UNIT 9

Energy in the Earth System

Chapter 25

Measuring Heat

Why do some substances warm up and cool down faster than others? What is the difference between temperature and heat? How is heat transferred from one place to another? In this chapter, you will learn the answers to these and other questions as you study temperature scales, specific heat, and heat transfer.

25.1	**Measuring Heat**	*How is temperature measured?*

In this Investigation you will graph the Celsius temperature scale as a function of the Fahrenheit temperature scale. From this graph you will develop a mathematical relationship between the Fahrenheit and Celsius temperature scales.

25.2	**Flow of Heat**	*How efficient is an immersion heater?*

In this Investigation you will explore how much thermal energy is supplied to water by an immersion heater. You will also make some predictions on the change in temperature if the amount of water is changed. In addition, you will calculate the efficiency of the system.

25.3	**Heat Transfer**	*How much heat is transferred through convection?*

In this Investigation you will observe both natural and forced convection. A flask of hot water with red dye will be placed in a beaker filled with cool water. The hot red water will rise into the cooler water due to natural convection. You are going to observe the process and take temperature data to analyze how much heat is transferred via convection. You will also blow through a straw to force the red dye out of the flask into the larger beaker to explore forced convection.

Learning Goals

In this chapter, you will:

- Measure temperature.
- Convert between the Celsius and Fahrenheit temperature scales.
- Understand and demonstrate physical changes due to temperature.
- Develop a mathematical relationship that describes how much the temperature of water increases when heat is added to the water.
- Discuss the relationship of heat and energy.
- Calculate the efficiency in a heating system.
- Explain three methods of heat transfer and describe applications of each.
- Analyze how energy can be transferred through convection.
- Describe the motion of liquid due to temperature differences within the system.

Vocabulary

British thermal unit (Btu)	Fahrenheit scale	latent heat	thermal energy
calorie	first law of thermodynamics	radiation	thermal equilibrium
Celsius scale	heat	specific heat	thermal insulator
conduction	heat-temperature rule	temperature	thermometer
convection	joule	thermal conductor	thermostat

25.1 Measuring Heat

If you observe a group of people waiting for a bus on a brisk winter morning, you may notice that more people have chosen to sit on a wooden bench than on a metal one. Why? Does the wooden one feel warmer? If both types of benches are found at the same bus stop, shouldn't they be the same temperature? In this chapter, you find the answer to this and other questions about temperature, the flow of heat, and thermal energy.

Figure 25.1: *On a cold day, more people will choose to sit on a wooden bench than a metal one. Can you explain why?*

Temperature

What is temperature?

You have probably used a thermometer to find the **temperature** outside. Temperature is the measurement we use to quantify the sensations of hot and cold. A steaming mug of hot cocoa has a higher temperature than a frosty glass of iced tea. But what does temperature actually measure?

What does temperature measure?

If we were to blow up a balloon we would fill it with billions upon billions of molecules of air. All of these molecules are constantly moving. As a result, they have *kinetic energy*—energy of motion. Some of the molecules are moving fast, some are moving slowly. They can move up, down, and sideways. Fast particles have more kinetic energy than slow particles. If we were to add up the kinetic energy of every single molecule in a balloon, and divide this sum by the total number of molecules, we would have an *average* of the kinetic energy for molecules in the balloon. This average is what temperature measures.

Temperature is a measure of the average kinetic energy of the molecules of an object.

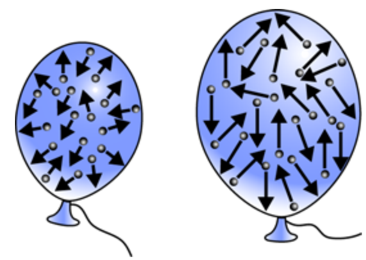


Figure 25.2: *As temperature increases, so does the average kinetic energy of the molecules. The size of the arrows represents the amount of kinetic energy of the molecule.*

Indirect measurement is used to find temperature

Of course, it is difficult to measure the speed of individual molecules in an object, since they are much too small to see. We commonly use *indirect measurement* to find an object's temperature. An increase in the average kinetic energy of an object's molecules can cause changes in other physical properties of the object, such as its volume or electrical resistance. In the next section, you will learn how we use these physical changes to measure an object's temperature.

How does a thermometer work?

Thermometers

Have you ever wondered how a thermometer works? The most common thermometers contain either a red fluid, which is alcohol containing a small amount of red dye, or a silvery fluid, which is mercury. You may have also used a thermometer with a digital electronic readout. Thermometers detect a physical change in a material that results from a change in temperature. Alcohol and mercury thermometers measure the *thermal expansion* of the liquid, while digital thermometers measure *electrical resistance*.

What is thermal expansion?

Most materials expand when you raise their temperature. This process is called thermal expansion. The expansion comes from the increase in molecular motion that occurs with the rise in temperature. If molecules are moving around more, they tend to bump each other around and so take up more space. That's why an inflated balloon will expand when held over a warm radiator. If you put the balloon in the refrigerator, it will shrink. Likewise, warmer liquids take up more space than cold liquids. You can easily see this in a thermometer (Figure 25.3).

How liquid-filled thermometers work

Thermal expansion is the basic principle of a liquid-filled thermometer. The expansion of the liquid is directly proportional to the change in temperature. For example, for every degree the thermometer heats up, the fluid inside might expand so that it takes up one more millimeter of space in the narrow tube.

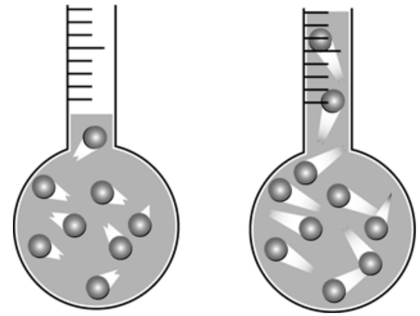
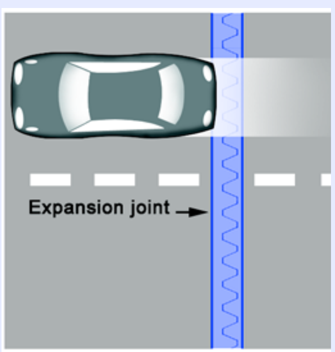


Figure 25.3: *The expansion of liquid in a thermometer is directly proportional to the increase in temperature.*

Temperature changes and bridges



Most solids also expand in response to an increase in temperature, but the expansion is very small. For solid steel, the thermal expansion is on the order of one ten-thousandth. This means that a 1-meter steel rod will expand 0.01 millimeters for every degree Celsius of temperature increase. Although this may seem difficult to detect, temperature changes can have dramatic effects on large structures such as buildings and bridges. For instance, a 100-meter-long bridge could be up to 10 centimeters longer on a hot summer day than on a cold winter day. In order to prevent damage to the structure, civil engineers use expansion joints in bridges as shown in the figure at left.

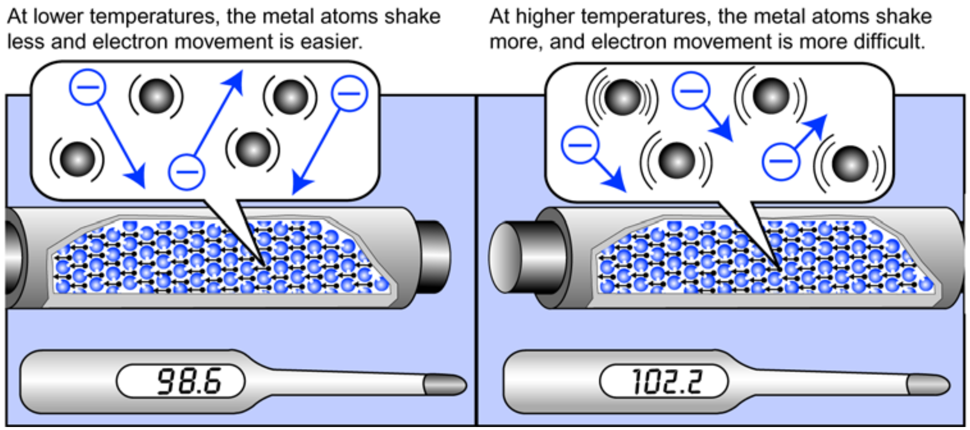
Science in your home

Have you ever had trouble opening a jar of salsa or jelly because the lid was too tight? One method of opening the jar is to run it under warm water. As the glass jar and metal lid heat up, they both expand. However, the expansion rate of the metal is more than twice the rate of the glass. Thus the lid will loosen as you heat the jar!

A note of caution: If the water is extremely hot, the glass may break.

How digital thermometers work

Another physical property that changes with temperature is electrical resistance. The resistance of a metal wire increases with temperature. Since the metal is hotter, its atoms are shaking more. The shaking interferes with the movement of electrons, causing greater resistance. Digital thermometers measure this change in resistance. Most commonly, platinum metal is used in digital thermometers.



