# 8.1 Energy Transfer in the Climate System

**Key Terms**
system
feedback loop
electromagnetic radiation
thermohaline circulation
energy budget

Earth's climate is a complex system. A **system** consists of a combination of parts that function as a whole. For example, your digestive system is made up of organs that work together to digest your food. Scientists further divide the systems they study into two major types: open systems and closed systems.

An *open system* is a system in which energy and matter cross the system's boundary. Your body is an open system, as shown in **Figure 8.1**. You take in food, water, and oxygen, and you release waste materials and heat.

A *closed system* is a system that allows energy but not matter to cross the system's boundary. The upper edge of the atmosphere marks the outer boundary of Earth's climate system. Although meteors bring small amounts of matter into Earth's climate system and hydrogen atoms sometimes escape Earth's atmosphere and move into space, Earth generally behaves like a closed system. Energy from the Sun continually flows into Earth's atmosphere and eventually passes back out into space. Nearly all the matter that forms the land, oceans, atmosphere, and living things on the planet remains within the system's boundary.

Earth maintains a temperature balance by radiating as much energy out into space as it absorbs from the Sun. Between the time solar energy is absorbed and the time it passes back into space, it produces wind, rain, ocean currents, fog, snow, and all of the other features of Earth's climate system.

**system** a group of interdependent parts that work together to form a single, functioning whole

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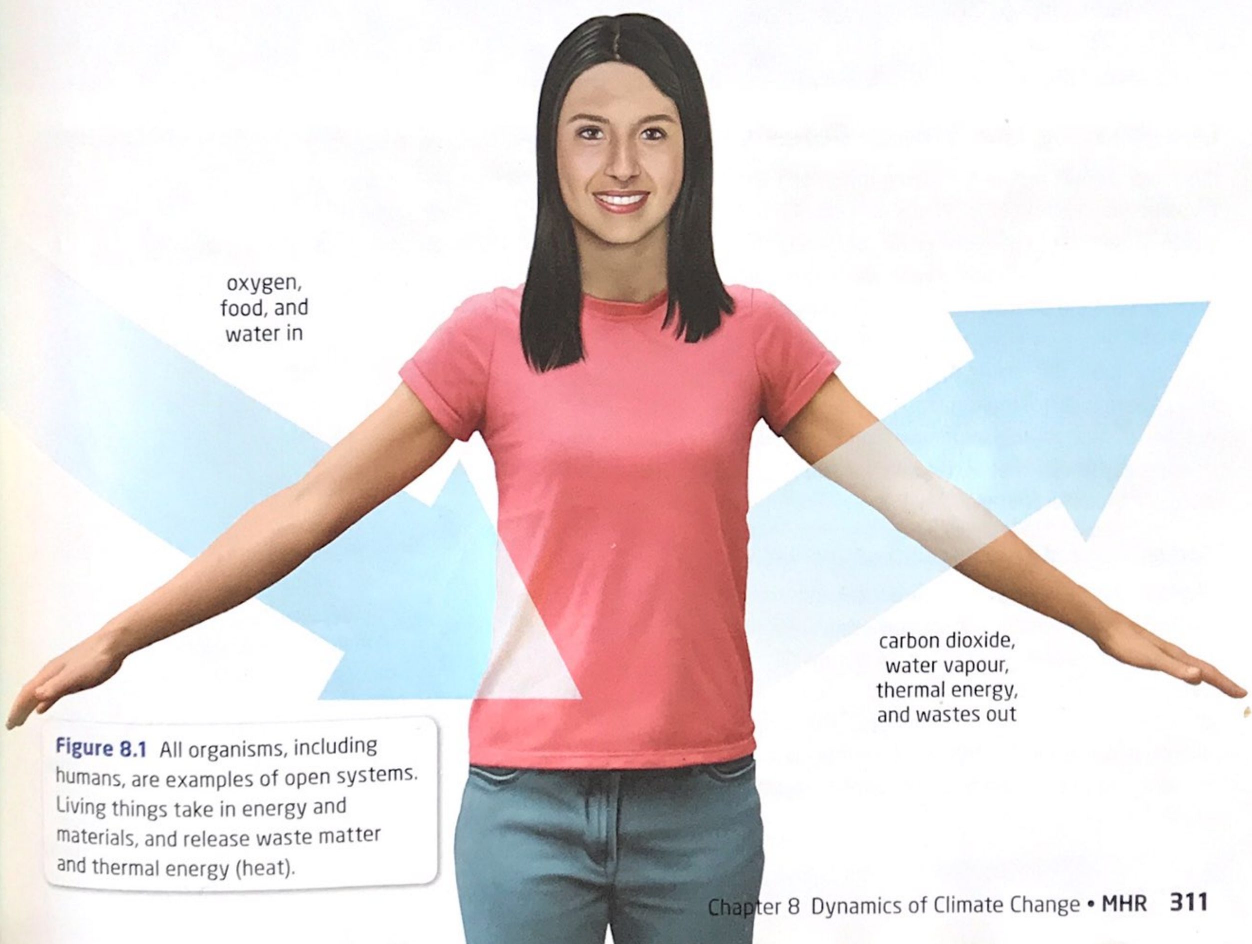



**Figure 8.1** All organisms, including humans, are examples of open systems. Living things take in energy and materials, and release waste matter and thermal energy (heat).

## Effects of Feedback Loops on the Earth System

**feedback loop** a process in which part of a system's output is returned, or fed back, to the input

As a closed system, Earth must constantly cycle the matter and energy within its boundary. Interactions among different forms of matter and energy in Earth's climate system often create feedback loops. A **feedback loop** is a process in which part of a system's output is returned (fed back) to the input. In Earth's climate system, many feedback loops affect the conditions of the atmosphere, ocean, and land.

### Positive Feedback Loops

A *positive feedback loop* acts to increase the effects of the interacting parts. For example, the effect of melting ice on albedo, as shown in **Figure 8.2**, is a positive feedback loop. Because of positive feedback loops, small initial changes in climate can lead to larger and larger changes before the system as a whole achieves a new balance.

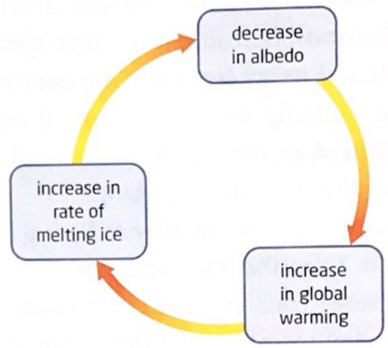



**Figure 8.2** This diagram shows a positive feedback loop that involves rising temperatures, decreasing albedo, and melting polar and glacial ice.

## STSE Case Study

### Overheating the Ocean's Forests

It is a well-known fact that all living things on Earth depend on plants for survival. Why? Plants perform photosynthesis, which is the process responsible for converting the gas carbon dioxide into the oxygen we breathe. Where does most of the photosynthesis on Earth take place? Not in the leaves of trees in the world's forests, but in phytoplankton–tiny plants that live in Earth's oceans and lakes. Though microscopic in size, they are abundant in number. In fact, phytoplankton perform about two thirds of the photosynthesis that occurs on Earth. But they are at risk from the effects of global warming.

#### Converting and Trapping Carbon Dioxide

Phytoplankton live at or near the ocean's surface, as shown in the photograph, because they need sunlight and carbon dioxide for photosynthesis. Every year, millions of tonnes of carbon dioxide are absorbed from the air into ocean water. This carbon dioxide is converted by phytoplankton into sugars and is passed on to the organisms that eat the plankton.

This satellite image shows billions of individual phytoplankton, like the ones shown in the inset photograph, clustered together off the coast of Newfoundland. The sunlight is reflecting off the chlorophyll and other pigments in their cells, making them visible as a light blue trail from space.

### Negative Feedback Loops

A *negative feedback loop* decreases the effects of the interacting parts and helps to maintain a system's equilibrium. In other words, the processes in a negative feedback loop act as checks and balances to prevent, slow, or reverse change in a system. For example, global warming increases the rate of evaporation of water. An increase in water vapour in the atmosphere creates more clouds. An increase in cloud cover increases albedo, which has a cooling effect. Therefore, although the feedback loop began with global warming, the net result of the feedback loop is a decrease in global average temperature. This process is shown in **Figure 8.3**.

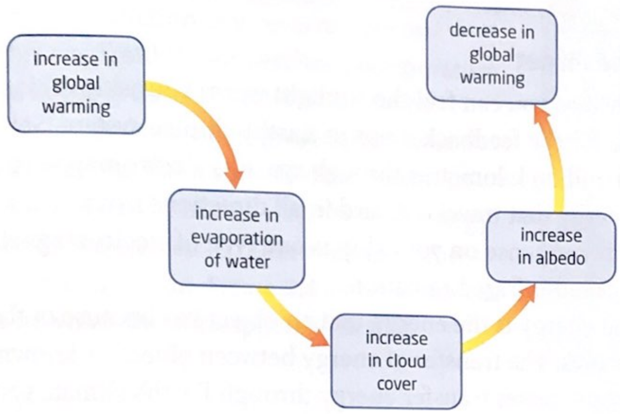
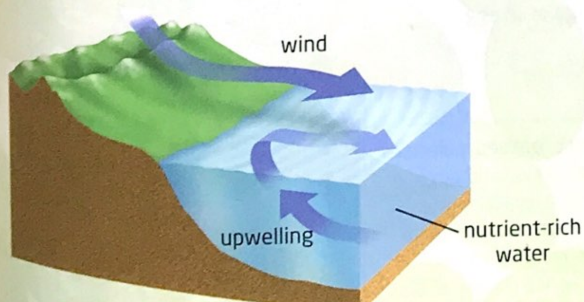



**Figure 8.3** This diagram shows a negative feedback loop. It demonstrates how an increase in evaporation can reduce global warming.

When phytoplankton die, they sink to the bottom of the ocean, where the carbon that is inside their cells gets trapped. The larger the population of phytoplankton is, the more carbon will be removed from Earth's atmosphere.

#### Phytoplankton at Risk

Nutrient-rich water from the deep ocean comes to the surface through a process called upwelling. When warm surface waters do not move away from shore, upwelling cannot occur, and fewer nutrients reach the phytoplankton at the surface.




During upwelling, warm surface water moves away from shore and cold, nutrient-rich deep water rises to the surface.

Because fewer phytoplankton consume the carbon dioxide necessary for photosynthesis, they store less carbon. In turn, more carbon dioxide resides in Earth's atmosphere, which increases global warming. Increased global warming may continue to reduce the phytoplankton population.

