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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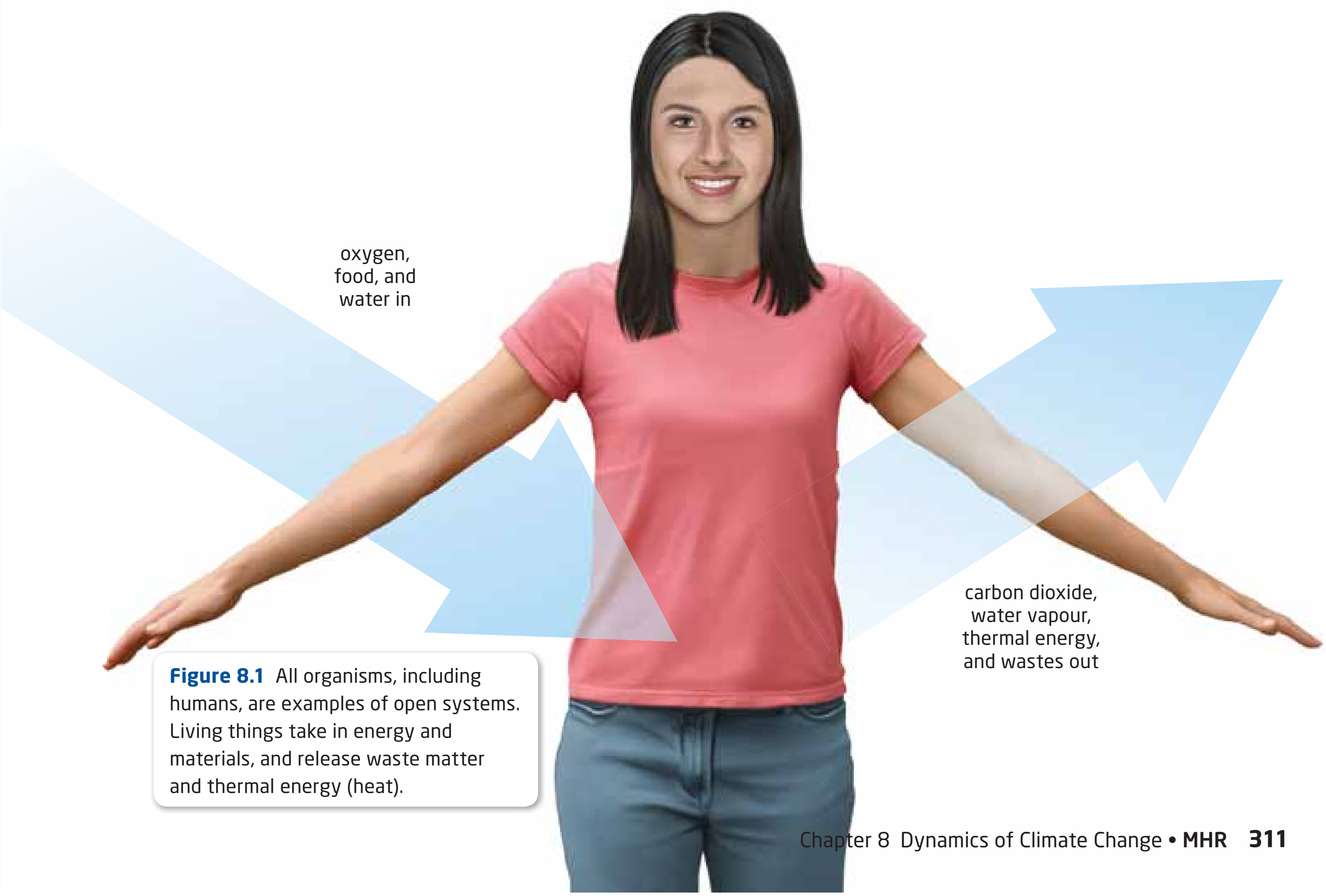


Figure 8.1 All organisms, including humans, are examples of open systems. Living things take in energy and materials, and release waste matter and thermal energy (heat).

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.