Temperature scales

The Fahrenheit scale

You are probably most familiar with the English system of measuring temperature, known as the **Fahrenheit scale**. It was developed in 1714 by Gabriel Fahrenheit (1686-1936), a German physicist who was the first person to use a mercury thermometer. He chose the lowest temperature he could create in his lab (using water, salt, and ice) to be the zero point of his scale. For the other end of the scale he used the temperature of the human body as 100 degrees. Eventually the Fahrenheit scale was standardized so that the freezing point of water is 32 degrees and the boiling point is 212 degrees.

The Celsius scale

In 1742, Anders Celsius (1701-44), a Swedish astronomer, invented a temperature scale in which there were 100 degrees between freezing and boiling. He called this scale the centigrade scale. In 1948 this official scale of the metric system was named the **Celsius scale** in honor of him. Most countries in the world use the Celsius scale (Figure 25.4).

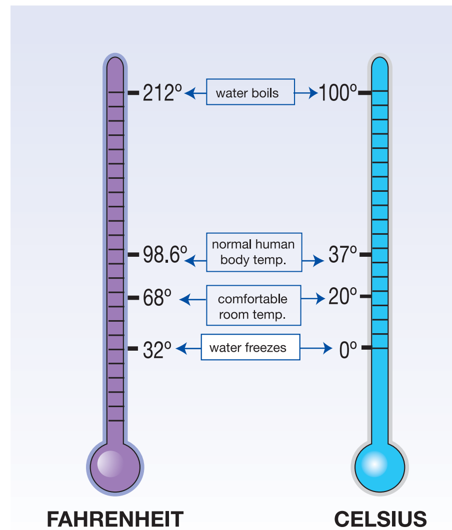


Figure 25.4: *A comparison of the Fahrenheit and Celsius temperature scales.*

Thermal energy and heat

Energy changes

As you have read, changes in temperature are directly related to changes in energy. When you heat a pot of soup with an electric hot plate, *electrical energy* is converted into *thermal energy*.

What is thermal energy?

Thermal energy and temperature are not the same. Temperature measures the *average* kinetic energy of the molecules of a material. **Thermal energy** is the *sum* of all the kinetic energy of the molecules of a material.

Thermal energy is the sum of all the kinetic energy of the molecules of a material.

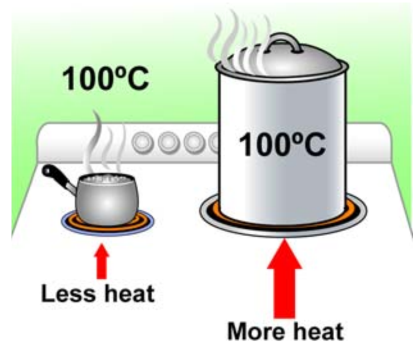


Figure 25.5: *Even though the two containers of soup are at the same temperature, the large pot contains more thermal energy because it took more energy to heat it.*

Same temperature, but different thermal energies

Suppose you are asked to heat up a single cup of soup and a huge pot of soup. Both have to reach the same temperature. Which takes more energy? Heating up the huge pot takes more energy because it is like heating up many individual cups. Even though the two containers of soup are at the same temperature, the pot contains more thermal energy because it took more energy to heat it (Figure 25.5).

What is heat?

What happens when you hold an ice cream cone on a hot day? Thermal energy flows from your hand and the surrounding air to melt the ice cream (Figure 25.6). We call this flow of thermal energy **heat**.

Heat is the flow of thermal energy due to a temperature difference between two objects.

Figure 25.6: *On a hot day, thermal energy flows from your hand and the surrounding air to melt the ice cream.*

When does heat flow?

In the scientific sense, heat occurs only when there is a difference in temperature. Heat flows naturally from the warmer object to the cooler one. In the case of the melting ice cream, the thermal energy lost by your hand and the surrounding air is equal to the thermal energy gained by the ice cream. The total amount of energy stays balanced.

Measuring heat

Understanding heat is important

The flow of thermal energy (which we call heat) is happening around us all the time. Thermal energy from the sun, for example, warms our planet every day. At night, some of this heat flows back out to space. The flow of thermal energy is also found whenever a car (or any other large machine) is running. These machines have special systems like radiators and fins to manage heat.

The calorie

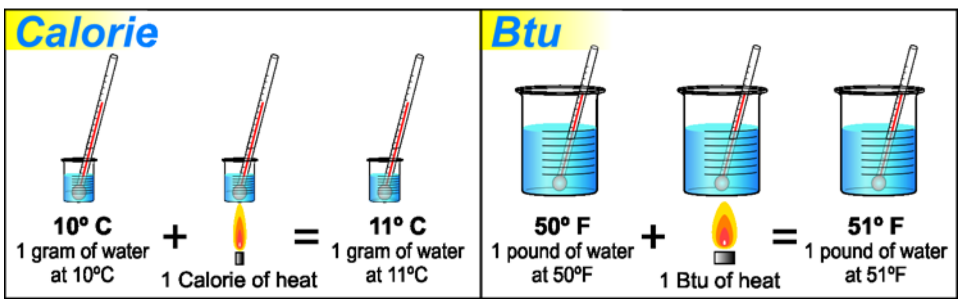
Heat is an important concept in so many aspects of our lives. There are three different units of energy that relate directly to heat. The metric unit usually used in chemistry to measure heat is the calorie. The **calorie** is defined as the quantity of heat needed to increase the temperature of 1 gram of water by 1 degree Celsius. You may have noticed that most food packages list "Calories per serving." The unit used for measuring energy content of the food we eat is the kilocalorie, which equals 1,000 calories. The kilocalorie is often written as Calorie (with a capital C). If a candy bar contains 210 Calories, it contains 210,000 calories!

The joule

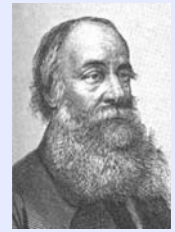
The **joule** is the most common unit of heat used for physics and engineering. The joule is a unit used to measure all forms of energy, not just heat. The joule is smaller than the calorie. There are 4.18 joules in one calorie (Figure 25.7).

The British thermal unit

Still another unit of heat you may have heard of is the **British thermal unit**, or Btu. The Btu is often used to describe heat produced by heating systems or heat removed by air-conditioning systems. A Btu is the quantity of heat it takes to increase the temperature of 1 pound of water by 1 degree Fahrenheit.



James Prescott Joule



In the 1840s, English physicist James Prescott Joule (1818-89) proved that the law of conservation of energy also applied to heat. Until then, physicists only considered the law of conservation of mechanical energy, which did not include heat. Joule showed that when he converted electrical energy and kinetic energy into thermal energy, energy was still conserved. The unit for heat and energy is named in his honor.

Unit	Equals
1 calorie	4.186 joules
1 Calorie	1000 calories
1 Btu	1055 joules
1 Btu	252 calories

Figure 25.7: *Conversion table for units of heat.*

25.2 Flow of Heat

When you take an apple pie out of the oven, why is the filling sometimes hot enough to burn your mouth while the crust is barely warm? Why does a cast-iron skillet heat up faster than an aluminum one? Why does the water in an outdoor swimming pool feel cool during the day and warm at night? The answer to each of these questions involves the concept of *specific heat*. In this section, you will define specific heat, learn to use the heat equation to solve problems involving heat transfer, and discover how the law of energy conservation applies to situations involving thermal energy.

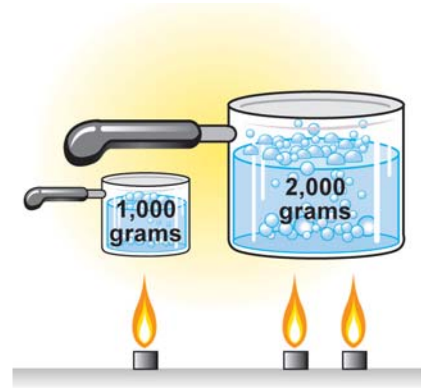


Figure 25.8: *It takes twice as much energy to heat 2,000 grams of water to boiling temperature as to heat 1,000 grams to the same temperature.*

Measuring heat

Temperature and mass

If you add heat to an object, how much will its temperature increase? It depends in part on the mass of the object. If you double the mass of the object you are going to heat, you need twice as much energy to increase the temperature (Figure 25.8).

Temperature and type of material

The amount of temperature increase also depends on the kind of material you are heating. It takes more energy to raise the temperature of some materials than others. Suppose you apply 100 calories of heat to a beaker containing 100 grams of water. The temperature goes up one degree. If you add the same amount of heat to 100 grams of iron, the temperature goes up 20 degrees (Figure 25.9). As water and iron illustrate, substances vary greatly in their resistance to temperature change. Knowing how materials resist temperature change is important. For example, if you know that apple pie filling is much less resistant to temperature change than pie crust, you might test the filling temperature before taking a bite!