#### Your Turn

1. Use the information in this article to construct a feedback-loop diagram that shows how global warming and phytoplankton are related. Explain whether it is a positive or negative feedback loop.
2. Brainstorm a list of possible economic and environmental consequences of reduced numbers of phytoplankton. Would the consequences affect only the area of the ocean in which the phytoplankton live, or would they affect a larger area? Explain your answer.
3. Research an ocean food web. Assess the impact of removing phytoplankton from this food web.

## Learning Check

1. Why is Earth considered a closed system?
2. Give an example of a negative feedback loop in the climate system.
3. Using an example, describe how a positive feedback loop affects a system.
4. Look at **Figure 8.1**. Use the diagram to describe a feedback loop that may happen in your body system to maintain your temperature balance.

**electromagnetic radiation** energy that travels as waves that move outward in all directions from a source; includes infrared radiation, ultraviolet radiation, radio waves, X rays, gamma rays, and visible light

### Heating the Planet

On a sunny day, you can feel the sunlight warm your skin. This sunlight is responsible for the feedback loops in Earth's climate system. Solar energy travels 150 million kilometres through space as **electromagnetic radiation**, waves of energy that travel outward in all directions from their source. The warmth you sense on your skin is one type of electromagnetic radiation, called infrared radiation.

Thermal energy is the energy that an object has because of the motion of its molecules. The transfer of energy between objects is known as heat. Three main processes transfer energy through Earth's climate system: radiation, conduction, and convection. These processes are outlined in **Table 8.1**.

**Table 8.1** Types of Energy Transfer

| Type | Description | Example |
|---|---|---|
| **Radiation** | Radiation is the transfer of energy, including thermal energy, as electromagnetic radiation. Energy travels from the Sun to Earth as radiation, and heat travels from a fire to your body as radiation. All matter radiates some thermal energy—not only the Sun, but pebbles, bicycles, you, and even ice cubes. Because no matter is necessary to conduct radiation, this form of energy can travel through the vacuum of space. When radiation encounters matter, such as the atmosphere or your hand, it interacts with the matter. The matter may absorb the radiation, reflect it, or refract it. |  |
| **Conduction** | Conduction is the transfer of thermal energy between two objects or substances that are in direct physical contact. The thermal energy always moves from a region of higher temperature to a region of lower temperature. For example, a hotplate conducts thermal energy to a skillet placed on it. In turn, the skillet conducts thermal energy to an egg. |  |
| **Convection** | Convection is the transfer of thermal energy by highly energized molecules moving from one place to another. This movement can occur in liquids and gases, but not in solids. For example, when you turn on a lava lamp like the one shown to the right, a waxy substance at the bottom of the lamp is warmed by conduction. The wax expands and rises, carrying thermal energy by convection to the top of the lamp. The rising and sinking of wax bubbles create a pattern of circulation called a convection current. |  |

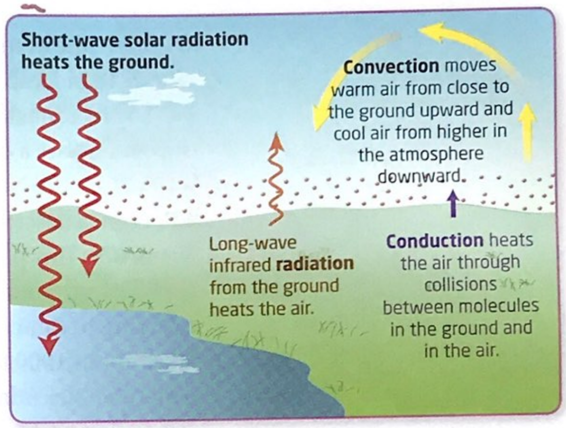
## Energy Transfer in the Atmosphere

Land and water gain thermal energy by absorbing the Sun's short-wave radiation. As Earth's surface grows warmer, it converts some of its thermal energy into long-wave radiation. Earth emits (gives off) the long-wave radiation into the atmosphere, where it is absorbed by gases such as water vapour and carbon dioxide. This process heats the air and is the basis of the greenhouse effect. The transfer of thermal energy through the atmosphere drives the feedback loops that regulate Earth's climate.

After land and water have absorbed energy from the Sun, their molecules move more rapidly. Some of these molecules collide with air molecules and transfer thermal energy to the atmosphere by conduction. Air receives thermal energy in this way until the air reaches a temperature close to that of the ground or water it is next to.

When the lowest layer of air grows warmer, it expands and rises. As the warm air rises, cooler air descends and replaces it. In this way, thermal energy is continuously transferred to other regions of the atmosphere by convection. **Figure 8.4** summarizes the three ways in which the atmosphere is heated.

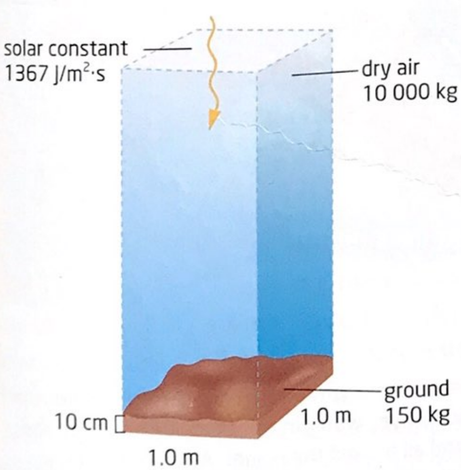
**Figure 8.4** Conduction, convection, and radiation transfer heat in Earth's atmosphere.




# Activity 8-2

## What Heats the Atmosphere?

How much solar energy reaches Earth's surface? In this activity, you will calculate the changes in temperature of the air and soil after a period of 1.0 h.




This column of dry air has a specific heat capacity of 1.00 J/g·°C and a cross-sectional area of 1.0 $m^2$. The specific heat capacity of soil is 0.85 J/g·°C. Diagram not to scale.

### Procedure

1. Calculate the amount of solar energy that reaches the column of air at the top of the atmosphere by multiplying the solar constant of 1367 J/$m^2$·s, by 3600 s.
2. If the atmosphere absorbs 19 percent of the solar energy, how much energy does it absorb in 1.0 h?
3. If Earth's surface absorbs 51 percent of the solar energy, how much energy does it absorb in 1.0 h?
4. Use the equation $\Delta T = \frac{\text{heat absorbed}}{(\text{mass}) \times (\text{heat capacity})}$ to find the change in temperature for the air and the soil.
5. Calculate the temperature changes of (a) the air and (b) the soil. Use the heat capacities and masses provided in the diagram. Convert units where necessary.

### Questions

1. Which heats Earth's atmosphere more: the Sun or Earth's surface?
2. How do you think your results would differ if the air were over water or ice instead of soil?

## Energy Transfer in the Oceans

The exchange of thermal energy between ocean currents and the atmosphere has a major influence on climates around the world and on climate change. In Chapter 7, you learned how uneven heating of the planet creates winds. Winds create currents of water that redistribute thermal energy at the ocean surface. Deeper, colder currents also move slowly along the ocean floor.

Like air masses, large masses of water can move vertically as well as horizontally. The density of water drives these vertical and horizontal movements. Cold water is dense, so it sinks to the ocean floor and pushes warmer water out of the way. The density of water also depends on salinity—the amount of dissolved salt the water contains. Salt water is denser than fresh water, so the salt water sinks.

The relationships between the temperature, salinity, and density of water create a continuous, twisting ocean current that mixes ocean water from the North Atlantic to the South Pacific oceans. This current, sometimes described as "the great ocean conveyor belt," is illustrated in **Figure 8.5**. This pattern of ocean circulation is known as **thermohaline circulation**, from the roots *thermo*, referring to temperature, and *haline*, referring to salt content. The entire journey of this ocean conveyor belt takes about 1000 to 1500 years. By mixing waters from the Arctic, the Antarctic, the Atlantic Ocean, and the Pacific Ocean, thermohaline circulation creates a global system of thermal energy distribution.

**thermohaline circulation**
a three-dimensional pattern of ocean circulation driven by wind, heat, and salinity that is an important component of the ocean-atmosphere climate system

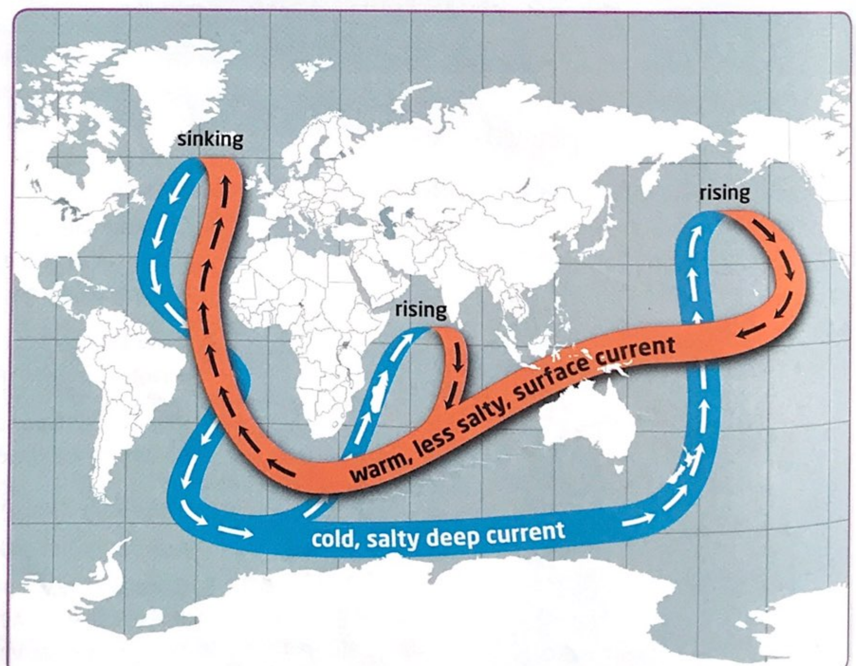



**Figure 8.5** The *great ocean conveyor belt* moves water in a continuous loop from the surface of the ocean to the ocean floor and all around the planet. As the water moves, it carries thermal energy around Earth's surface.

### Global Warming and Thermohaline Circulation

Climate scientists are concerned that global warming may disrupt the current pattern of thermohaline circulation by altering ocean salinity. Warming temperatures increase the rate at which ice melts, which can lead to an increase in fresh water that lowers salinity in northern oceans. At the same time, global warming increases the rate of evaporation, which can lead to an increase in salinity in tropical oceans. Thus, the polar water would become less dense and the tropical water would become more dense. As a result, the polar water would be less likely to sink toward the ocean floor, which is the main driving force for the thermohaline circulation system. Some studies suggest that these changes in water density will lead to a slowing of thermohaline circulation and will affect future transfer of thermal energy between the oceans and atmosphere.