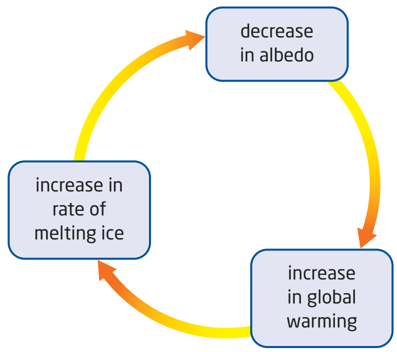


Figure 8.2 This diagram shows a positive feedback loop that involves rising temperatures, decreasing albedo, and melting polar and glacial ice.

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**.

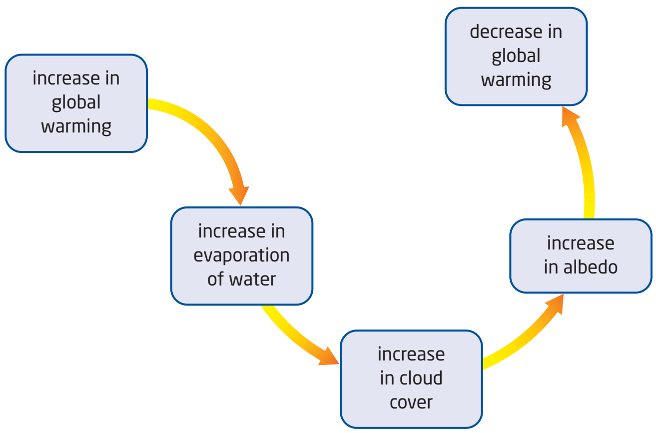
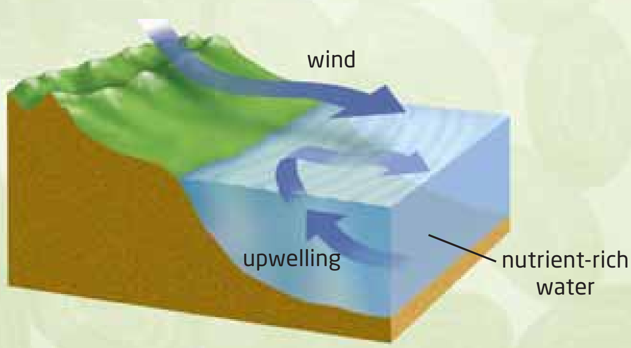


Figure 8.3 This diagram shows a negative feedback loop. It demonstrates how an increase in evaporation can reduce global warming.

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.	

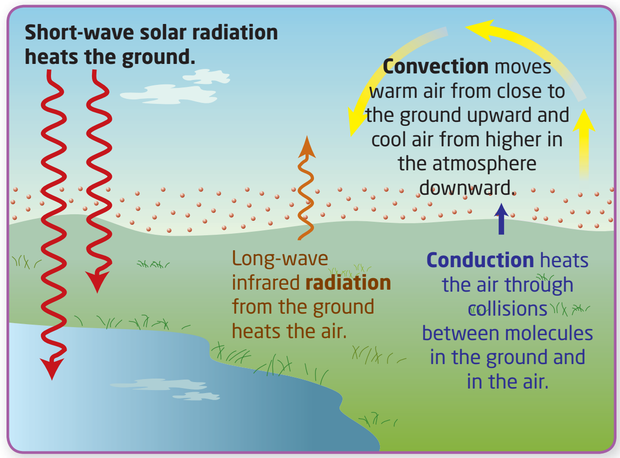
Energy Transfer in the Atmosphere

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.

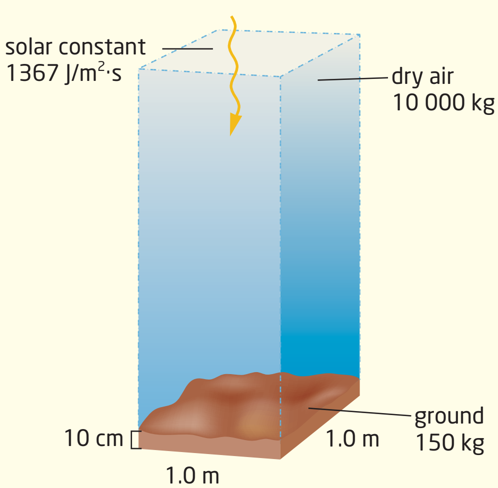
Figure 8.4 Conduction, convection, and radiation transfer heat in Earth's atmosphere.