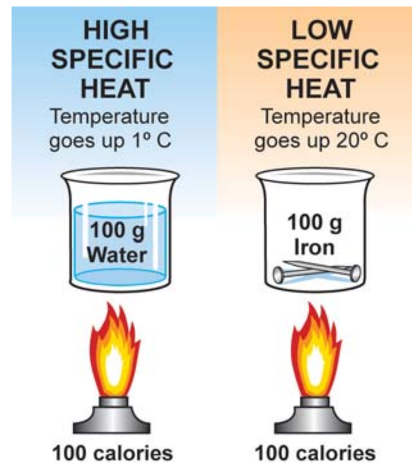


Figure 25.9: *When the same amount of heat is added to 100 grams of water and 100 grams of iron, the iron's temperature gain is 20 times the temperature gain of the water.*

Specific heat

The **specific heat** is a property of a substance that tells us how much heat is needed to raise the temperature of one gram by one degree Celsius. A large specific heat means you have to put in a lot of energy for each degree increase in temperature. Specific heat is usually measured in calories per gram per degree Celsius $\frac{\text{calorie}}{\text{gram°C}}$.

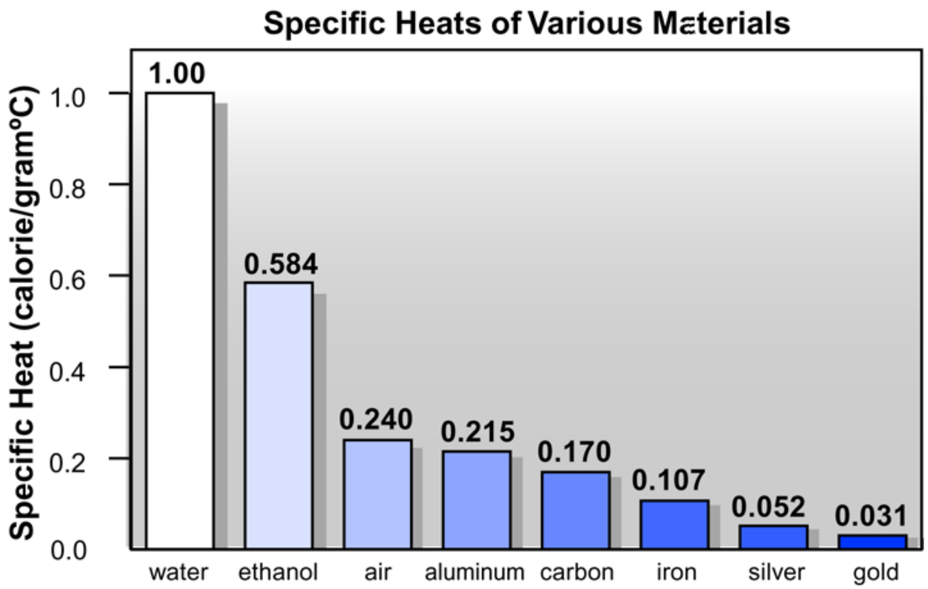
The specific heat of a substance is the amount of heat needed to raise the temperature of one gram by one degree Celsius.

Specific heat and engineering

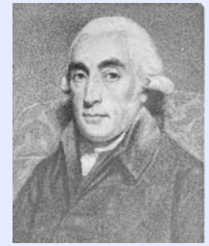
Engineers use specific heat to design better products

Knowing the specific heat of substances helps engineers design better products. For example, playground slides used to be made of steel. When these slides absorbed thermal energy on a hot summer day, their temperature would increase so much that they would be too hot to use. Now, most playground slides are made of durable plastic, which has a much higher specific heat. A plastic slide remains at a safe and comfortable temperature, even on a hot summer day.

The graph below compares the specific heats of various materials.



Joseph Black



Scottish chemist Joseph Black (1728-99) developed the theory of specific heat in 1760. Black also recognized the difference between heat that increases the temperature of a substance and heat that melts or boils a substance. For instance, if we add heat to water, the temperature starts to rise. Once the temperature of water reaches 100°C, it boils. Any heat added to boiling water causes water to turn to gas, but it does not raise the temperature. Black called the heat used to boil or melt substances latent heat because it could not be sensed with a thermometer. Latent means *hidden*.

The specific heat of water

Water has a high specific heat

Water has a higher specific heat than many other common materials. Its specific heat is over four times greater than that of air. When the sun shines on a body of water like a swimming pool, thermal energy flows into the water and the surrounding air. The temperature of the water does not rise as fast as the air temperature because of the difference in specific heat. That is why the water in a swimming pool feels refreshingly cool even on a hot summer day.

Water has greater resistance to temperature change than does air

Although the temperature of the pool water doesn't increase much over a hot sunny day, the water absorbs a great deal of thermal energy. At night, the water has to release a whole calorie of thermal energy per gram in order to cool one degree Celsius. By contrast, the air only has to release 0.240 calorie per gram to cool one degree. Therefore, at night, the water cools more slowly than the air. If you jumped into the pool several hours after sunset, the water would feel warmer than the surrounding air.

Figure 25.10: *About 75 percent of Earth's surface is covered by water.*

Water's high specific heat helps regulate Earth's temperature

The high specific heat of water is very important to our planet. Water covers about 75 percent of Earth's surface (Figure 25.10). One of the fundamental reasons our planet is habitable is that the huge amount of water on it helps regulate the temperature. Land, because it has a low specific heat, experiences large changes in temperature when it absorbs heat from the sun. Water tends to have smaller changes in temperature when it absorbs the same amount of heat. During the daytime, oceans help keep Earth cool, while at night, they keep Earth warm by slowing the rate at which heat is emitted back into space.

The heat equation

How could you figure out how much energy it would take to heat a swimming pool or boil a liter of water? The whole story of heat flow is told by the equation below. The equation tells you how much heat (*Q*) it takes to change the temperature (ΔT) of a mass (*m*) of a substance with specific heat (*c*).

Heat equation

$$\text{Heat energy (calories)} \rightarrow Q = \overset{\text{Mass (g)}}{m}\,\overset{\text{Specific heat }\left(\frac{\text{calorie}}{\text{gram °C}}\right)}{c}\,\underbrace{\Delta T}_{\text{Change in temperature (°C)}}$$

Example:

How much heat energy is needed to raise the temperature of 1,000 grams (1 liter) of water from 20°C to 100°C?

1. Identify the variables in the equation.

   Heat equation: $Q = mc\Delta T$

   Q = trying to determine

   m = mass of water = 1,000 grams

   c = specific heat of water = 1 calorie/g °C

   ΔT = 100 °C - 20 °C = 80 °C

2. Plug the variables into the equation and solve.

   $Q = (1{,}000\text{ g}) \times (1\text{ calorie/g °C}) \times (80\text{ °C})$

   $Q = 80{,}000$ calories

Heat flow and the origin of the word *calorie*

We now understand that the flow of heat is due to the transfer of energy. However, until the 1840s, scientists thought that heat traveled by an invisible fluid called *caloric*, which comes from the Latin word for heat. We still use the word *calorie* even though we no longer believe in a fluid called caloric.

Flow of heat and equilibrium

Energy can flow from one object to another

When heat flows from a warm mug of hot cocoa to your hand, there is an exchange of energy for both objects. The warm mug loses energy and cools down. Your hand gains energy and warms up. When you touch the mug, your hand is in *thermal contact* with the mug (Figure 25.11).

What is thermal equilibrium?

Have you ever filled your kitchen sink with hot water to wash dishes? If the water was too hot, you may have added cold water to cool down the hot water. The temperature of the water in the sink eventually reaches a balance where everything is evenly warm. Whenever you have a hot object or substance in thermal contact with a cold one, heat will flow from the hot object to the cold object until they are at the same temperature, which means they are in thermal equilibrium.

Energy loss is equal to energy gain

Suppose you were able to take some objects or substances in thermal contact with each other and place them in a container that would not allow any energy to leave the system. For example, you place a cup of hot water mixed with a cup of ice into the container. Because the hot-water-and-ice mix is isolated from the outside, the energy that the hot water loses must equal the energy that the ice gains. This is an example of the law of conservation of energy. When we are talking about heat, this law is also known as the first law of thermodynamics. Both laws state that the energy in an isolated system is conserved.

The first law of thermodynamics states that in an isolated system the total amount of thermal energy remains constant.

When do objects reach thermal equilibrium?

Objects reach thermal equilibrium when they reach the same temperature. When you submerge a thermometer in water to measure its temperature, you need to wait for a few seconds until you see that the mercury or alcohol level of the thermometer stops rising. At that point, the thermometer and the water will have reached the same temperature. Both objects transfer energy (heat) until they reach thermal equilibrium. Thus, the reading you get is the thermometer's own temperature.