Changes in ocean circulation patterns may have a negative effect on living things in the ocean by changing patterns of upwelling. Upwelling is the upward vertical motion of an ocean current. Upwelling brings nutrients from the sea floor into the surface currents. Areas where upwelling occurs are a rich source of food for marine organisms. If normal patterns of upwelling change, the survival of many marine species, such as the manta ray shown in **Figure 8.6**, may be at risk.

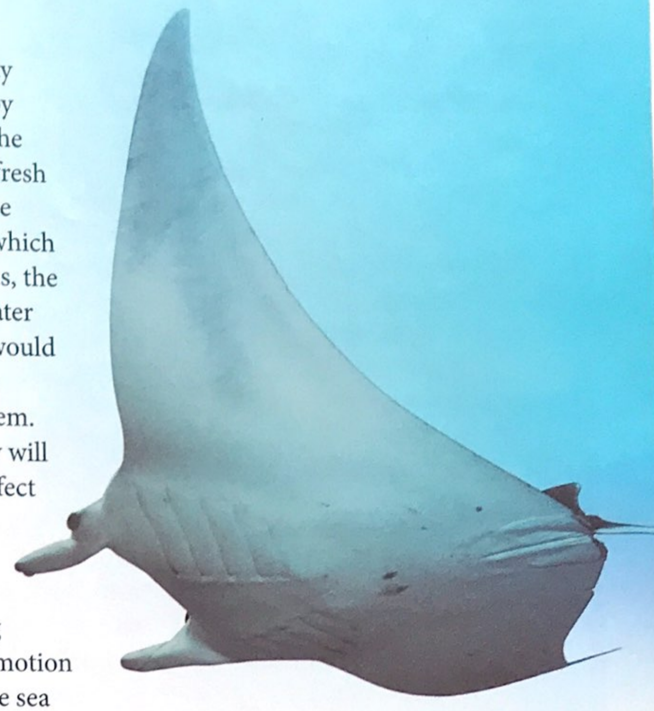


**Figure 8.6** Manta rays, which can grow to a size of almost 8 m across, feed on the microscopic organisms that bloom where upwelling occurs.

**Learning Check**

5. How is conduction different from convection?
6. The Sun provides energy to drive a number of processes on Earth. Identify one process driven by each type of heat transfer shown in **Figure 8.4**.
7. Compare the processes by which heat is transferred in the atmosphere and in the oceans.
8. Describe two methods by which heat could reach your hand if you held it above a hot stove.

### Energy Transfer, El Niño, and La Niña

The importance of winds and ocean currents to global climate is most clearly seen when normal patterns of the ocean–atmosphere system are disrupted. A major disruption of this system happens every few years in the tropical Pacific during the events known as El Niño and La Niña. Both El Niño and La Niña are "sea-surface temperature anomalies." In other words, during both El Niño and La Niña, the temperature of the ocean surface in the Southern Pacific Ocean changes. These changes have dramatic effects on the transfer of thermal energy and, therefore, on climate change. These events are described in **Figure 8.7** on the next two pages.

**Suggested Investigation**

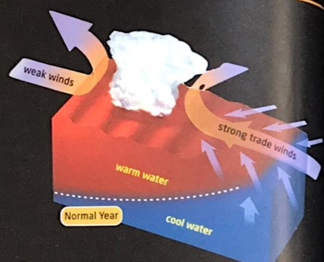
Real World Investigation 8-A, Recognizing the Effects of El Niño and La Niña on Southern Canada, on page 341

NATIONAL GEOGRAPHIC

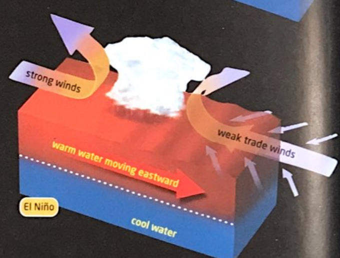
# VISUALIZING EL NIÑO AND LA NIÑA

**Figure 8.7**

Weather in Canada can be affected by changes that occur thousands of kilometres away. Out in the middle of the Pacific Ocean, periodic warming and cooling of a huge mass of seawater–phenomena known as El Niño and La Niña, respectively–can impact weather across North America. During normal years (right), when neither El Niño nor La Niña is in effect, strong winds usually keep warm surface waters contained in the western Pacific while cooler water wells up to the surface in the eastern Pacific.

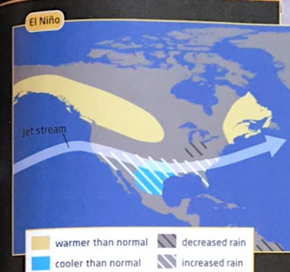



**EL NIÑO** During El Niño years, winds blowing west weaken and may even reverse. When this happens, warm waters in the western Pacific move eastward, preventing cold water from upwelling. This change can alter global weather patterns and trigger changes in precipitation and temperature across much of North America.



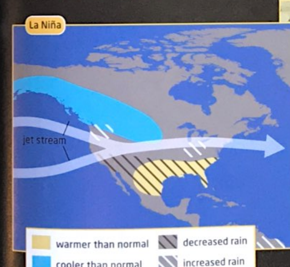


**LA NIÑA** During La Niña years, stronger-than-normal winds push warm Pacific waters farther west, toward Asia. Cold, deep-sea waters then well up strongly in the eastern Pacific, bringing cooler temperatures to northwestern North America.




Sun-warmed surface water spans the Pacific Ocean during El Niño years. Clouds form above the warm ocean, carrying moisture aloft. The jet stream, shown by the white arrow above, helps to bring some of this warm, moist air to the southern parts of North America.

▲ **LANDSLIDE** Heavy rains in California resulting from El Niño can lead to landslides. This upended house in Laguna Niguel, California, took a ride downhill during the El Niño storms of 1998.




During a typical La Niña year, warm ocean waters, clouds, and moisture are pushed away from North America. A weaker jet stream often brings cooler weather to the northern parts of the continent and hot, dry weather to southern areas.

▲ **PARCHED LAND** Some areas may experience drought conditions, like those that struck these cornfields during a La Niña summer.

## Earth's Energy Budget

You have learned that incoming solar energy is absorbed by the land, water, and atmosphere and heats the planet. However, nearly a third of the solar energy that reaches Earth is not absorbed at all. It is reflected back into space by aerosols (suspended particles, such as dust, chemicals, and bacteria), by clouds, and by Earth's surface. **Table 8.2** summarizes what happens to incoming solar energy that enters Earth's atmosphere.

What happens to the 70 percent of solar energy that is absorbed? The thermal energy warms the ground, water, and air, which makes the planet's surface habitable. The energy moves from the land and water to the air and back through various interactions of the land, oceans, and atmosphere. It must also eventually leave the system, or Earth would continue to get warmer and warmer. Evidence indicates that over millions of years, Earth's average temperature has been relatively stable. In order to maintain a stable average global temperature, incoming energy and outgoing energy must balance each other exactly. This balance is called Earth's **energy budget**. **Figure 8.8** summarizes the various incoming and outgoing paths of energy that make up Earth's balanced energy budget.

**Suggested Investigation**

Plan Your Own Investigation 8-B, Comparing Heat Absorption of Water and Soil, on page 343

**energy budget** a description of the total energy exchange within a system; a summary of how energy from the Sun enters, moves through, and leaves the Earth system

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**Table 8.2** Reflection and Absorption of Solar Radiation

| Reflection of Solar Radiation | | Absorption of Solar Radiation | |
|---|---|---|---|
| • Aerosols in atmosphere | 6% | • Gases in atmosphere | 16% |
| • Clouds | 20% | • Clouds | 3% |
| • Surface | 4% | • Surface | 51% |
| Total reflected | 30% | Total absorbed | 70% |

**Study Toolkit**

**Making Connections to Visuals** When examining **Figure 8.8**, remember to read the caption and labels. What process is illustrated by the wavy orange arrows in the lower right corner of the diagram?

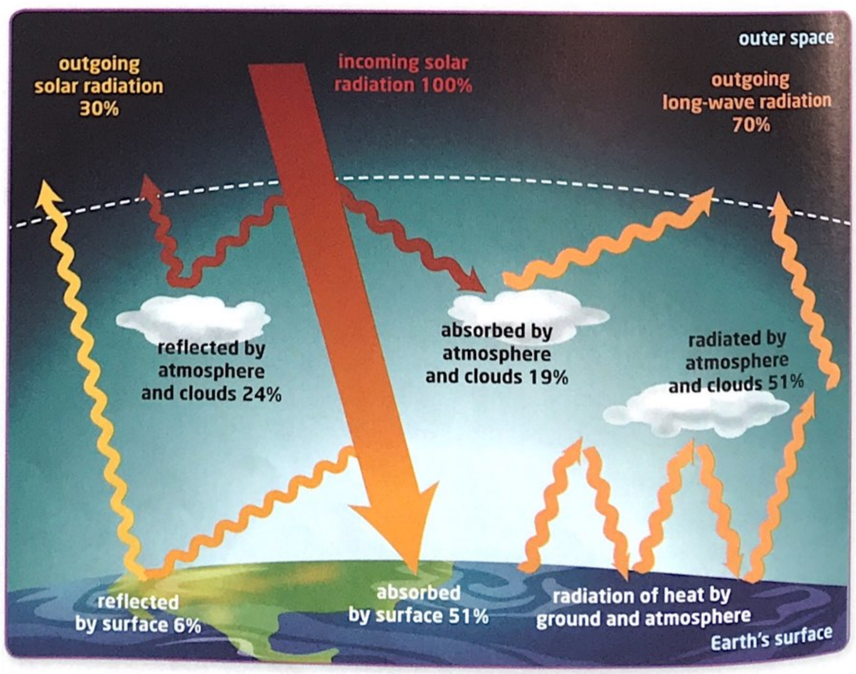



**Figure 8.8** This diagram shows what happens to solar radiation that enters Earth's atmosphere. Of the total incoming solar radiation, 30 percent is reflected and 70 percent is absorbed. All of the absorbed radiation is eventually radiated back into space.