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

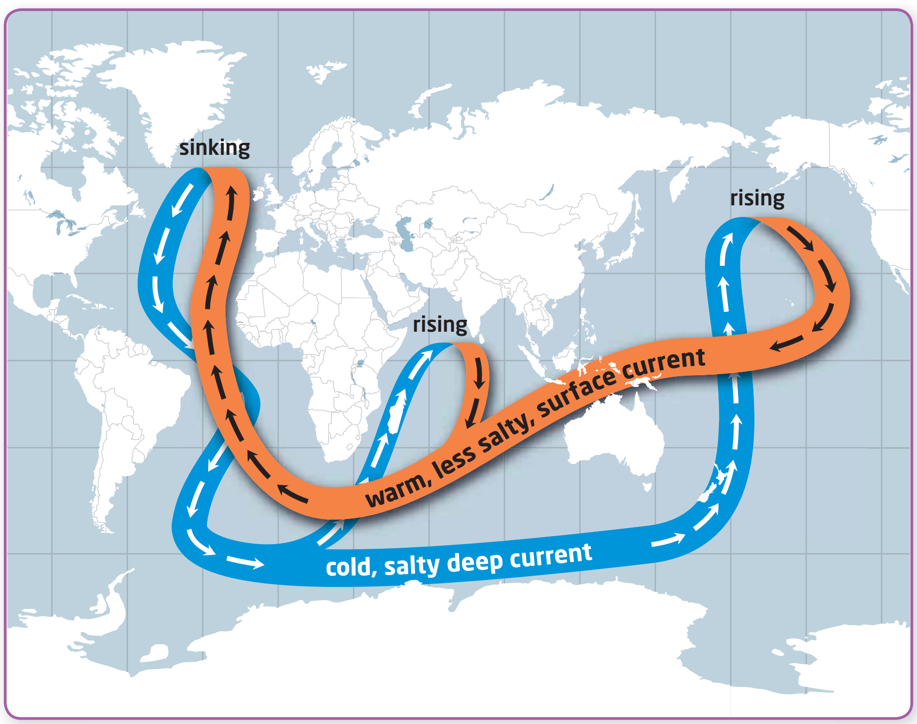


Figure 8.5 The *great ocean conveyor belt* moves water in a continuous loop from the surface of the ocean to the ocean floor and all around the planet. As the water moves, it carries thermal energy around Earth's surface.

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.

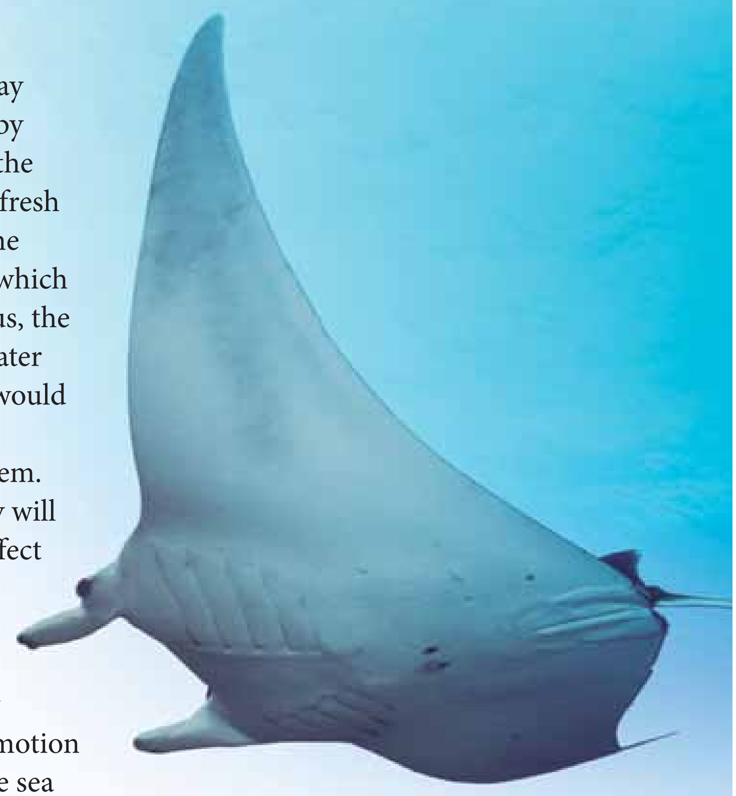


Figure 8.6 Manta rays, which can grow to a size of almost 8 m across, feed on the microscopic organisms that bloom where upwelling occurs.