Figure 25.11: *When you hold a mug of hot chocolate, your hand is in thermal contact with the mug.*

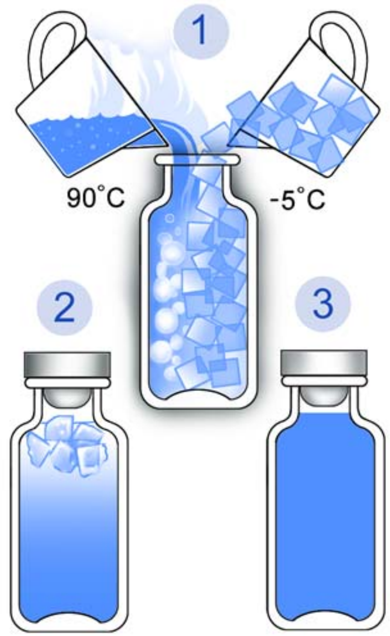


Figure 25.12: *When hot water and ice are placed in a closed system, (1) the energy lost by the hot water is equal to (2) the energy gained by the ice. Eventually, the contents reach thermal equilibrium (3).*

25.3 Heat Transfer

Thermal energy flows from a material at a higher temperature to a material at a lower temperature. This general process is called heat transfer. How is heat transferred from material to material, or from place to place? It turns out there are three quite distinct mechanisms of heat transfer. In this section, you will learn about conduction, convection, and radiation.

What is conduction?

What is conduction? Conduction is the transfer of heat by the direct contact of particles of matter. If you have ever grabbed a mug of hot cocoa, you have experienced conduction. Conduction occurs between two materials at different temperatures when they are touching each other. Conduction can also occur *through* a material. For example, if you stir a cup of boiling water with a metal spoon, the heat will be transmitted from the water through the spoon to your hand (Figures 25.13 and 25.14).

Conduction is the transfer of heat by the direct contact of particles of matter.

How is thermal energy transferred? When your hand wraps around a mug of hot cocoa, the fast-moving molecules in the mug collide with the slower-moving molecules in the skin of your hand. The average kinetic energy of the molecules of your skin increases and, as a result, your skin temperature increases.

What happens as these collisions take place? The transfer of energy between molecules is like a bumper car ride at an amusement park. Some bumper cars start out going fast and others slow. Soon they are all hitting each other. When a fast car bounces into a slow car, the fast car slows down a bit and the slow car speeds up a bit. The cars may change direction as well. As each car changes direction it then hits other cars around it. Pretty soon all the cars in the arena are bouncing off each other at about the same average speed. When this happens, they are in equilibrium.

Figure 25.13: *A metal spoon placed in hot water quickly transmits the heat to your hand.*

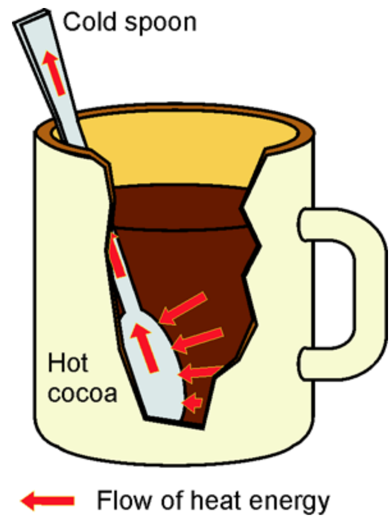


Figure 25.14: *When a warmer material, like the hot water in this cup, comes in contact with a cooler material, like the spoon, there are lots of collisions between the atoms and molecules of each material.*

Collisions allow the transfer of energy needed to reach thermal equilibrium

The same thing happens at the atomic level. As collisions occur, the atoms and molecules of the warmer material slow down, and the atoms and molecules of the cooler material speed up. Some of the kinetic energy of the hotter material is transferred, one collision at a time, to the cooler material. Soon, both materials are at the same temperature. This is how two materials reach thermal equilibrium by conduction.

Conductors and insulators

Which state of matter conducts best?

Conduction can happen in solids, liquids, and gases. However, the more densely packed atoms or molecules of a solid can conduct more heat because there are many more collisions taking place. The low density of gases means that relatively fewer collisions occur, making air, for instance, a poor conductor of heat. This explains why many materials used to keep things warm, such as fiberglass insulation and down jackets, contain air pockets that slow the transfer of heat.

What are thermal insulators and thermal conductors?

In general, materials that conduct heat easily are called **thermal conductors** and those that conduct heat poorly are called **thermal insulators**. For example, metal is a thermal conductor, and a foam cup is a thermal insulator. You may remember that the words *conductor* and *insulator* are also used to describe a material's ability to conduct electrical current. There is a reason for this common usage. In general, good electrical conductors like silver, copper, gold, and aluminum are also good heat conductors. Remember, metals are good conductors of current because there are many free electrons among the metal atoms. When a metal conducts heat, these free electrons transfer the kinetic energy through the material.

A thermos uses a vacuum to prevent heat transfer by conduction

Conduction happens only if there are atoms and molecules available to collide with one another. In the vacuum of space, heat transfer by conduction cannot occur. One way to create an excellent thermal insulator on Earth is to mimic this vacuum. A thermos bottle (also known as a "vacuum flask") keeps liquids hot for hours using a vacuum as insulation. A thermos bottle consists of a small glass bottle surrounded by a slightly larger one (Figure 25.16). Air molecules have been removed from the space between the layers of glass. This prevents heat transfer by conduction. A small amount of heat is conducted through the cap and the glass (where the two walls meet), so eventually the contents will cool.

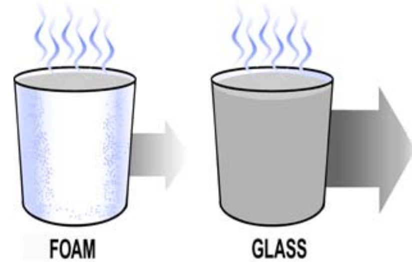


Figure 25.15: *A foam cup is a better thermal insulator than a glass cup. Therefore, liquid in a foam container will retain heat longer than it would in a glass container.*

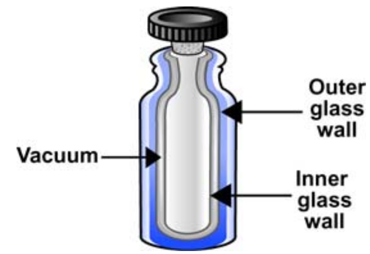


Figure 25.16: *Inside a thermos. Although the space between the two glass walls isn't a perfect vacuum, enough air molecules are removed to prevent most heat transfer by conduction and convection.*

What is convection?

The second type of heat transfer is called convection. This type of heat transfer is involved in processes like heating our homes, increasing the speed at which water boils, and transferring energy through the atmosphere.

What is convection?

Have you ever warmed your hand by placing it over a candle? Most of the heat energy from the flame is moved from it to your hand by the movement of air. The air right above the flame heats up and expands. Because the expanded air is less dense, it rises, bringing the heat to your hand (Figure 25.17). This heat transfer process is called convection. Convection comes from a Latin word meaning *to carry together.*

Figure 25.17: *The air right above the flame heats up and expands, transferring heat to your hand.*

Convection is the transfer of heat by the actual motion of a fluid (liquid or gas) in the form of currents.

Convection can occur in all fluids, whether liquids or gases. Convection occurs because warmer fluids are less dense and rise. Cooler fluids are denser and sink. This motion of fluids causes currents.

Sea breezes are due to convection

Near coastlines, convection is responsible for *sea breezes*. During the daytime, the land is much hotter than the ocean. A sea breeze is created when hot air right above the land expands and rises. This rising air exerts pressure on the air high above the land. The air high above the land gets pushed aside, toward the sea. The air over the sea sinks as it is cooled because of the water's temperature. This air is compressed as it sinks. Because the air pressure is lower over the land, the cooling, sinking, compressing air over the sea rushes toward the land. This convection cycle creates a sea breeze (Figure 25.18).

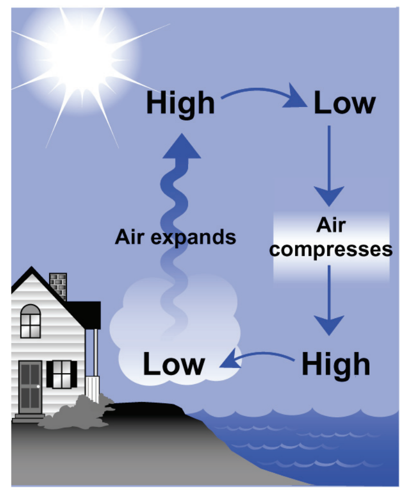


Figure 25.18: *A convection cycle creates a sea breeze.*

In the evening, the ground cools rapidly but the ocean remains warm because of water's high specific heat. Now warm air rises over the water and is replaced with cooler, denser air from over land. The cycle reverses. This is known as a land breeze.

