans, making the water more acidic. Precipitation patterns appear to be changing, and precipitation events are becoming more intense. It is also likely that severe hurricanes are becoming more frequent, and mid-latitude weather is being affected by changes in the jet stream.

6. Based on **climate sensitivity**, it is estimated that a doubling of atmospheric carbon dioxide would cause Earth's temperature to increase somewhere between 2°C and 4.5°C. **General circulation models (GCMs)** can be used to make more detailed projections about how anthropogenic forcings will affect the climate. These models are complex computer models designed to simulate the workings of the atmosphere and, as much as possible, how the atmosphere interacts with the oceans, the land, ice, and life. In order to make use of GCMs to forecast future climate, we need to estimate future greenhouse gas emissions. This is done using four socioeconomic scenarios known as representative concentration pathways (RCPs). The results of multiple GCMs run using the four RCPs were documented in the IPCC's Fifth Assessment Report. Based on the scenario of immediate and severe reductions in greenhouse gas emissions, we can expect Earth to warm about 1.6°C relative to pre-industrial temperatures by 2100. At the other extreme, the business-as-usual scenario would cause Earth to warm about 4.3°C relative to pre-industrial temperatures by 2100.
7. There are three main approaches for dealing with climate change. At present, the best strategy is to make every effort to **mitigate** the causes of climate change, and to **adapt** to changes that are occurring. A more controversial approach is to counteract climate change by intervening in the climate system using **geoengineering**.
8. The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992 with the aim of preventing "dangerous anthropogenic interference with the climate system" (UN, 1992, p. 4). Although international conferences have been held annually since 1995 to carry out the goals of this convention, there has been little action to prevent climate change. At the twenty-first session of the Conference of the Parties (COP21), held in Paris in December 2015, it was agreed that warming should be kept to well below 2°C. This goal will require immediate and severe cuts in greenhouse gas emissions. However, based on our increased scientific understanding of climate change and its effects, such a goal is now considered necessary to accomplish the aim first stated in 1992.

## Key Terms

**Acid rain** Rain with a pH less than about five. (p. 444)

**Adaptation** Taking steps to adjust to actual or expected climate changes. (p. 474)

**Air pollutant** Any gaseous, liquid, or solid substance present in the atmosphere in sufficient quantity to negatively impact the health of people and animals, or harm plants or materials. (p. 443)

**Air Quality Health Index (AQHI)** An index used to report the health risk associated with certain levels of air pollutants. (p. 449)

**Carbon dioxide equivalent** The amount of carbon dioxide that would have the same global warming potential as a given amount of another greenhouse gas. For example, the carbon dioxide equivalent of 1 tonne of methane is 25 tonnes. (p. 470)

**Geoengineering** Deliberate intervention in the climate system to counteract climate change. (p. 474)

**Global warming potential (GWP)** A measure of the capacity of a greenhouse gas to impact global temperatures, relative to the warming potential of carbon dioxide. (p. 463)

**Halocarbons** Substances containing carbon and one or more halogen atoms (i.e., chlorine, bromine, fluorine, iodine). (p. 454)

**Halons** A type of halocarbon that contains carbon, bromine, and other halogen atoms. (p. 455)

**Mitigation** Taking steps to reduce further climate change by reducing emissions or enhan ing sinks of carbon dioxide. (p. 474)

**Ozone hole** A roughly circular area in the ozone layer where the amount of stratospheric ozone is about 50 per cent less than it is in the surroundings. (p. 455)

**Particulate matter** Atmospheric pollutants in solid or liquid form. (p. 443)

**Photochemical smog** A mixture of toxic gases that forms when gases emitted by motor vehicles react in sunlight. (p. 444)

**Primary pollutant** A pollutant emitted directly into the atmosphere. (p. 443)

**Secondary pollutant** A pollutant that forms in the atmosphere. (p. 443)

## Answers to Selected Review Questions (p. 481)

1. **How are primary pollutants different from secondary pollutants?**

   Primary pollutants are emitted directly into the atmosphere and secondary pollutants form in the atmosphere as a result of chemical transformations.