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

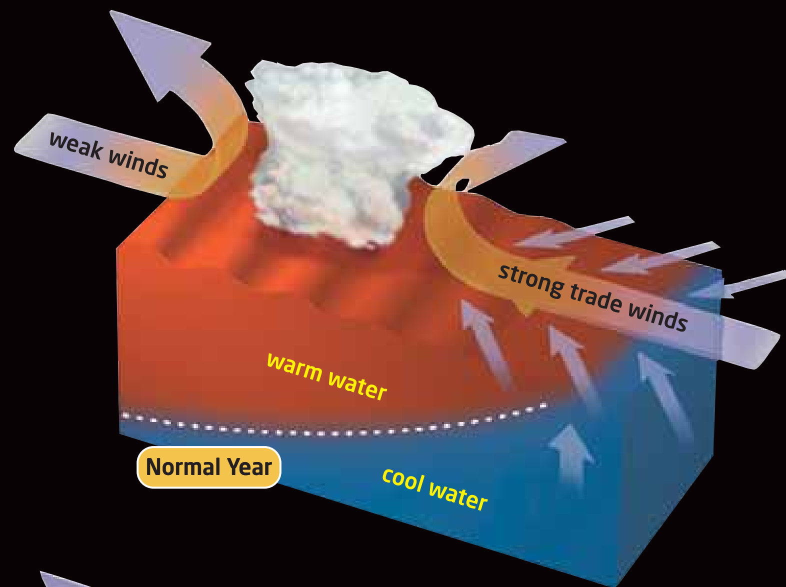
Real World Investigation 8-A, Recognizing the Effects of El Niño and La Niña on Southern Canada, on page 341