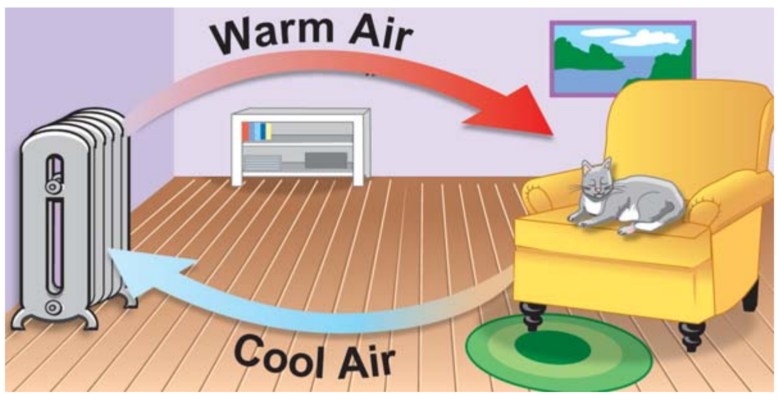
Convection happens all around you

Why wearing a sweater keeps you warm

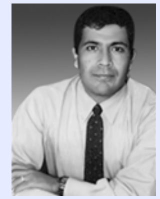
Through the process of convection, the air surrounding your body warms up, rises, and carries the heat away. A wool sweater prevents this from happening by trapping air in many small pockets so that it cannot flow and carry the heat away. Similarly, in cold weather birds trap pockets of warmer air by fluffing their feathers.

Radiators heat rooms through convection

Convection enables a radiator to heat an entire room. The air surrounding the radiator warms due to conduction, and becomes less dense than the cold air on the far side of the room. The warmer air rises and cooler air from the far side of the room replaces it. Then the cooler air is warmed and rises. This air circulation transfers heat from the radiator to the far side of the room.



Alfonso Ortega



Does your computer ever freeze up when you are playing a game with lots of graphics? Sometimes this happens because computer processors can overheat when they have to perform a lot of complicated tasks.

Dr. Alfonso Ortega, a mechanical engineer and professor at Villanova University, is searching for better ways to help computers keep their cool.

Dr. Ortega studies how convection can be used to carry heat away from the processor. He runs cool liquid past the processor. The processor's heat is transferred to the liquid. The hot liquid is carried away, cooled down, and circulated back to the processor again.

In order to figure out how to use convection efficiently, Dr. Ortega used the human brain as a model. The brain is cooled by bringing blood in contact with it. The heat from the brain is transferred to millions of tiny blood vessels. These vessels empty into larger veins. Then the blood circulates through the body, cooling down in the process.

Source: SACNAS.org

What is radiation?

If you stand in the sun on a cold day and it is not too windy, you will feel the sun's warmth, no matter how cold it is outside. How does the warmth of the sun reach Earth? In this section, you will learn about another type of heat transfer known as **radiation** which is responsible for the way the sun warms our planet.

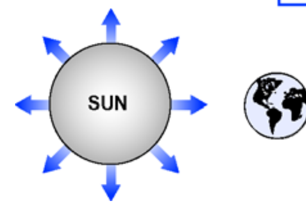


Figure 25.19: *The sun's electromagnetic radiation heats Earth.*

Radiation can occur in the vacuum of space

You know that conduction and convection require matter to transfer heat. Neither of these methods can transfer heat from the sun to Earth, because space is a vacuum. However, electromagnetic waves can transfer energy through a vacuum. This is fortunate because the Earth receives most of its heat in the form of electromagnetic radiation from the sun (Figure 25.19). Most of the sun's energy that is radiated to Earth is in the form of visible light or infrared radiation, along with a small amount of ultraviolet radiation. (These are types of electromagnetic waves.)

Radiation is the direct transfer of energy by electromagnetic waves.

Reflectors and absorbers

When electromagnetic waves from the sun strike Earth, some are absorbed and others are reflected. Black and dark colored objects tend to absorb all the light that falls on them. White objects, on the other hand, reflect light of all wavelengths. That's why you will stay cooler if you wear a white T-shirt outdoors on a hot sunny day rather than a dark colored one. The dark T-shirt would absorb more of the sun's energy, so you would feel hotter. Shiny objects also tend to reflect radiation, while a dull object made from the same material is a better absorber.

Some recipes call for you to cover the edges of a pie crust with aluminum foil while baking to prevent them from browning too quickly. Which side of the foil would you place outward, the shiny or the dull side? Why?

Emitters of radiation

Objects that are good absorbers of radiation are also good emitters of radiation. Thus, after sunset, a black road surface emits radiation and cools quickly, whereas the white sandy surface of a beach would not emit radiation efficiently and would cool slowly (Figure 25.20).

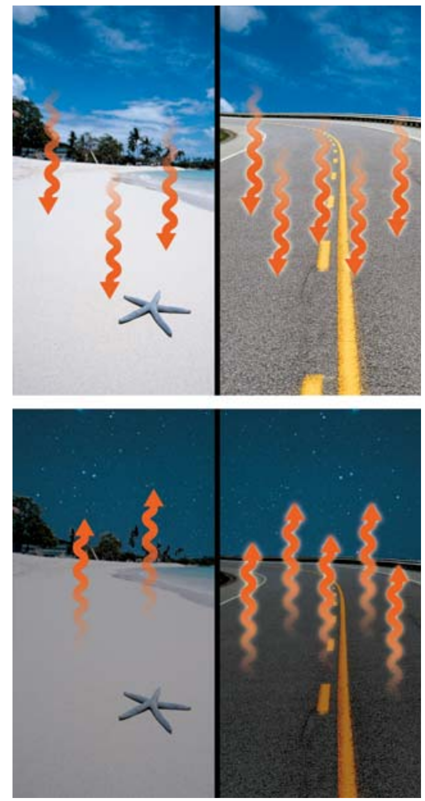


Figure 25.20: *A black road surface is a good absorber and good emitter of radiation. A white sand beach is a poor absorber and poor emitter of radiation.*

Chapter 25 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. temperature	a. A property of most materials: they expand when heated
2. thermal expansion	b. The sum of all the kinetic energies of the molecules of a material
3. thermal equilibrium	c. A measure of the average kinetic energy of the molecules of an object
4. thermal energy	d. The flow of thermal energy due to a temperature difference between two objects
5. heat	e. If two objects are at the same temperature, they must contain the same amount of this
	f. When two objects in thermal contact have reached the same temperature

Set Two

1. specific heat	a. Transfer of heat by actual motion of a fluid in the form of currents
2. first law of thermodynamics	b. Transfer of heat by direct contact of particles
3. conduction	c. Amount of heat needed to increase the temperature of 1 gram of water 1° Celsius
4. convection	d. Transfer of heat by electromagnetic waves
5. radiation	e. An object will remain at rest unless acted on by an unbalanced force
	f. In an isolated system, the total amount of thermal energy remains constant

Concept review

1. How does a thermometer work?
2. Explain the difference between temperature and thermal energy.
3. Water is used in many machines to cool moving parts that would otherwise overheat due to friction. Why is water a good choice?
4. What happens to the individual molecules in an object when you increase the object's temperature? Why does this cause the object's size to increase?
5. Describe the flow of thermal energy that occurs when you hold a cold can of soda in your hand.
6. Due to its large mass, an iceberg has more thermal energy than a hot cup of coffee. Describe the flow of thermal energy that occurs if the cup of coffee is placed in thermal contact with an iceberg.
7. Why are some solid materials good thermal insulators while others are good conductors? Give an example of each.

8. Why is air a poor conductor of heat? How can air be used as an insulator? Give two examples.

9. Why does hot air rise?

10. Why doesn't convection occur in a solid material?

11. A blacktop road leads to a white sand beach. On a warm sunny day, which surface will heat up faster? Which will cool down faster at night? Explain why.

12. Using what you have learned about conductivity, explain why, on a cold winter day, a metal park bench feels colder than a wooden park bench, even though they are really the same temperature.

Problems

1. Convert the temperature at which paper burns, 451° Fahrenheit, to degrees Celsius.

2. A teapot contains 500 milliliters of water. Five thousand calories of heat are added to the teapot. What is the increase in the temperature of the water?