3. **What is photochemical smog? Under what conditions will it form? Why does it often reach its highest concentration in the afternoon?**

   Photochemical smog is a mixture of toxic gases that forms when gases emitted by motor vehicles react in sunlight. It will form during sunny conditions. It reaches its highest concentration in the afternoon because by that time of day the nitrogen oxides and VOCs have accumulated in the air from the morning rush hour and the ample amount of sunlight around noon has transformed the primary pollutants into the mix of ozone and other secondary pollutants that make up photochemical smog.

5. **Why do we want ozone in the stratosphere, but not in the troposphere?**

   Ozone in the stratosphere is essential to life because it absorbs harmful ultraviolet radiation from the sun. Ozone in the troposphere is detrimental to life because it is toxic.

7. **How do CFCs destroy the ozone layer? What other gases can destroy ozone? What are their sources?**

   CFCs encounter ultraviolet radiation in the stratosphere. This radiation has the intensity to break them down. When CFCs are broken down, chlorine is released. Once released, chlorine can react with ozone, producing chlorine monoxide and molecular oxygen; in the process, the ozone is destroyed.

Nitrogen oxides and bromine can also destroy ozone. Sources of nitrogen oxides include nitrogen fertilizers and supersonic jets. Halons in fire extinguishers are sources of bromine.

**9. Why will destruction of the ozone layer continue for a long time even though CFCs have been banned?**

Destruction of the ozone layer will continue because CFCs have residence times in the atmosphere of, on average, about 100 years.

**11. How can radiative forcing and global warming potential (GWP) be used to evaluate the human impact on climate?**

Radiative forcing is a change in the flows of radiation in the Earth-atmosphere system that will upset the energy balance and, thus, force climate to change.

Global warming potential is a measure of the capacity of a greenhouse gas to impact global temperatures, relative to the warming potential of carbon dioxide.

Long-lived greenhouse gases, halocarbons, tropospheric ozone, stratospheric water vapour from methane, and surface albedo (black carbon on snow) create positive forcings.

Stratospheric ozone, surface albedo (land use), the direct aerosol effect, and the cloud albedo effect create negative forcings.

Radiative forcings and global warming potential provide us with a method for evaluating the human impact on climate by comparing the effects of the various changes that impact climate to pre-industrial conditions.

**13. How do the feedback effects associated with global warming operate?**

Feedback effects that influence warming rates directly:

- The *radiative feedback* is a negative feedback that works to stabilize temperature when an energy imbalance occurs. Temperature will continue to change until an energy balance is restored.
- The *water vapour feedback* is a positive feedback. As temperature increases, evaporation will increase the amount water vapour in the atmosphere, which will further amplify the warming since water vapour is a greenhouse gas.
- The *ice-albedo feedback* is a positive feedback. As temperature increases, ice will melt, resulting in a lower planetary albedo. With a lower albedo, Earth will absorb more of the sun's radiation, resulting in further warming, which will lead to further melting of ice and further heat absorption.
- Research suggests the *cloud feedback* will be a positive feedback since warmer temperatures will result in a lower amount of low cloud (responsible for cooling), though there is much uncertainty in the way in which clouds will respond to warming.

Feedbacks that influence GHG concentrations (rather than warming directly):

- Melting permafrost, due to rising temperatures, is releasing stored carbon dioxide and methane. While this positive feedback increases the sources for greenhouse gases, other feedbacks may cause decreases in the sinks for these gases, potentially turning sinks into sources as warming progresses. Current sinks include the oceans and the land, however, warmer ocean temperatures (resulting in less carbon dioxide absorption) and increased biological activity (resulting in increased soil carbon emissions) may turn these current sinks into sources.

- Increased amounts of atmospheric carbon dioxide might increase the rates of plant growth and hence increase rates of photosynthesis, which would then increase the sink for carbon dioxide. This feedback remains an area of active research.
- A warmer atmosphere may lead to stormier conditions with more lightning. The increase in lightning means there will be more hydroxyl (OH), which reacts with methane, effectively removing it from the atmosphere.