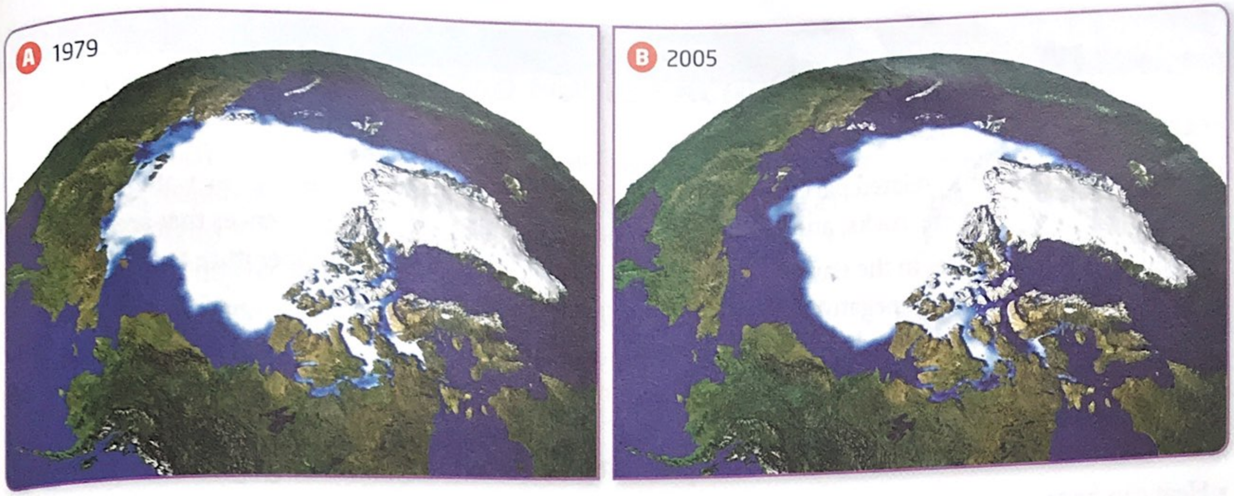



Figure 8.9 These satellite composite images show how the minimum area of the Arctic ocean that was covered by sea ice diminished between A 1979 and B 2005.

## Changing Albedo and the Energy Budget

The biggest influences on Earth's albedo come from clouds, snow, and ice. A change in any of these factors can produce a change in the amount of energy in the atmosphere. For example, melting of glaciers and polar icecaps, as shown in **Figure 8.9**, will decrease the albedo of the surface and may warm the planet. On the other hand, an increase in cloud cover may increase albedo and cool the planet.

Since the late 1990s, NASA satellites have been observing the upper atmosphere by using sensors known as CERES, which is short for Clouds and the Earth's Radiant Energy System. One purpose of this research is to track changes in Earth's energy budget by monitoring changes in the overall amount of energy Earth reflects or emits. CERES researchers found that snow and ice cover in the Arctic declined from 2002 to 2005, as shown in **Figure 8.10**. Surprisingly, however, the albedo did not change during that time.

Scientists think that melting sea ice exposed a larger water surface to evaporation. A greater concentration of water vapour in the air led to increased cloud cover. The increased amount of energy reflected by white clouds matched the decreased amount of energy reflected by ice, keeping the polar albedo unchanged. This process is an example of a natural, negative feedback loop that acts to slow climate change and maintain Earth's current global temperature.

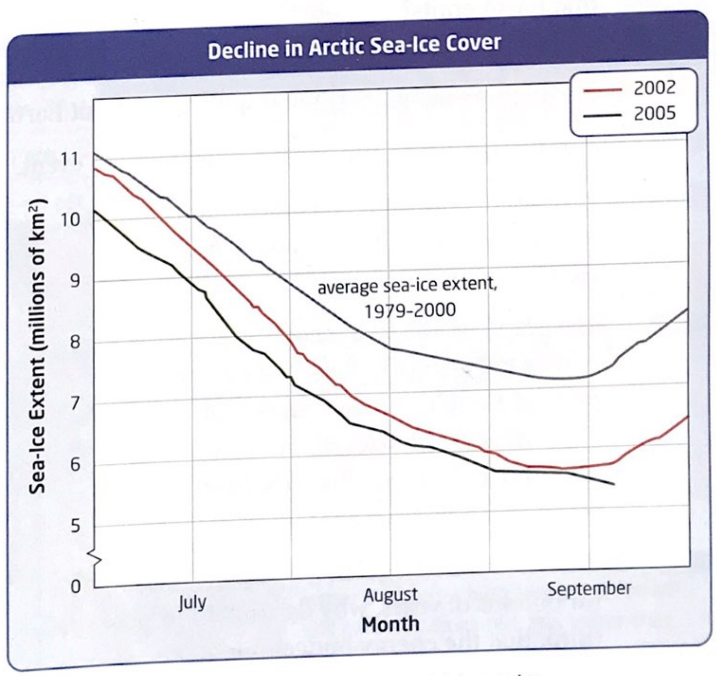



Figure 8.10 This graph shows the rate at which sea-ice cover above the Arctic Circle has declined over 20 years.

# 8.2 Greenhouse Gases and Human Activities

**Key Terms**

concentration
parts per million (ppm)
greenhouse gas
sink
ozone
chlorofluorocarbon (CFC)
anthropogenic greenhouse effect
global warming potential (GWP)

The greenhouse effect is an important part of Earth's energy budget. Without the greenhouse effect, Earth would be too cold to support life as we know it. But just as the absence of greenhouse gases in the atmosphere would result in a much colder Earth, so an increase in greenhouse gases will produce a warmer Earth. In this section, you will explore the roles of various greenhouse gases in climate change and discover why human production of greenhouse gases is a cause for concern.

## Concentrations of Gases in the Atmosphere

The measure of the amount of one substance within a mixture is called **concentration**. **Figure 8.11** shows an example of concentration in liquids. In 1958, researchers began to make frequent, regular measurements of concentrations of carbon dioxide ($CO_2$) in the atmosphere. These systematic measurements were the first direct indication that levels of greenhouse gases have been steadily increasing in recent decades.

The concentration of carbon dioxide in Earth's atmosphere increased from an average of about 315 parts per million in 1960 to about 370 parts per million in 2000. **Parts per million (ppm)** is a measure of the number of parts of one substance relative to one million parts of another substance. For example, 300 ppm of carbon dioxide in the atmosphere means that one million units of atmosphere contain 300 units of carbon dioxide plus 999 700 units of other atmospheric gases. **Table 8.3** describes units that are commonly used when measuring concentrations.

**concentration** the amount of a particular substance in a specific amount of another substance

**parts per million (ppm)** a unit of measurement that indicates the number of parts of a substance per million parts of another substance; for example, for salt water, 1000 ppm of salt means 1000 parts salt in 1 000 000 parts of pure water

**Table 8.3 Measurements of Concentration**

| Measurement | Example |
|---|---|
| Parts per million (ppm) | 1 mg per kg = 1 ppm |
| Parts per billion (ppb) | 1 mg per tonne = 1 ppb |
| Parts per trillion (ppt) | 1 mg per kilotonne = 1 ppt |

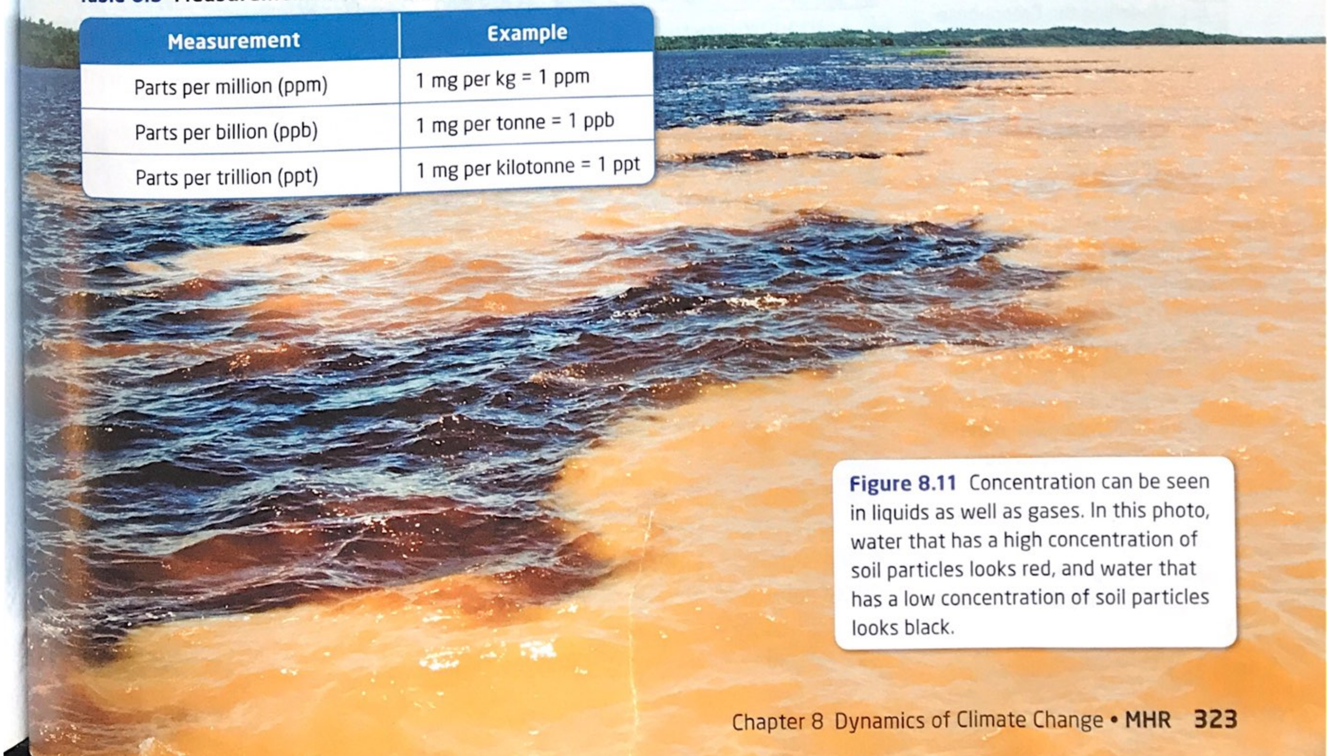


**Figure 8.11** Concentration can be seen in liquids as well as gases. In this photo, water that has a high concentration of soil particles looks red, and water that has a low concentration of soil particles looks black.

## Greenhouse Gases and Global Warming

**greenhouse gas** a gas in Earth's atmosphere that absorbs and prevents the escape of radiation as thermal energy; examples include carbon dioxide and methane

**sink** a process that removes greenhouse gases from the atmosphere

Ninety-nine percent of the atmosphere is made up of only two gases: nitrogen ($N_2$) and oxygen ($O_2$). However, neither of these two gases absorbs infrared radiation, and neither gas contributes to the greenhouse effect. Gases that absorb and re-emit infrared radiation are known as **greenhouse gases**. Molecules of the greenhouse gases all have three or more atoms each. Their molecular structure allows them to interact with radiation of different wavelengths. They produce a warming effect by absorbing and emitting energy. In **Figure 8.12** the gases highlighted in green show that carbon dioxide and water are the most abundant greenhouse gases in Earth's atmosphere.