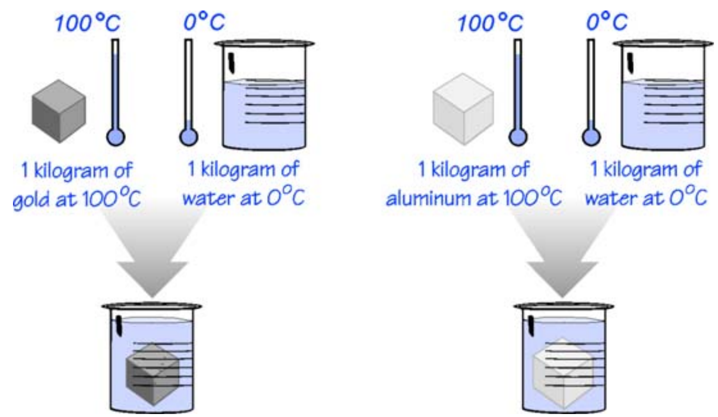
3. How much energy will it take to increase the temperature of 200 milliliters of water by 12°C?

4. One liter of water at 20°C is mixed with 3 liters of water at 80°C. What is the equilibrium temperature of the mixture?

5. In the previous problem, how many calories of heat are transferred from the hot water to the cold water?

6. A microwave oven uses microwave radiation to vibrate water molecules in food. The vibration increases the average kinetic energy of the water molecules, which increases the temperature of the food. If you place a ceramic coffee mug filled with water into the microwave oven and heat it for 90 seconds, the water will be very hot. Although the ceramic material contains no water, the cup itself gets warm. Why? Does the handle of the cup get hot too? Why or why not? Use the words radiation, conduction, and convection in your answer.

7. Two beakers each contain 1 kilogram of water at 0°C. One kilogram of gold at 100°C is placed in the first beaker. One kilogram of aluminum at 100°C is dropped into the other beaker.



a. Compare the amount of thermal energy contained in the aluminum and gold.

b. After each beaker has reached thermal equilibrium, will they be at the same temperature or different temperatures? If they are different, tell which is warmer.

c. Explain your answer to part (b). Use the concept of specific heat in your explanation.

Applying your knowledge

1. Look at or have someone show you the water level in an automobile radiator. You will notice that the radiator is filled up to the cap with water. Next to the radiator there is an overflow container. As the car runs and the water gets very hot, what happens to the water? What have engineers included in the design of the radiator system to return the water from the overflow into the radiator?

2. The first settlers in Colorado were very concerned about fruits and vegetables freezing in their root cellars overnight. They soon realized that if they put a large tub of water in the cellar, the food would not freeze. Explain why.

3. For one or more of the following write a short paper or give a presentation of your research:
   a. Scottish chemist Joseph Black (1728-1799) developed the theories of specific and latent heat. Research his life and how he made these discoveries.
   b. Lord Kelvin (1824-1907), a British Physicist, developed the idea of absolute zero, the coldest attainable temperature. Research absolute zero, the Kelvin scale, and Lord Kelvin's life.

4. A thermostat controls the switch on a furnace or air conditioner by sensing the temperature of the room. Explain, using conduction, convection, and radiation, where you would place the thermostat in your science classroom. Consider windows, outside and inside walls, and where the heating and cooling ducts are located. You can also sketch your answer—draw your classroom, showing room features and placement of the thermostat.

5. Building materials such as plywood, insulation, and windows are rated with a number called the "R value." The R value describes a material's insulating ability. Use the Internet or visit a building supply store to research the R value of at least three building materials used in the exterior walls of homes in your community. Then draw a diagram or build a three-dimensional model that shows a cross-section of a typical exterior wall. Label the R value of each material. Add the R values together to give the total R value for the wall.

6. Find out how much insulation is recommended for homes in your community. Where is the most insulation recommended—in the ceiling, walls, or floors? Using what you know about heat transfer, explain why.

7. Professional chefs often use convection ovens for baking cakes, pies, and other desserts. What is the difference between a convection oven and a conventional oven? Name some advantages of baking with a convection oven.

8. If you ask a group of third-graders what a refrigerator does, they may tell you that it "makes things cold." They might be surprised if you told them that a refrigerator is a machine that moves heat. Find out how a refrigerator works, and prepare a short presentation for an elementary-school class to share your knowledge. Create a worksheet with a simple diagram for the students to label and keep.

UNIT 9

Energy in the Earth System

Chapter 26

Energy in the Atmosphere

In this chapter, you will learn what is in Earth's atmosphere, and why it contains more oxygen than other planets' atmospheres. You will learn how to measure atmospheric pressure and how pressure changes affect athletes. You will learn about layers of Earth's atmosphere and how ozone depletion is changing one layer. Finally, you will learn about energy in the atmosphere and the issues of greenhouse gas emission and global warming.

26.1	**The Atmosphere**	*Can you measure pressure in the atmosphere?*

In this Investigation you will build your own barometer. You will design a system to calibrate your barometer's pressure reading and to compensate for temperature changes to ensure an accurate measurement.

26.2	**Layers of the Atmosphere**	*Where do you find high concentrations of ozone?*

In this Investigation you will explore ozone concentrations in the lower atmosphere. You will test and compare ozone levels in locations around your school.

26.3	**Energy in the Atmosphere**	*Understanding factors that affect Earth's temperature*

In this three-part investigation you will first construct a model to demonstrate the effect of greenhouse gases on Earth's temperature. Next, you will graph the heat of fusion of ice and explore how this property allows ice to act as a thermal buffering system for Earth. Finally, you will compare the specific heat of water and air, and learn how water's high specific heat keeps Earth from experiencing extreme temperature changes.

Photo courtesy NASA/JPL-Caltech

Learning Goals

In this chapter, you will:

- ✔ Learn about the thermal structure and chemical composition of Earth's atmosphere.
- ✔ Compare and contrast the atmospheres of Venus, Earth, and Mars.
- ✔ Find out how life on Earth has changed Earth's atmosphere.
- ✔ Build and calibrate a barometer to measure atmospheric pressure.
- ✔ Learn how changing atmospheric pressure affects the weather.
- ✔ Describe the layers and the corresponding temperature changes in the atmosphere.
- ✔ Learn about ozone's helpful role in the stratosphere and harmful role in the troposphere.
- ✔ Measure ozone levels in your school.
- ✔ Describe energy transfer in the atmosphere.
- ✔ Discuss greenhouse gas emission reduction and other means of slowing global warming.
- ✔ Model factors affecting Earth's temperature, including greenhouse gases, thermal buffering properties of ice, and water's high specific heat.

Vocabulary

atmosphere	exosphere	mesosphere	troposphere
atmospheric pressure	global warming	ozone	
barometer	greenhouse effect	stratosphere	
chlorofluorocarbons	ionosphere	thermosphere	

26.1 The Atmosphere

Earth's atmosphere is a layer of gases surrounding the planet, protecting and sustaining life. It insulates us so that we don't freeze at night. Its ozone layer protects us from the sun's ultraviolet rays, which cause eye and skin damage. Earth's atmosphere also contains the carbon dioxide needed by plants for photosynthesis, and the oxygen we need to breathe.

What's in Earth's atmosphere?

Earth's atmosphere is 78% nitrogen

You may be surprised to learn that the most abundant gas in Earth's atmosphere is nitrogen (N_2). Nitrogen gas makes up about 78 percent of Earth's atmosphere (Figure 26.1). Nitrogen is released into the air by volcanoes and decaying organisms. Nitrogen is a vital element for most living things. Protein, an essential substance in body tissues, contains nitrogen. However, this nitrogen is not absorbed directly from the air. Instead, the nitrogen is changed into nitrates (NO_3) by nitrogen-fixing organisms in the soil. Plants absorb nitrates from the soil and use them to make proteins. We eat plants (especially their seeds) or meat to obtain these proteins. Figure 26.2 describes Earth's nitrogen cycle.

21% oxygen

The second most abundant gas is oxygen, which makes up 21 percent of Earth's atmosphere. Atmospheric oxygen enables us to process the fuel we need for life. The remaining 1 percent of Earth's atmosphere is made up of 0.93 percent argon and 0.04 percent carbon dioxide. There are also tiny amounts of neon, helium, methane, krypton, and hydrogen, which we call trace gases.

Why Earth's atmosphere exists

This wonderful protective layer exists around Earth because our planet has just the right balance of size and distance from the sun. Scientists explain that at the time of Earth's formation, the heat from the sun drove off most of the lightweight elements such as hydrogen and helium. Earth would have remained a rocky airless world except that as it cooled, earthquakes and volcanoes spewed out heavier gases like nitrogen and carbon dioxide. Earth's mass gives it enough gravitational pull that these gases stayed around. Although the planet Mercury was formed in a similar way, its mass is too small and it is too close to the sun to have retained much of a layer of gas surrounding it. Venus, Earth, and Mars, however, retained their atmospheres.