**15. How do scientists make projections to determine how the climate will change as a result of human activity?**

Scientists use complex general circulation models (GCMs) in order to develop projections of how human activity may influence future climate. Future concentrations of greenhouse gases are described using four possible socio-economic scenarios called representative concentration pathways (RCPs), where each RCP represents a different amount of radiative forcing by the year 2100. Output from numerous models is used to produce a range of results that describe possible climate projections for each RCP.

**17. Why are some approaches to dealing with climate change better than others?**

There are three broad approaches for dealing with climate change—mitigation, adaptation, and intervention. Mitigation involves taking steps to reduce further climate change by addressing the causes, mainly by reducing greenhouse gas emissions, particularly carbon dioxide as it has a higher forcing than other anthropogenic forcings.

The most effective way to mitigate sources of carbon dioxide is to reduce reliance on fossil fuels by switching to renewable sources of energy. Technological improvements towards increased energy efficiency continue however, energy conservation can be challenging, as it requires a change of behavior.

Further mitigation methods for reducing carbon dioxide emissions focus on land restoration to restore degraded land from deforestation, overgrazing, or poor agricultural practices—where increased carbon dioxide emissions result from accelerated breakdown of organic material. Many of the methods used to restore degraded land will also strengthen carbon dioxide sinks.

Adapting to climate change is difficult when there are many uncertainties with projected changes; though necessary as climate change is already taking place.

Intervening through Geoengineering is controversial as there are many side effects (known and unknown) to the proposed methods thus far.

Iron fertilization, the idea of removing atmospheric carbon through fertilizing the ocean with iron to encourage the growth of algae, and hence increase photosynthesis, resulting in the captured carbon to sink to the bottom of the ocean when the algae eventually dies, does not appear to be effective in the long-term and will have adverse effects on marine life.

Carbon capture and sequestration (CCS) involves removing carbon dioxide during the process of fossil fuel combustion, and storing the captured carbon deep in the oceans or deep underground. Until technologies can be developed to capture carbon dioxide directly from the ambient air, CCS is currently limited to point sources of carbon dioxide.

Injecting sulphate aerosols into the stratosphere to mimic the effects of a large volcanic eruption to reduce the amount of solar radiation reaching Earth's surface (with the aim of offsetting the warming effect of greenhouse gases) could lead to a decrease in stratospheric ozone, as well as a disruption in the occurrence of monsoons.

## Study Questions

For suggested answers, see below.

1. How does the appearance of a smokestack plume change depending on atmospheric stability?
2. What is the IPCC? What is its purpose?
3. What are the sources of methane?
4. How might jet contrails impact climate?
5. Why is it such a great concern if Earth's temperature increases by higher than 3°C?

# Answers to Study Questions

1. With neutral stability, the plume will form a cone shape. With unstable conditions, the plume will form a looping pattern. With stable conditions, the plume will look like a fan from above. When a mixed layer is capped by a subsidence inversion, the effect on the plume is described as fumigation, as it can lead to high pollution concentrations near the surface. When a neutral layer lies above an inversion, the resulting plume is described as lofting. There is little risk that pollutants will reach ground level in this situation because they will be prevented from doing so by the stable layer below. (p. 447)

2. The Intergovernmental Panel on Climate Change (IPCC) is composed of physical, natural, and social scientists from around the world. It was formed to maintain an interdisciplinary and international approach to our effort to understand and deal with climate change. Its purpose is to compile and evaluate climate change research with particular focus in assessing the science of the processes involved, observed and predicted impacts, possible adaptations to these impacts, and actions for reducing emissions. (p. 460)

3. Methane is produced naturally, primarily by anaerobic decomposition in wetlands and, to a slightly lesser extent, through the emissions of termites. Anthropogenic sources of methane include rice paddies, grazing animals, landfills, and the extraction of fossil fuels. (p. 462)

4. It is likely that jet contrails have a warming effect. High, thin clouds tend to have a net warming effect because of their relatively low albedos. (p. 463)

5. If temperature increases are higher than 3°C, a threshold could be reached at which runaway feedback effects will begin to operate. These feedback effects might continue to drive climate change even without further increases in greenhouse gases. (p. 466)