The concentrations of many greenhouse gases have fluctuated throughout Earth's history. Processes that add greenhouse gases to the atmosphere are called *sources* of greenhouse gases. Processes that absorb greenhouse gases from the atmosphere are called **sinks**. Both sources and sinks can be natural or can be caused by human activities.

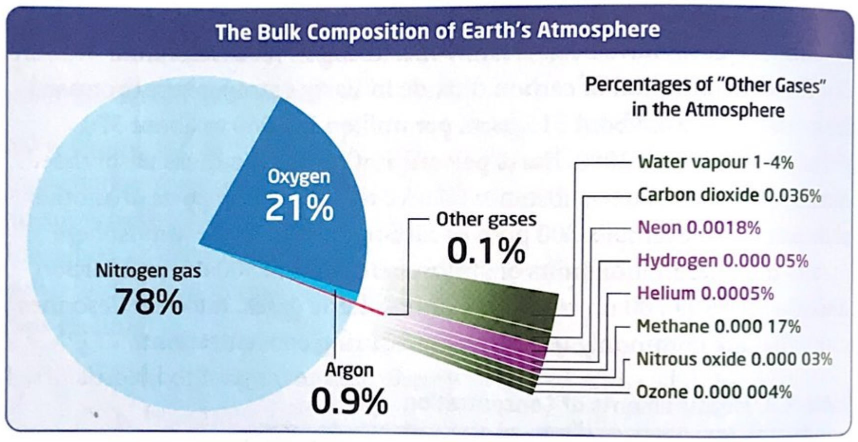



**Figure 8.12** This pie graph illustrates the percentages of different gases in the atmosphere. The greenhouse gases are highlighted in green.

**Suggested Investigation**

Problem-Solving Investigation 8-C, Modelling the Greenhouse Effect, on page 344

### Water Vapour as a Greenhouse Gas

**Figure 8.12** shows that water vapour is the most abundant greenhouse gas in Earth's atmosphere. Scientists estimate that water vapour is responsible for between 65 and 85 percent of the greenhouse effect. However, water vapour is not added to or removed from the atmosphere in significant amounts by human activities. The concentration of water vapour in the atmosphere at any particular time is directly related to one factor—temperature.

Water vapour enters the atmosphere by evaporation. The rate of evaporation depends on the temperature of the air and oceans. The higher the temperature is, the higher the rate of evaporation is. This relationship creates a positive feedback loop. A warmer atmosphere leads to an increase in the rate of evaporation; increased evaporation leads to more water vapour in the atmosphere; and more water vapour absorbs more thermal energy and produces a warmer atmosphere.

**Sense of scale**

On average, only one in every 2000 molecules in the atmosphere is a greenhouse gas and contributes to the greenhouse effect. Therefore, even a small increase in greenhouse gases can have a large effect on climate.

## Carbon Dioxide Sources and Sinks

The main natural source of atmospheric carbon dioxide ($CO_2$) is animal respiration. The main human source is combustion of fossil fuels. Carbon dioxide is removed from the atmosphere by plants when they convert it into stored carbon during photosynthesis. Because of this role, plants, such as those shown in **Figure 8.13**, are carbon sinks. Deforestation increases the amount of carbon dioxide in the atmosphere by clearing large areas of trees, which are important carbon sinks.

As you learned in Section 8.1, phytoplankton in the oceans also play a major role in the absorption and storage of carbon dioxide. Scientists estimate that the oceans currently absorb between 30 and 50 percent of the carbon dioxide produced by the burning of fossil fuels.

**Figure 8.13** Canada's forests, such as this one in northern Alberta, form an important carbon sink. They help to remove carbon dioxide from the atmosphere.

## Interaction of Water Vapour and Carbon Dioxide

Because carbon dioxide and water vapour are both greenhouse gases, the effect of one is added to the effect of the other to form a positive feedback loop. For example, some scientists estimate that a doubling of carbon dioxide in the atmosphere would, by itself, warm Earth by about 1°C. However, this amount of warming would increase the rate of evaporation, and thus increase the amount of water vapour in the atmosphere. The additional warming effect of the water vapour would double the temperature increase to about 2°C. When other feedbacks are also added, such as a lowered albedo due to melting ice, the total warming from a doubling of carbon dioxide is raised to about 3°C.

The amplifying effect of water vapour also applies to atmospheric cooling. For example, in 1991 a massive eruption of Mount Pinatubo in the Philippines sent huge amounts of ash and greenhouse gases into the atmosphere, as shown in **Figure 8.14**. The particles suspended high in the atmosphere increased Earth's albedo, reflecting sunlight and cooling the planet for a period of several years. The cooling led to atmospheric drying, which caused the global temperature to drop even further.

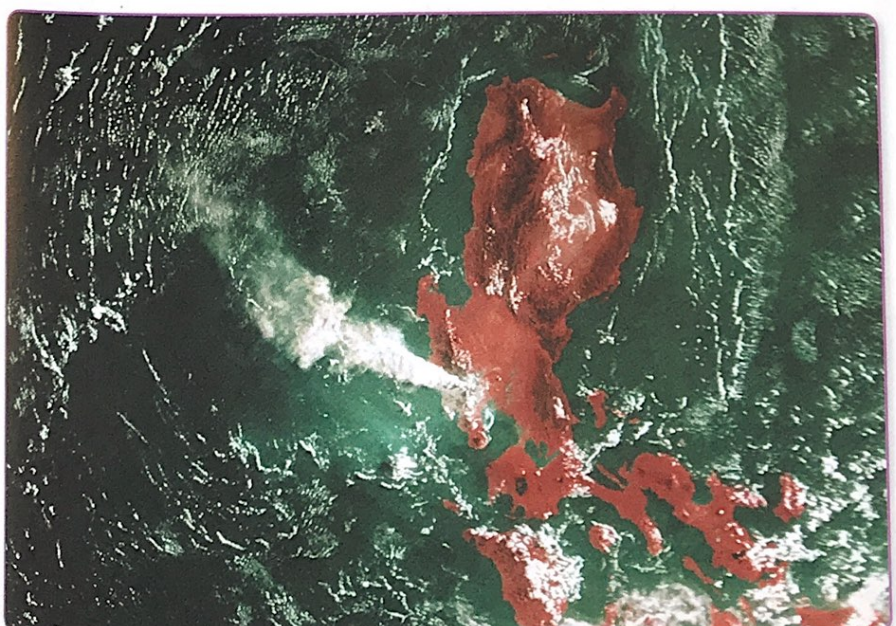


**Figure 8.14** The white and grey plume in this satellite image is the column of ash and dust thrown into the air during the 1991 eruption of Mount Pinatubo in the Philippines. The brown area is the island of Luzon, which is about 225 km wide. This eruption cooled Earth's global average temperature by as much as 0.2°C for five years.

## Sources of Methane

Methane ($CH_4$) is produced by bacteria that break down waste matter in oxygen-free environments. A major natural source of methane is wetlands (bogs and swamps), where large amounts of organic material decompose under water. Like wetlands, rice paddies also produce methane. Termites and cattle both produce methane during their normal digestive processes. Additional human sources include decomposing garbage in landfills, processing of coal and natural gas, and tanks of liquid manure from livestock production.

Scientists have suggested some unique ways to capture, or sequester, carbon from methane. One suggestion involves having cattle wear backpacks to capture the methane released from their digestive tract, as you saw at the beginning of this chapter. This methane could be collected for use as a fuel. Other scientists suggest that simply feeding cattle clover and alfalfa rather than corn and grain will reduce methane emissions by those animals by 25 percent. Some environmental activists have proposed a simple switch in human diets. These groups have started a campaign to convince people to stop eating beef and start eating camels and kangaroos, such as those shown in **Figure 8.15**. The digestive tracts of these animals do not produce the same greenhouse gases that the stomachs of cattle and sheep do.

### Learning Check

1. Why do scientists need to measure greenhouse gases in parts per million?
2. What does the word *sink* mean when used in the phrase *carbon sink*?
3. Create a flowchart that illustrates how water vapour and carbon dioxide interact to form a positive feedback loop.
4. What two human activities might cause methane to accumulate in the atmosphere?

**Figure 8.15** Kangaroo meat is produced in Australia and New Zealand and shipped to markets around the world. The digestive systems of these animals produce almost no methane.

### Natural and Anthropogenic Sources of Nitrous Oxide

Most natural production of nitrous oxide ($N_2O$) comes from damp tropical soils and the oceans. Nitrous oxide also forms when nitrogen-rich compounds are broken down by bacteria. Human sources include chemical fertilizers, manure and sewage treatment, and vehicle exhausts.

### Stratospheric Ozone: Earth's "Sunscreen"

Another greenhouse gas, called **ozone** ($O_3$), is composed of three atoms of oxygen. Ozone occurs naturally in the upper atmosphere at altitudes between 10 and 50 km. The ozone layer blocks harmful ultraviolet radiation from the Sun, preventing it from reaching Earth's surface. Ultraviolet radiation can cause skin cancers in humans and genetic damage in other organisms.

**ozone** a greenhouse gas that is composed of three atoms of oxygen; it is commonly found in a concentrated layer in the stratosphere

### Ozone Depletion and the Ozone "Hole"

Since the 1970s, there has been a slow, steady decline in the total volume of ozone in the stratosphere. Beginning during the same period, an ozone "hole" has appeared over the Antarctic each year from September to December. The Antarctic ozone hole is shown in **Figure 8.16**. The ozone hole is not actually a hole; it is a large region in which ozone concentration is declining, which creates a thinning area in the stratospheric ozone layer. In this region, ozone levels have fallen to as little as one third of the concentration before 1970.

The main cause of ozone depletion is the addition to the atmosphere of human-made gases that contain chlorine. The depletion of the ozone layer results in an increase in the amount of ultraviolet light that reaches Earth's surface. However, scientists are also concerned by a positive feedback loop that results from the breakdown of stratospheric ozone. Because ozone acts as a greenhouse gas, reduced ozone levels will cause the stratosphere to cool. This cooling could lead to the formation of polar stratospheric clouds (PSCs). Within these clouds, chemical reactions result in the formation of free chlorine. The chlorine reacts with ozone and breaks apart the ozone, further reducing the amount of ozone in the stratosphere.