NATIONAL GEOGRAPHIC

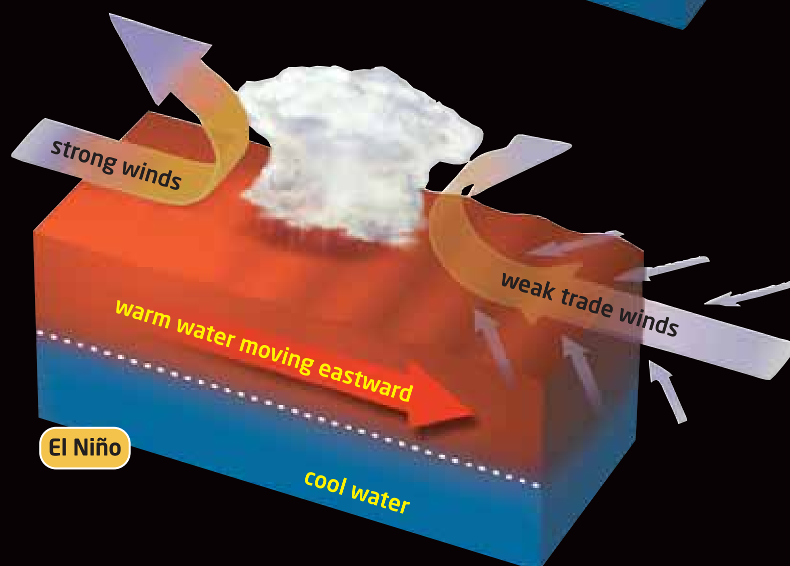
VISUALIZING EL NIÑO AND LA NIÑA

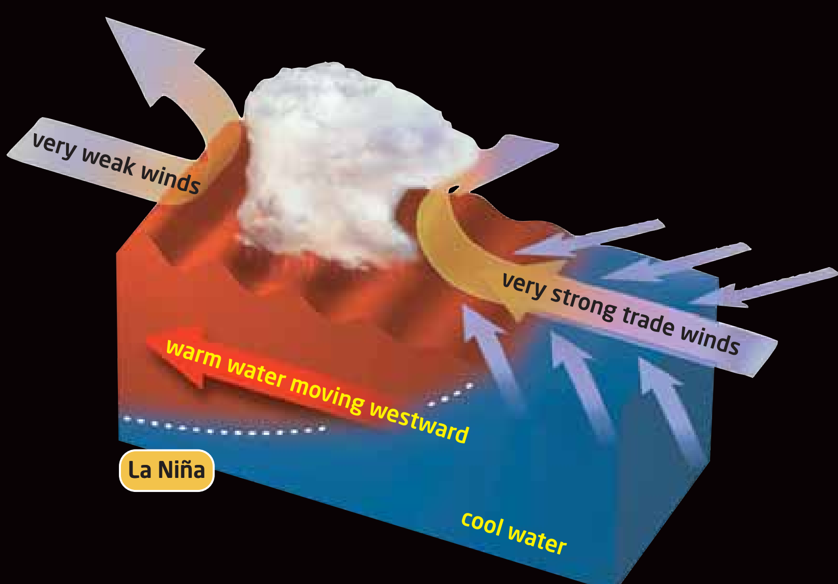
Figure 8.7

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.

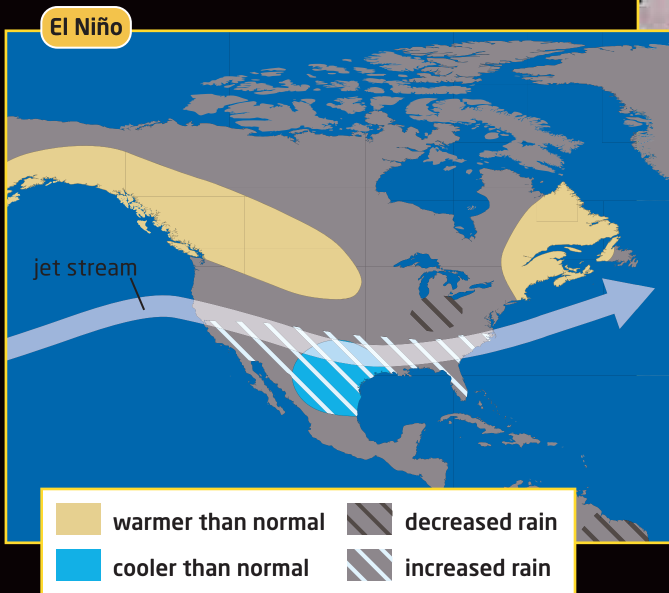


EL NIÑO During El Niño years, winds blowing west weaken and may even reverse. When this happens, warm waters in the western Pacific move eastward, preventing cold water from upwelling. This change can alter global weather patterns and trigger changes in precipitation and temperature across much of North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



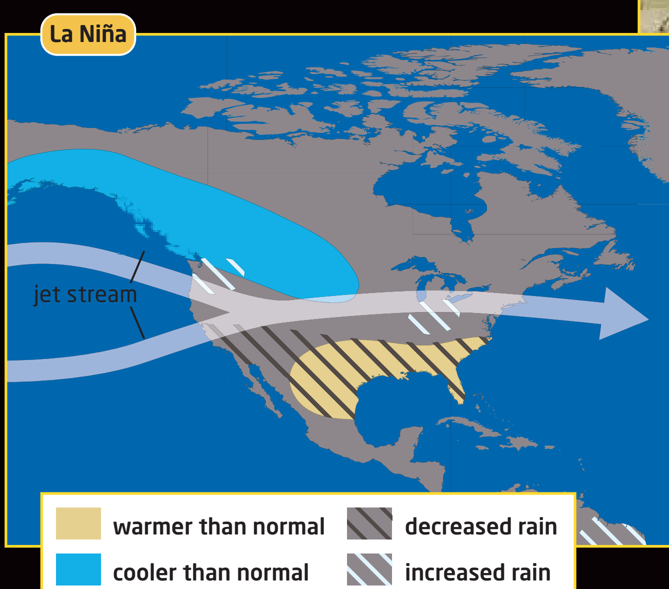


LA NIÑA During La Niña years, stronger-than-normal winds push warm Pacific waters farther west, toward Asia. Cold, deep-sea waters then well up strongly in the eastern Pacific, bringing cooler temperatures to northwestern North America.



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

Suggested Investigation

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

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.

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?