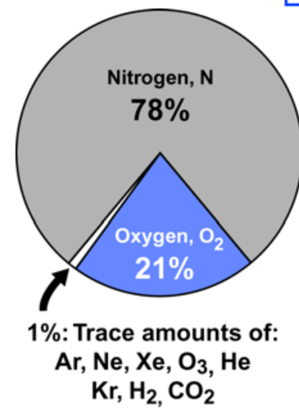


Figure 26.1: *Gases in Earth's atmosphere*

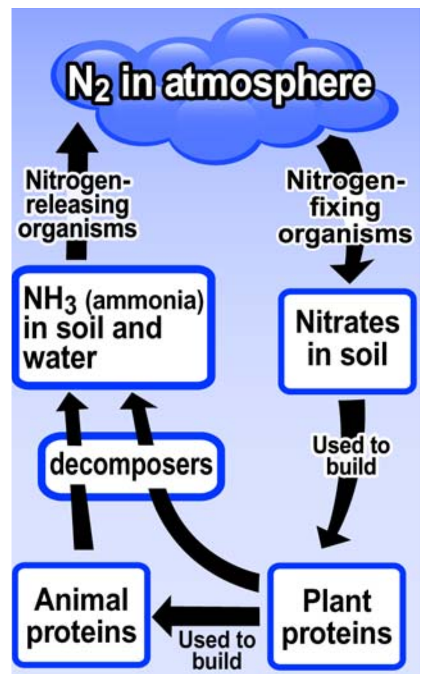


Figure 26.2: *The nitrogen cycle.*

Why does Earth's atmosphere have more oxygen than other planets?

The atmospheres of Venus, Earth, and Mars were formed in similar ways, so we might expect them to contain similar elements. Table 26.1 compares the atmospheres of these planets.

Table 26.1: ***The atmospheres of Venus, Earth, and Mars***

Planet	Major gases in atmosphere			
Venus	96% CO_2	3% N_2	0.1% H_2O	
Earth	0.04% CO_2	78% N_2	21.0% O_2	0.93% Ar
Mars	95% CO_2	3% N_2	1.6% Ar	

Similarities between Venus and Mars

Venus and Mars show striking similarities in the makeup of their atmospheres. They are mostly carbon dioxide, with a small amount of nitrogen. Earth, on the other hand, is very different. Ours is the only planet with a large amount of oxygen and just a tiny amount of carbon dioxide. Why is Earth so different?

Life changed Earth's atmosphere

Through photosynthesis, life on Earth has actually changed the planet's atmosphere. Many of the earliest and simplest forms of life used (and still use) photosynthesis to obtain energy from the sun. This process breaks down carbon dioxide, uses carbon to build the organism, and releases oxygen into the air.

Where does the carbon go?

When organisms die and decompose, some of the carbon from their bodies is released as carbon dioxide back in to the air. However, if all of the carbon used by life processes returned to Earth's atmosphere, our atmosphere would still be like that of Venus and Mars. Instead, some of the carbon used to build living organisms ends up staying in the ground. Earth stores carbon in several ways.

How Earth stores carbon

Many water organisms use carbon (along with calcium) to form shells of calcium carbonate. When the organisms die, these shells sink to the bottom of the water and stay there. The carbon doesn't return to the atmosphere. Huge piles of calcium carbonate have built up over the years, creating some of our land forms. "Fossil fuels" (oil, coal, and natural gas) also store carbon from decaying plants and animals in the ground. Another process stores carbon in a type of rock called limestone.

Tiny builders

Phytoplankton such as this coccolithophore use carbon dioxide dissolved in seawater for photosynthesis. They also use the carbon to form intricate calcium carbonate shells like the one shown above. Although each organism is only 0.5 millimeters across, these and other calcium carbonate shells pile up over the centuries, creating beautiful structures like the White Cliffs of Dover in Britain.

What is atmospheric pressure?

Air pressure is the measurement of the force of air molecules pushing on the walls of a container, like inside a basketball.

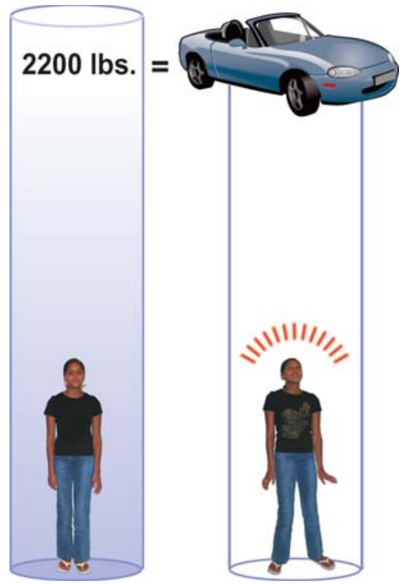
Air molecules exert pressure

Did you know that the air molecules on the outside of the basketball or other container are also exerting pressure? The pressure of air molecules in the atmosphere is a result of the weight of a column of air pressing down on an area. **Atmospheric pressure** is a measurement of the force of air molecules in the atmosphere at a given altitude.

> ***Atmospheric pressure is a measurement of the force of air molecules in the atmosphere at a given altitude.***

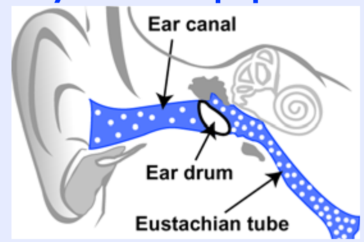
How we withstand air pressure

At sea level, the weight of the column of air above a person is about 9,800 newtons (2,200 pounds)! This is equal to the weight of a small car. Why aren't we crushed by this pressure? First, there is air inside our bodies that is pushing out with the same amount of pressure, so the forces are balanced. Second, our skeletons are designed to withstand the pressure of our environment.



Contrast these systems with those used by deep-sea animals. Fish that live at a depth of 10,000 feet are under pressure 300 times greater than we withstand. Instead of thick, strong bones, deep-sea creatures have cell membranes that contain a material that would be liquid at Earth's surface. The intense water pressure makes the material more rigid, so that the fish's body tissues hold their shape and function properly. Each organism on Earth is uniquely adapted to thrive in the pressure of its particular environment.

Why do ears "pop"?



Have your ears ever "popped" on an airplane? When an airplane goes through a rapid altitude change, the air pressure around your body changes, but the air pressure inside your body remains the same. For example, when an airplane ascends, the air in the ear canal becomes less dense than the air in the eustacian tube. Then the air inside the eustacian tube pushes outward on the eardrum.

If you yawn widely, you can sometimes equalize the air pressure pushing against your eardrum from the inside with the pressure pushing from the outside. Your eardrum "pops" when the pressure suddenly becomes equal again.

How is atmospheric pressure measured?

Barometers measure air pressure

Atmospheric pressure is measured with an instrument called a **barometer**. The oldest type of barometer is a *mercury barometer* (Figure 26.3). It consists of a tube sealed at one end and partially filled with mercury. The open end of the tube stands in a dish of mercury. As air presses down on the mercury in the dish, it forces the liquid in the tube to rise. When the air pressure is greater, the mercury travels farther up the tube. The air pressure at sea level generally causes the mercury in a barometer to rise 29.92 inches. The table below describes ways that air pressure is measured.

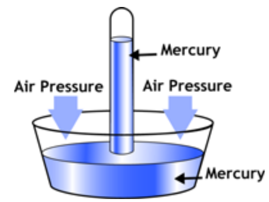


Figure 26.3: *A mercury barometer.*

Table 26.2: ***Units of air pressure***

Unit	Description	Relationship
inches of mercury (in Hg)	Unit describing the height of a column of mercury in a barometer.	29.92 in Hg = 1 atm
atmospheres (atm)	One atmosphere is the standard air pressure at sea level. Used by divers to compare pressure under water with surface pressure.	1 atm = 1.013 bar
pounds per square inch (psi)	English unit commonly used to measure pressure of air in a container, like a tire or ball.	1 psi = 6,895 pa
pascals (pa)	Metric unit commonly used to measure pressure of air in a container.	1 pa = 1 N/m^2
bars	Metric unit used to measure atmospheric pressure, most often in the form of millibars.	1 bar = 10,000 pa

Figure 26.4: *An aneroid barometer.*

Aneroid barometers

Mercury barometers have a downside: Mercury is a poisonous liquid, and it evaporates rapidly at room temperature, creating unhealthy vapors. You would not want to have a mercury barometer in your living room! Most barometers in use today are *aneroid barometers*. They have an airtight cylinder made of thin metal. The walls of the cylinder are squeezed inward when the atmospheric pressure is high. At lower pressures, the walls bulge out. A dial attached to the cylinder moves as the cylinder changes shape, indicating the change in air pressure.