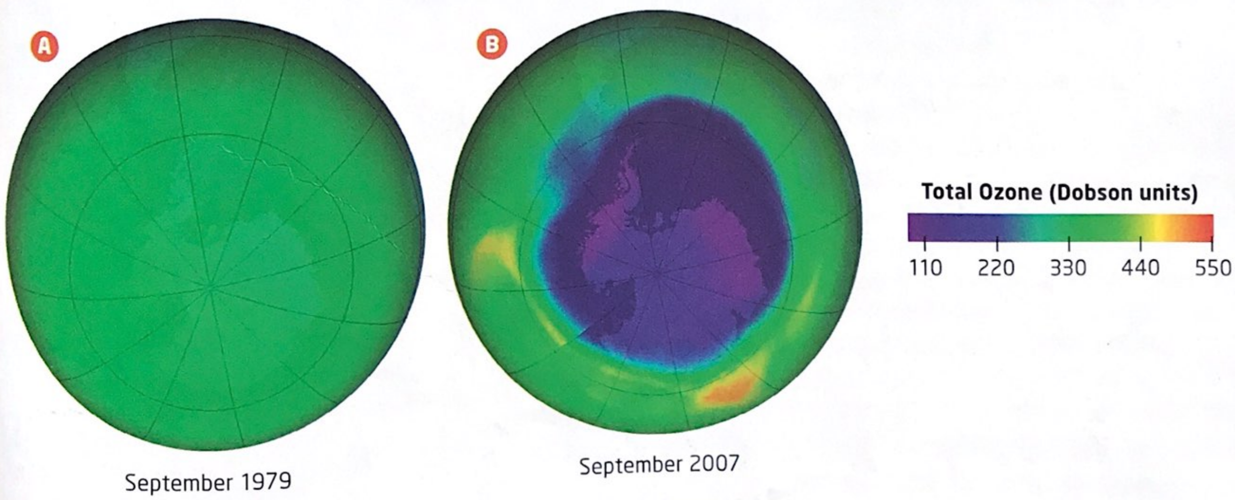



**Figure 8.16** As the legend on the right shows, the concentration of ozone over Antarctica decreased between **A** 1979 and **B** 2007. The largest measurement recorded for the size of the ozone hole is 29.5 million $km^2$–larger than the size of North America.

## Ground-Level Ozone

Ozone also occurs in the atmosphere near ground level as a smog-forming pollutant. This ozone is produced by a chemical reaction between sunlight and chemicals in vehicle exhaust—mainly hydrocarbons and nitrogen oxides—as shown in **Figure 8.17**. The greatest concentrations of polluting ozone are found over cities, but ozone can also be blown many kilometres from its source by winds. Ground-level ozone can cause damage to the lungs and heart, and produces cracks in rubber and plastic products. In addition, this greenhouse gas can trap thermal energy close to Earth's surface, which could contribute to global warming.

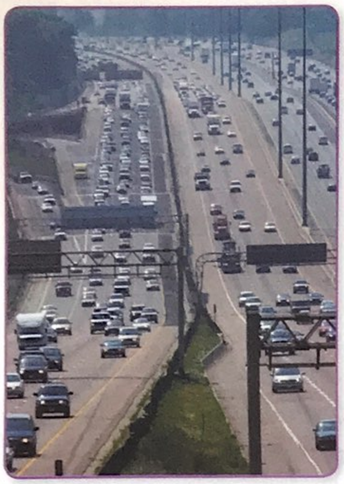


**Figure 8.17** Vehicle exhaust is a direct source of greenhouse gases. It is also an indirect source of ground-level ozone.

## Halocarbons

The other greenhouse gases you have learned about have natural sources as well as being produced by humans. However, halocarbons are formed only by industrial processes—no natural source of these powerful greenhouse gases exists. *Halocarbons* are a large group of chemicals formed from carbon and one or more halogens, such as chlorine, fluorine, or iodine. Halocarbon molecules are more efficient than carbon dioxide at absorbing infrared radiation. Some of them are very stable and can remain in the atmosphere for thousands of years before they are broken down.

The best-known halocarbons are **chlorofluorocarbons** (CFCs). Their main use is as solvents, cleaners, and coolants in refrigerators and air conditioners. As well as absorbing infrared radiation, CFCs break apart ozone molecules in the upper atmosphere. This reaction has led to depletion of the ozone layer and the formation of the ozone hole over the Antarctic. The use of CFCs has been banned in most developed nations since 1987. Because CFCs remain in the atmosphere for so long, however, they continue to damage the ozone layer.

**chlorofluorocarbon (CFC)** a human-made chemical compound that contains chlorine, fluorine, and carbon; when released into the atmosphere may cause depletion of the ozone layer

## Making a Difference

P.J. Partington thinks people interested in working for the environment should just "jump right into it." That's what he did. He started volunteering with the Canadian Youth Climate Coalition after a friend invited him to the coalition's first meeting. By the end of the meeting, P.J. was co-ordinator of the coalition's policy group. A month later he was helping to organize the youth delegation to the 2006 United Nations climate negotiations in Nairobi, Kenya. Soon after, P.J. began working for TakingITGlobal, an international, youth-led organization based in Toronto. In 2008, he was responsible for the Canadian Youth Delegation to the UN climate negotiations in Poznan, Poland.

P.J. studied environmental policy at the London School of Economics and Political Science in the United Kingdom. He is now a climate change policy analyst at The Pembina Institute.

**What local environmental group(s) could you volunteer to assist? What value do you see in "just jumping in"?**

## The Anthropogenic Greenhouse Effect

Levels of carbon dioxide in the atmosphere have varied widely over the past 800 000 years. However, human activities have significantly increased the quantities of carbon dioxide and other greenhouse gases since about 1750, as shown in **Table 8.4**. Most of the increase in $CO_2$ has come from the burning of fossil fuels. Deforestation and agriculture have added carbon dioxide, methane, and nitrous oxide. Industrial activities have produced ground-level ozone, CFCs, and other pollutants that affect the climate system. The increase in global average temperature since the 1960s is likely due mainly to the increase in greenhouse gases produced by human activities. This result is known as the **anthropogenic greenhouse effect**.

**anthropogenic greenhouse effect** the increased capacity of the atmosphere to absorb and prevent the escape of thermal energy because of an increase in greenhouse gases introduced by human activities

**Table 8.4 Greenhouse Gas Concentration Before and After the Industrial Revolution**

| Greenhouse Gas | Level Before 1750 | Current Level | Increase Since 1750 |
|---|---|---|---|
| carbon dioxide | 280 ppm | 384 ppm | 104 ppm |
| methane | 700 ppb | 1745 ppb | 1045 ppb |
| nitrous oxide | 270 ppb | 314 ppb | 44 ppb |
| CFCs | 0 ppt | 533 ppt | 553 ppt |

# Activity 8-3

## Graphing Changes in Carbon Dioxide

What effect has the burning of fossil fuels had on global temperature? In this activity, you will track the amount of carbon dioxide in the atmosphere and the global temperature increase over time.

### Materials

- graph paper
- coloured pencils or pens

### Procedure

1. Use the data from the table to make the following three line graphs: year versus industrial carbon dioxide emissions, year versus carbon dioxide concentration in the atmosphere, year versus temperature increase since 1861.
2. Using a different colour, extend each of the line graphs to 2020. For help in creating your graph, refer to Math Skills Toolkit 3 on pages 555–558.

### Questions

1. Describe the shape of each graph.
2. Describe the trends since 1861 for industrial carbon dioxide emissions, carbon dioxide concentration, and average global temperature increase.
3. "Human combustion of fossil fuels has resulted in rising global temperatures." How do the results of this activity affect your opinion about this statement?

**Changes in Carbon Dioxide and Average Global Temperature**

| Year | Industrial $CO_2$ Emissions (gigatonnes)* | $CO_2$ Concentration (ppm per volume) | Temperature Increase Since 1861 (°C) |
|---|---|---|---|
| 1861 | 0.67 | 285 | 0.00 |
| 1880 | 1.15 | 292 | 0.00 |
| 1900 | 2.63 | 298 | 0.05 |
| 1920 | 3.42 | 303 | 0.29 |
| 1940 | 4.95 | 307 | 0.46 |
| 1960 | 9.98 | 318 | 0.35 |
| 1980 | 20.72 | 340 | 0.41 |
| 2000 | 23.42 | 365 | 0.63 |

Source: Carbon Dioxide Information Analysis Center (CDIAC)
* 1 gigatonne = 1 billion tonnes

Go to **scienceontario** to find out more

**Learning Check**

5. Identify five sources of nitrous oxide.
6. Use the data in **Table 8.4** to calculate the percentage increase in greenhouse gases since the Industrial Revolution. How is this increase related to climate change?
7. How do halocarbons and ozone interact to change the upper atmosphere?
8. Summarize the sources of the greenhouse gases that contribute to the anthropogenic greenhouse effect.

## Comparing the Global Warming Potential of Greenhouse Gases

Which greenhouse gases should we be most concerned about? The contribution of a particular greenhouse gas to global warming depends on three things:

- the concentration of the gas in the atmosphere
- the ability of the gas to absorb heat
- the length of time the gas remains in the atmosphere

**global warming potential (GWP)** the ability of a substance to warm the atmosphere by absorbing thermal energy

To help compare the relative impact of one greenhouse gas with that of another, scientists use a measure called **global warming potential** (GWP). Carbon dioxide is assigned a GWP of 1. The warming effect of every other greenhouse gas is compared with the warming effect of the same mass of carbon dioxide over a specified period of time. **Table 8.5** compares the GWP of four major greenhouse gases. The table shows that methane is broken down in the atmosphere after about 12 years. However, since methane is able to absorb and emit more heat than carbon dioxide does, methane has a higher GWP.

Halocarbons account for less than 2 percent of all greenhouse gas emissions produced by human activities. But because they remain in the atmosphere almost indefinitely, concentrations of these gases will increase as long as emissions continue. Their ability to trap heat in the atmosphere over time can be thousands of times greater than that of carbon dioxide. Therefore, these gases are considered high GWP gases. Fortunately, many nations have banned the production and use of CFCs.

**Table 8.5** Global Warming Potential of Major Greenhouse Gases

| Greenhouse Gas | Chemical Formula | Atmospheric Lifetime (years) | Global Warming Potential (GWP) over 100 Years |
|---|---|---|---|
| carbon dioxide | $CO_2$ | variable | 1 |
| methane | $CH_4$ | 12 | 25 |
| nitrous oxide | $N_2O$ | 115 | 298 |
| chlorofluorocarbons (CFCs) | various | indefinite | 4750-5310 |

## Ways to Reduce Greenhouse Gas Production

Canada ranks among the top 10 nations in the world for the amount of greenhouse gases produced per person. You play a part in adding greenhouse gases to the atmosphere, even if you do not drive a vehicle. Almost one fifth of Canada's total greenhouse emissions come from people's homes. Here are some ways that you can help to reduce greenhouse gas production at home.