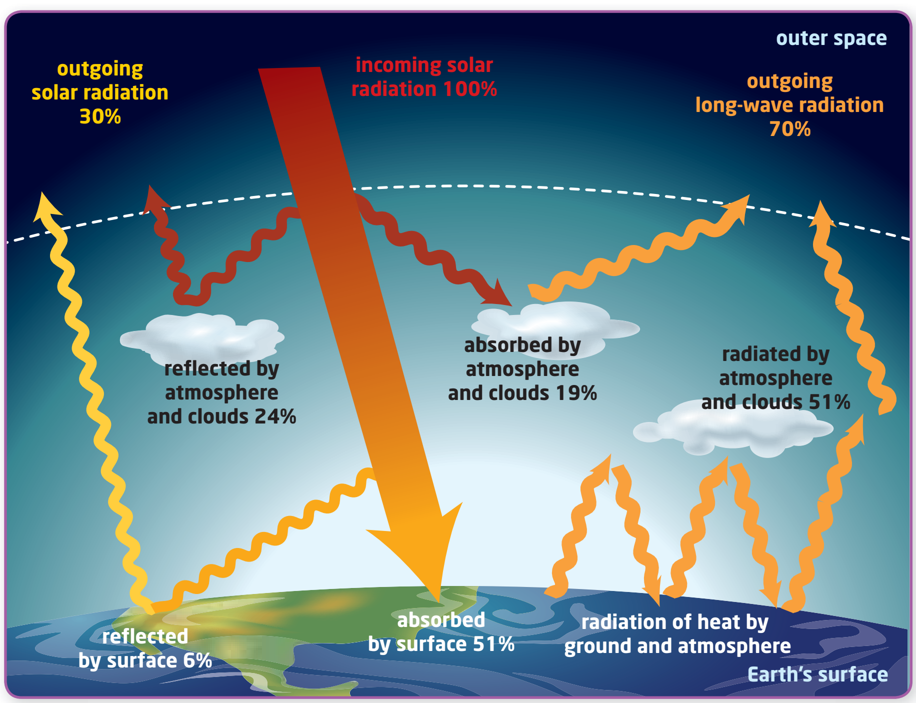

Figure 8.8 This diagram shows what happens to solar radiation that enters Earth's atmosphere. Of the total incoming solar radiation, 30 percent is reflected and 70 percent is absorbed. All of the absorbed radiation is eventually radiated back into space.

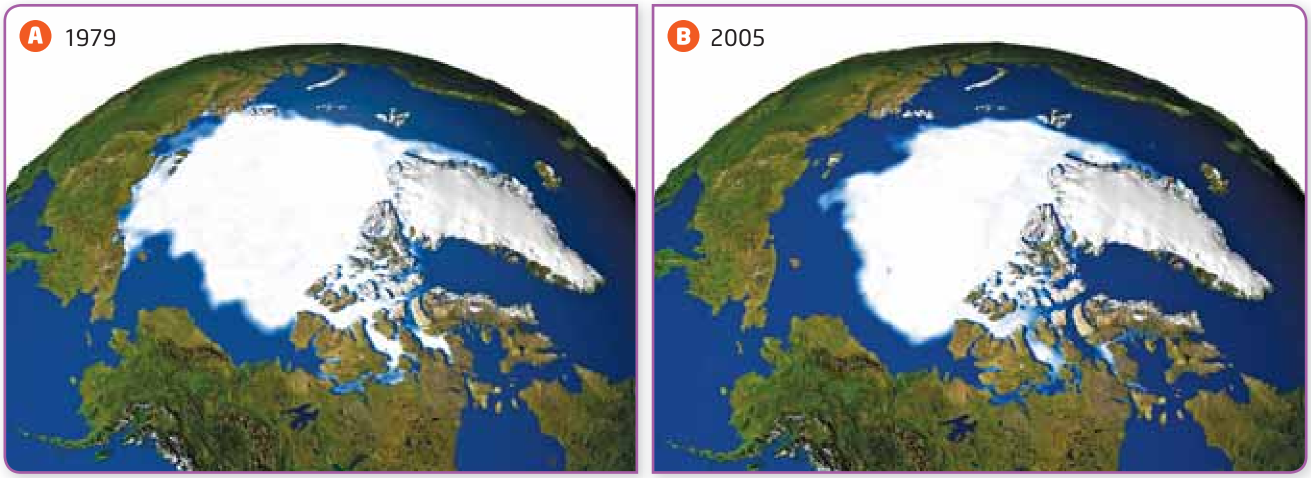

Figure 8.9 These satellite composite images show how the minimum area of the Arctic ocean that was covered by sea ice diminished between A 1979 and B 2005.

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.

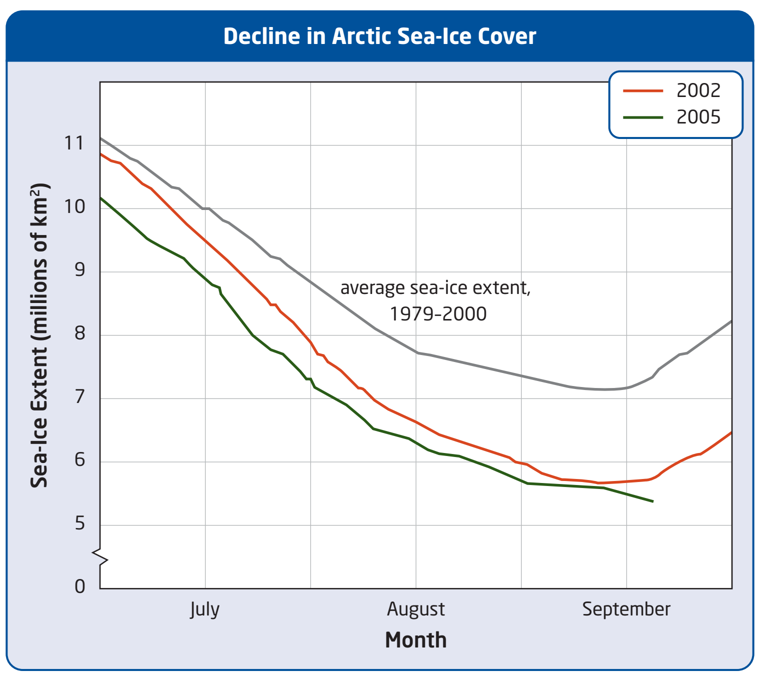

Figure 8.10 This graph shows the rate at which sea-ice cover above the Arctic Circle has declined over 20 years.

Section 8.1 Review

Section Summary

- Earth is a system of interrelated parts, including the atmosphere, hydrosphere, rocks, and living things.
- The interrelated processes in the Earth system form a variety of both positive and negative feedback loops, which affect the global climate system by increasing or decreasing the effects of climate change.
- The atmosphere redistributes heat, energy, and moisture around Earth's surface.
- Heat can be transferred by radiation, conduction, and convection.
- Earth's oceans transfer energy as water moves as a result of density differences that are caused by differences in the temperature and salinity of ocean water.
- El Niño and La Niña events are examples of the effects of heat transfer through the atmosphere and oceans.
- To maintain a stable average global temperature, incoming energy and outgoing energy must balance each other exactly. This balance is part of Earth's energy budget.

Review Questions

K/U **1.** Identify four components of Earth's climate system.

A **2.** One concern about global warming is that the polar icecaps will melt quickly and expose darker materials, such as rock and water, to sunlight. Ice and snow have a high albedo, but open water and rocks have a low albedo. Given the differences in albedo, describe the positive feedback loop that could occur as a result of the polar icecaps melting.

K/U **3.** How is the energy that Earth absorbs different from the energy that Earth emits?

C **4.** Draw a diagram that illustrates how the thermohaline circulation system distributes heat throughout Earth's surface.

K/U **5.** Summarize what happens during an El Niño event.

T/I **6.** How do El Niño and La Niña demonstrate the importance of feedback loops in Earth's climate system?

A **7.** The graph on the right shows what percentage of thermal energy is absorbed by different parts of Earth's climate system. Explain what effect the relative sizes of the oceans and atmosphere have on their role in storing and transferring thermal energy.

T/I **8.** If Earth has had a balanced energy budget for billions of years, why do climatologists think that the energy budget might be changing now?

Amount of Heat Absorbed by Different Parts of Earth's Climate System over the Last 20 Years