Figure 8.18 Simply replacing incandescent light bulbs with fluorescent bulbs can prevent thousands of kilograms of carbon dioxide from ever being emitted.

**Conserve electricity** Where do the electricity supplies to your home and school come from? Power plants that burn coal and other fossil fuels to generate electricity are a source of greenhouse gases. You can reduce emissions from power plants by reducing your use of electricity. For example, you can reduce emissions by using more energy-efficient light bulbs and appliances. **Figure 8.18** shows an energy-efficient compact fluorescent light bulb. You can also reduce your impact by the simple act of conserving energy. For example, turn off lights, televisions, computers, and other appliances when you are not using them.

**Improve home-heating efficiency** Most home furnaces and boilers burn oil or natural gas. Greenhouse gas production can be reduced by lowering the thermostat setting and improving insulation. Modern furnaces have improved energy efficiency compared with older furnaces, and they release lower amounts of greenhouse gases. Many building standards and codes are related to the energy efficiency of new structures. Some local and national programs also exist to help retrofit older buildings to make them more energy efficient.

**Reduce, re-use, and recycle** How does the garbage you throw out each week add to greenhouse gas emissions? First, producing all of the products you buy and use took energy. If you re-use and recycle items instead of throwing them out, as shown in **Figure 8.19**, you reduce the demand for energy to make more products. Second, garbage buried in a landfill produces methane, and garbage burned in an incinerator produces carbon dioxide. The less garbage you produce, the fewer greenhouse gases you produce.


Figure 8.19 Recycling programs help to reduce the amount of trash in landfills and the amount of greenhouse gases produced by companies that manufacture product packaging.

# 8.3 Cycling of Matter and the Climate System

**Key Terms**
biogeochemical cycle
store
global carbon budget
nitrogen fixation

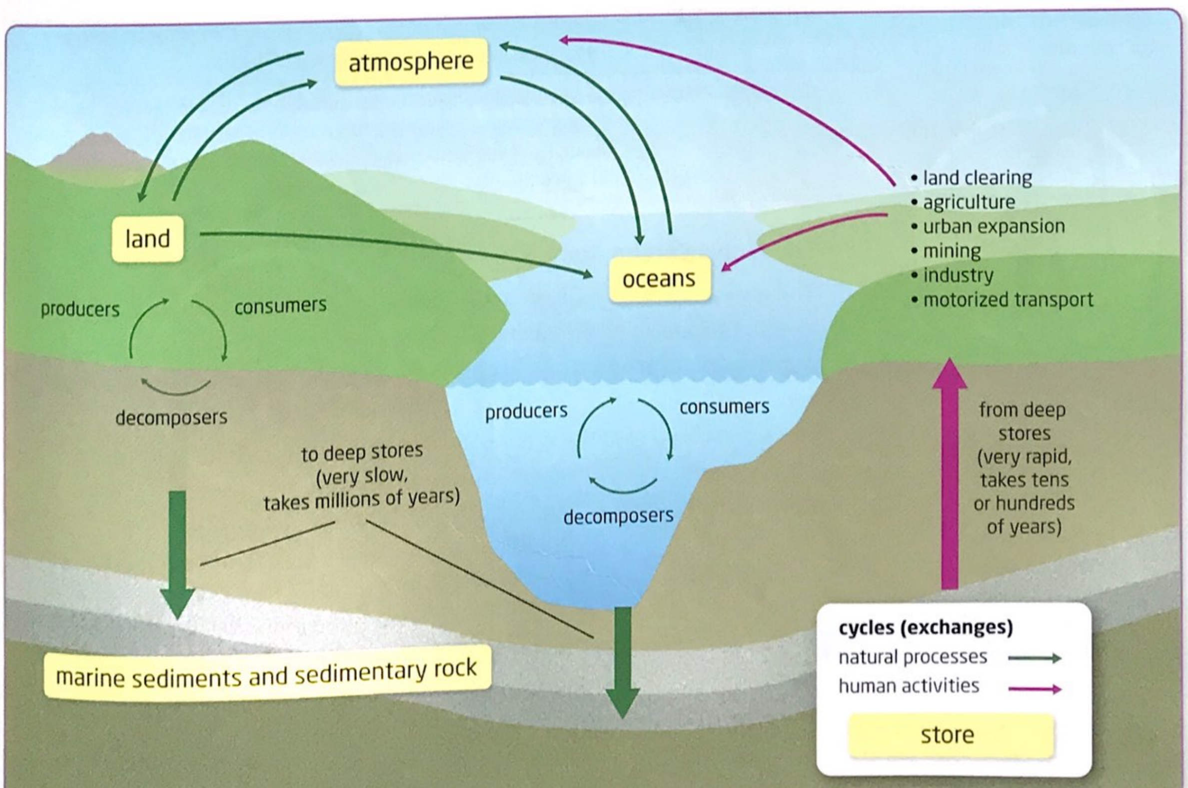
You have learned that Earth and its atmosphere behave as a closed system. This system contains a fixed amount of matter that cannot increase or decrease. However, you also know that the concentration of greenhouse gases in the atmosphere has been increasing. Where did these additional gases come from? The answer lies in natural cycles that transfer matter continuously among the atmosphere, land, water, and living things. An increase in matter in one part of the system is balanced by a decrease in matter in another part of the system. This circulation of matter is known as a **biogeochemical cycle**.

In a typical biogeochemical cycle, materials remain for a short or long period of time in part of the cycle before passing on to the next part of the cycle, as shown in **Figure 8.20**. Places where matter is stored for longer periods are known as **stores**. Stores are also commonly referred to as *reservoirs*. Usually, the cycle is in balance because the amount of material flowing into a store, such as the atmosphere, is nearly the same as the amount flowing out of the store. Human activities, such as coal mining and oil drilling, alter the balance of natural cycles by rapidly releasing large amounts of materials from stores, as illustrated in **Figure 8.20**. For example, burning fossil fuels releases carbon and nitrogen from stores underground and transfers them into the atmosphere. Disruptions of the carbon cycle and the nitrogen cycle by human activities have been a significant cause of recent climate change.

**biogeochemical cycle** a natural process that exchanges matter and energy between the abiotic environment to the biotic environment and back

**store** a part of a biogeochemical cycle in which matter or energy accumulates; also called a reservoir

**Figure 8.20** Human activities can disrupt natural cycles. The purple arrows indicate human activities that affect natural processes, which are illustrated by the green arrows.



## The Carbon Cycle and Climate Change

You already know that carbon dioxide is added naturally to the atmosphere by respiration and is removed from the atmosphere by photosynthesis. However, this balanced exchange of carbon compounds between living things and the atmosphere forms only one small part of the planet-wide carbon cycle, as shown in **Figure 8.21**. Carbon compounds are found in several stores on Earth, as shown in **Table 8.6**. These stores differ greatly in size and in the average length of time that carbon remains in each form. As you learned in Section 8.2, the gases carbon dioxide and methane contain carbon. Some rocks, such as limestone, and sediments on the sea floor contain solid forms of carbon, as do the bodies of living things. Carbon also exists as a solid in coal and as a liquid in oil. Carbon changes form as it moves through the carbon cycle; it can be a solid, a liquid, or a gas.

**Study Toolkit**

**Word Parts** Break the word *biogeochemical* into parts. Determine what each word part means. Then combine the meanings of the word parts to infer the definition of the whole word.

**Table 8.6** Major Stores of Carbon on Earth

| Store | Estimated amount of carbon (gigatonnes) | Residence time |
|---|---|---|
| Marine sediments and sedimentary rock | 68 000 000 to100 000 000 | Carbon is trapped in these rocks for millions or billions of years. |
| Oceans | 39 000 | Much of the dissolved carbon may remain in the ocean for 500 to 1000 years as the cold, slow-moving, deep currents move along the ocean floor. |
| Fossil fuels (coal, oil, and gas) | 3 300 | Converted into fossil fuels, the carbon can not cycle back into the atmosphere or into living things for hundreds of millions of years. |
| Vegetation, soil, and organic matter | 2 115 | Studies indicate that carbon stays in living things for an average of 5 years and in soil for approximately 25 years. |
| Atmosphere | 750 | Carbon dioxide remains in the atmosphere for a long time—between 50 and 500 years. Methane has a short atmospheric lifetime of only about 12 years. Nitrous oxide remains in the atmosphere for about 115 years. |

### The Global Carbon Budget

The **global carbon budget** is a way of describing the exchanges of carbon in different parts of the carbon cycle. In a balanced carbon budget, the rate at which carbon dioxide enters the atmosphere is approximately equal to the rate at which it leaves the atmosphere. As **Figure 8.21** shows, carbon moves from the atmosphere into the other stores mainly by photosynthesis and by dissolving in the ocean. Carbon is released into the atmosphere when carbon dioxide is released from vegetation, soil, and organic matter by the respiration of plants and animals, and by the decomposition of dead matter by microorganisms. Carbon dioxide is released from fossil fuels by combustion. In the ocean, carbon dioxide comes out of solution from warmer surface waters. Carbon dioxide is released from sedimentary rock when limestone breaks down. Volcanic eruptions also release carbon dioxide into the atmosphere.

**global carbon budget** the relative amounts of carbon in different stores; also an accounting of the exchanges (incomes and losses) of carbon between the stores of the carbon cycle


**Figure 8.21** The carbon cycle involves the movement of carbon between the oceans, atmosphere, rock, and living things on Earth. Changes in the balance of carbon in different carbon stores can result in climate change.

# Activity 8-4

## Modelling Carbon Stores

Which carbon store holds the most carbon? In this activity, you will use sticky notes to represent carbon that is stored in various stores.

### Materials

- 10 yellow sticky notes
- 1 pink sticky note
- 1 blue sticky note
- 5 photographs

### Rules

1 blue sticky note = 50 yellow sticky notes
1 pink sticky note = 100 000 yellow sticky notes

### Procedure

1. Use the list of stores in the table to identify the carbon stores represented by each photograph. Identify the form that carbon takes in each store. Record your answers on each photograph.
2. Arrange the photographs in a circle on a table.
3. Use the information in the table to identify the number of sticky notes that belong in each store. Place the proper number of sticky notes on each photograph.

### Questions

1. Which store holds the most carbon? How long does carbon remain in that store?
2. What factors affect how much carbon is in the fossil-fuels store? How would you model the recent change in the rate at which carbon remains in that store?
3. How does the thermohaline circulation pattern in the ocean affect the amount of carbon in the ocean?
4. Can you see any relationship between the amount of carbon in a store and the length of time that the carbon remains in the store?

**Major Stores of Carbon on Earth Relative to the Atmosphere**

| Store | Relative Amount in Store |
|---|---|
| Rock and sediments | 91 000–130 000 |
| Oceans | 52 |
| Fossil fuels | 4 |
| Vegetation, soil, and organic matter | 3 |
| Atmosphere | 1 |

### How Human Activities Affect the Carbon Cycle

Human activities alter the carbon cycle by changing the relative amounts of carbon in each store and the length of time that carbon remains in each store. For example, carbon compounds are stored as fossil fuels for hundreds of millions of years. When humans burn fossil fuels, these carbon compounds are released into the atmosphere in much larger amounts and in a much shorter time period than they would be naturally. As a result, carbon compounds build up in the atmosphere, which leads to global warming.

When the amount of carbon dioxide in the atmosphere increases, the oceans begin to absorb additional carbon dioxide from the atmosphere. This process is part of a natural negative feedback loop that acts to maintain the amount of carbon dioxide in the atmosphere and, thus, the global average temperature. However, this absorption of carbon dioxide by the oceans causes the oceans to become warmer and more acidic, and their ability to absorb carbon dioxide is reduced. This imbalance could result in a positive feedback loop that accelerates the rate of global warming.

### Learning Check

1. What is the relationship between the terms *biogeochemical cycle* and *store*?
2. Identify the five carbon stores described in **Figure 8.21**.
3. Draw a time line that illustrates the relative amounts of time that a single carbon atom would spend in each reservoir if it were traced through the entire carbon cycle.
4. How does driving to school upset the global carbon budget?

## The Nitrogen Cycle and Climate Change

Eighty percent of the atmosphere consists of nitrogen gas ($N_2$). In this form, nitrogen is very stable and non-reactive. However, nitrogen is used by living things in many physical processes. Before nitrogen can enter other parts of its cycle and be used by living things, it must be converted into a chemically reactive form such as ammonium ($NH_4^+$) or nitrate ($NO_3^-$). In these forms, and in gases such as nitrous oxide ($N_2O$), nitrogen plays a significant role in climate change.

### Nitrogen Fixation

Because nitrogen gas is very stable, it takes large amounts of energy to split apart each molecule. The process that converts nitrogen gas into compounds that contain nitrate or ammonium is called **nitrogen fixation**. This process transfers nitrogen from the atmosphere to the land, water, and organisms. Three routes are responsible for most nitrogen fixation on the planet. The first two are natural and are shown in **Figure 8.22**. The third is exclusively a result of human activity.

**nitrogen fixation** the process by which atmospheric nitrogen is changed into forms that can be used by plants and other organisms

In the early 20th century, a new industrial method called the Haber–Bosch process created a revolution in agriculture and had a major impact on the nitrogen cycle. The process uses high temperatures and pressures to combine nitrogen from the atmosphere with hydrogen to make ammonia ($NH_3$). The ammonia is used to manufacture nitrate fertilizers.

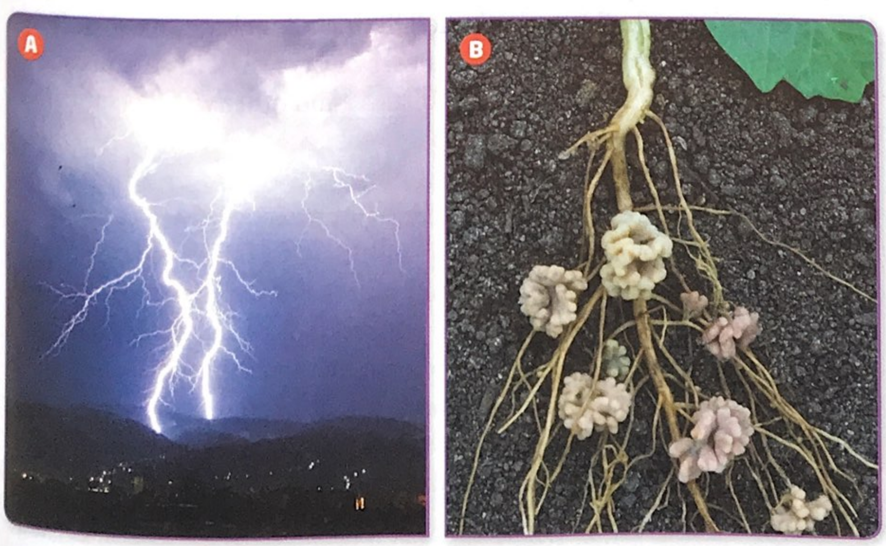



**Figure 8.22** **A** The extreme temperature at the edge of a lightning bolt allows nitrogen gas to bond with oxygen to form nitrates that living plants can use. **B** Bacteria in the roots of a pea plant convert nitrogen from the soil into a form of nitrogen that the plant can use.

## How Humans Affect the Nitrogen Cycle

As shown in **Figure 8.23**, human activities have an impact on the functioning of the nitrogen cycle. In general, these human activities can be classified into three categories: addition of nitrogen to the land, addition of nitrogen to water, and addition of nitrogen to the atmosphere.

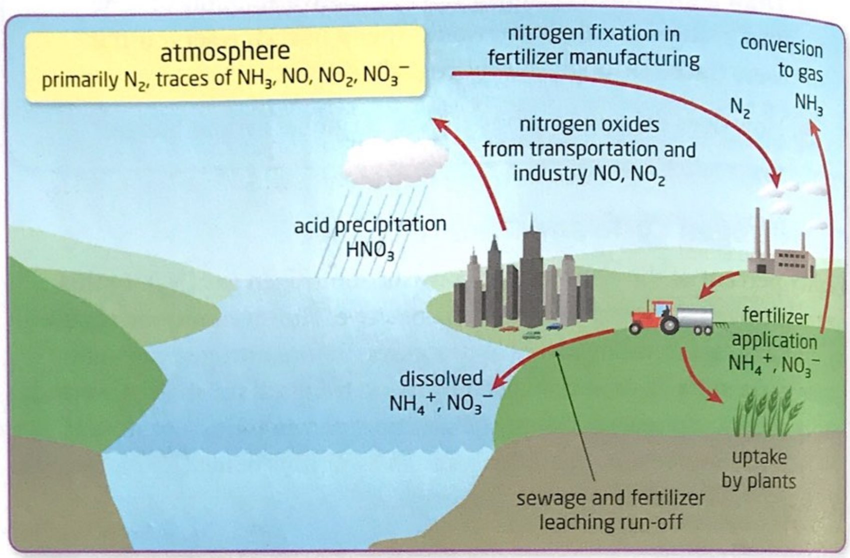



**Figure 8.23** Human activities, such as industry and agriculture, alter the nitrogen cycle.

### The Effect of Agriculture on the Nitrogen Cycle

Experts estimate that agricultural activities now account for as much as one half of all nitrogen fixation on Earth. Modern agriculture involves the use of manufactured fertilizers over a large area. Industrial processes manufacture over 100 million tonnes of nitrogen fertilizer per year. This fertilizer helps to grow crops that sustain about one third of Earth's population. But while artificial fertilizer helps to reduce starvation in some parts of the world, its overuse contributes to many environmental problems, including climate change.

### Water Pollution and the Nitrogen Cycle

When farmers add more fertilizer to fields than their crops can take up, the excess nitrogen builds up in the soil. Rain and melting snow wash the nitrogen from the soil and carry it to nearby waterways. In streams and lakes, the nitrates cause rapid growth of algae and other water plants. Algal blooms clog waterways and deprive other aquatic organisms of oxygen. Nitrates in both surface water and ground water can also cause harm to human health, because nitrates in drinking water may lead to cancer.

At the mouths of rivers, massive quantities of fertilizers, sewage, and livestock waste pour into the ocean, creating *dead zones*. In these areas, algal blooms have created huge masses of dead algae. As the algae decompose, oxygen in the water is used up, making these areas unfit for all organisms that require oxygen. About 150 dead zones currently exist in the world's oceans, covering hundreds of thousands of square kilometres. In Canada, this problem is most noticeable in Québec and in Lake Winnipeg in Manitoba.

### How Air Pollution Affects the Nitrogen Cycle

If you have ever been downwind of a large livestock farm, you may have caught a whiff of ammonia ($NH_3$) in the air. Ammonia reacts with other compounds in the air to form *smog*. Agriculture is also a source of the greenhouse gas nitrous oxide ($N_2O$).

Millions of tonnes of nitrogen are added to the atmosphere every year from the combustion of fossil fuels in power plants and vehicles. Nitric oxide (NO) from vehicle exhaust is a common ingredient in smog and ground-level ozone. Reactive forms of nitrogen from these sources dissolve in moisture in the atmosphere to form nitric acid ($HNO_3$). This compound returns to Earth's surface in acid rain, which damages lakes, soil, vegetation, bridges, and buildings.

### Reducing the Effect of Nitrogen on Climate Change

By reducing the amount of excess nitrogen produced and used by farms and other industries, climate scientists hope to reduce the amount of greenhouse gases that enter the atmosphere. Scientists have proposed several ways to reduce the amount of nitrogen-containing compounds in the air. These actions are outlined in **Table 8.7**. For example, in the midwestern United States, researchers have introduced a program to educate farmers about fertilizer use. The program encourages farmers to use the least amount of fertilizer possible. Participating farmers apply substantially less fertilizer to most of their land than they did previously. This decrease in fertilizer use decreases the excess nitrogen available for fixation. Because water that runs off the land and through rivers eventually reaches the oceans, this practice helps to reduce the size of dead zones in the area.

In Canada, the increased use of precision-farming techniques promises to reduce the amount of nitrogen-based fertilizers used by Canadian farmers in the future. In precision farming, farmers use satellites and geographic information systems to determine exact locations of areas that require fertilizers. Thus, the farmers can apply an appropriate amount of fertilizer to only the specific part of a field that requires fertilizer. This technique will reduce the amount of excess fertilizer that enters rivers, lakes, and oceans.

**Study Toolkit**

**Synthesizing** Use the flowchart on page 310 to explain how the use of nitrogen-rich fertilizers may lead to sea-level rise.

**Table 8.7 Methods of Reducing Nitrogen Emissions**

| Course of Action | Estimated Maximum Reduction in Reactive Nitrogen Emissions |
|---|---|
| Controlling nitrogen oxide emissions from the burning of fossil fuels | 25 billion kg/year |
| Increasing the efficiency of fertilizing crops | 15 billion kg/year |
| Improving management of livestock | 15 billion kg/year |
| Providing sewage treatment for half the world's urban population | 5 billion kg/year |