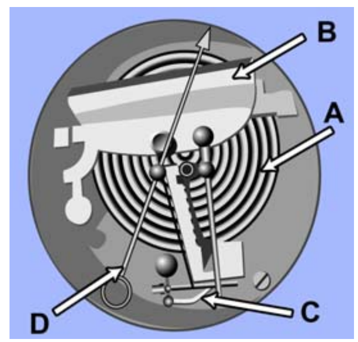


Figure 26.5: *Inside an aneroid barometer. Letter A shows the airtight cylinder, to which a spring, B, is attached. C is a series of levers that amplify the spring's movement. A small chain transfers the movement to the pointer, D.*

Atmospheric pressure changes with altitude

Why do climbers attempting to reach the summit of Mount Everest carry oxygen tanks? Why do sports teams from coastal areas want to arrive several days before their event in Denver, Colorado? The answer to both questions is: because the pressure of the atmosphere changes as you rise above sea level. Read on to find out more.

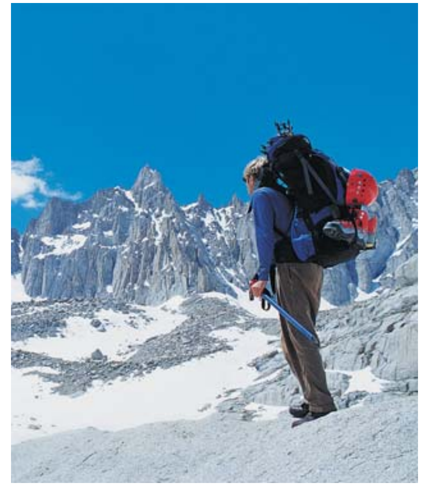


Figure 26.6: *Supplemental oxygen is needed by mountain climbers at high altitudes.*

A giant pile of cotton balls

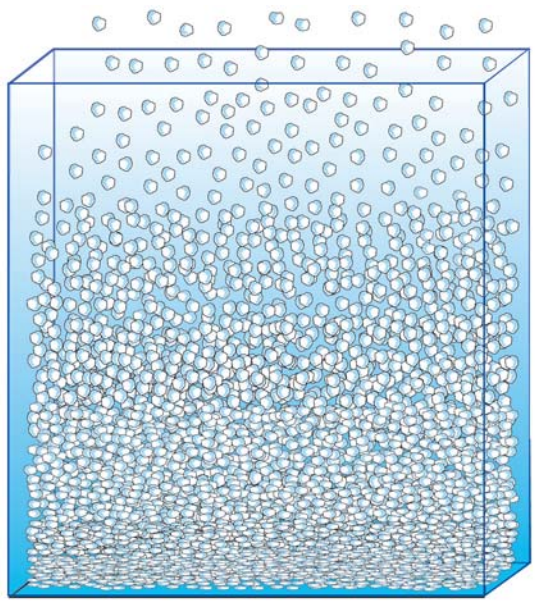
Earth's gravity prevents the nitrogen and oxygen molecules that make up 99 percent of our atmosphere from flying off into space. You can imagine the molecules of the atmosphere to be like a giant pile of cotton balls. At the top of the pile, the cotton balls would be loosely spread out. But the cotton balls at the top press down on the ones underneath, and those cotton balls press down on the ones below them. The cotton balls at the bottom of the pile are packed together much more tightly than the ones at the top.

Greatest pressure at the bottom

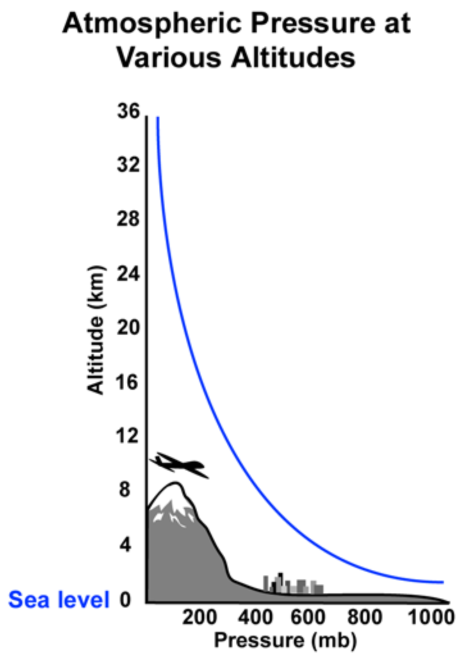
Think about what it would be like to be a cotton ball at the bottom of the pile. You would feel like you were getting squashed by the pressure of all the cotton balls above you!

Air pressure is greatest at sea level

A similar thing happens in the atmosphere. The molecules at the bottom are packed together very densely, because the weight of the molecules above presses down on them. The air pressure is greatest at sea level (the bottom of the atmosphere). As you get farther and farther from sea level, the molecules get more and more spread out, so that there are fewer molecules above you pushing down. These two factors mean that air pressure decreases very rapidly as you gain altitude.



As altitude increases, atmospheric pressure decreases rapidly



This graph shows that as altitude increases, atmospheric pressure decreases rapidly. At sea level, atmospheric pressure averages about 1,013 millibars. At the top of Mount Washington, New Hampshire (the highest point in the northeastern United States, at 1.917 kilometers), the average atmospheric pressure is 800.3 millibars. At the top of Mt. Everest, a height of 8.85 kilometers, atmospheric pressure averages only 334 millibars, only one-third of the pressure found at sea level.

Adjusting to high altitudes

How does the human body react to high altitude? Our bodies have to adjust to lower oxygen levels in less dense air. In Denver (nicknamed the "mile-high city" because it is about one mile, or 1.609 kilometers, above sea level), athletes who have trained at sea level need about a week to become acclimated to their new surroundings. Within a week, their bodies undergo several changes. Breathing becomes deeper and larger portions of the lungs become involved in oxygen exchange. They produce extra red blood cells so that they can transport the available oxygen more efficiently. They also release more of an enzyme that helps the blood release oxygen to the body tissues. Without these changes, even well-conditioned athletes would feel tired and winded in so-called "thin air."

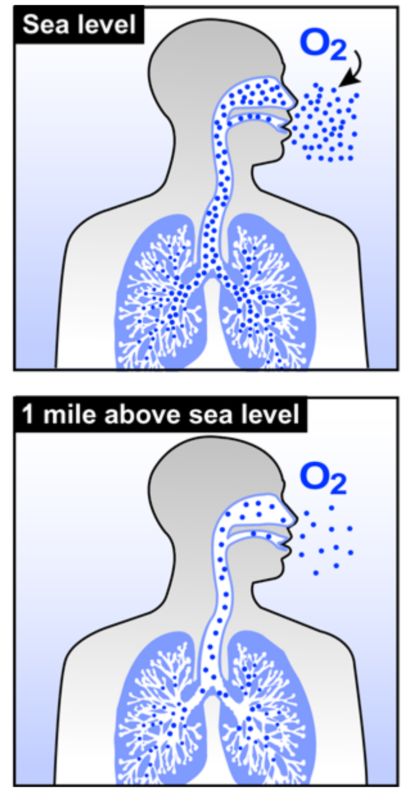


Figure 26.7: *One breath of air at sea level contains many more oxygen molecules than one breath at 1.609 kilometers (one mile above sea level).*

26.2 Layers of the Atmosphere

You probably know that temperature at the top of a high mountain is usually colder than at the base. But did you know that the temperature doesn't just keep decreasing as you go farther and farther up in the atmosphere? Actually, the temperature first decreases, then increases, then decreases, and then increases again. Scientists divide Earth's atmosphere into four different layers. As you will see, the divisions are based on these zigzags in temperature.

The four layers

The troposphere

We live in the **troposphere**, the layer that extends from 0 to approximately 11 kilometers (36,000 feet) above Earth's surface. About 90 percent of the atmosphere's mass is found in the troposphere. Almost all of Earth's water vapor, carbon dioxide, dust, airborne pollutants, and terrestrial life forms exist here.

Temperature decreases as you go up in the troposphere

The troposphere is heated by the infrared radiation from Earth's surface; therefore, it is warmest closest to that surface. On average, for every one kilometer you go up in the atmosphere, the temperature drops about 6.5° Celsius. At the top of the troposphere, the temperature is about -60°C. At this temperature, the water vapor has changed to ice. Without this cold region, water molecules could rise to a point where they would break down into hydrogen and oxygen. The lightweight hydrogen could then escape into space. Earth would lose the water that is so critical to life.

Weather occurs in the troposphere

The name troposphere contains the Greek root *tropo*, meaning "to turn or change." The troposphere is the region where clouds form and dissipate, and where all the weather happens. When you hear about airplanes "flying above the weather," this means that they are flying above the troposphere.

Temperature increases as you go up in the stratosphere

Above the troposphere lies the **stratosphere**, extending from about 11 kilometers to 50 kilometers above Earth's surface. In the stratosphere, the temperature actually *increases* as you go up. Why? High in the stratosphere there is a thin layer of **ozone**, the three-atom form of oxygen (O_3). The ozone absorbs the high-energy ultraviolet radiation from the sun. This process not only warms the stratosphere, it also protects us from the skin and eye damage caused by ultraviolet radiation.

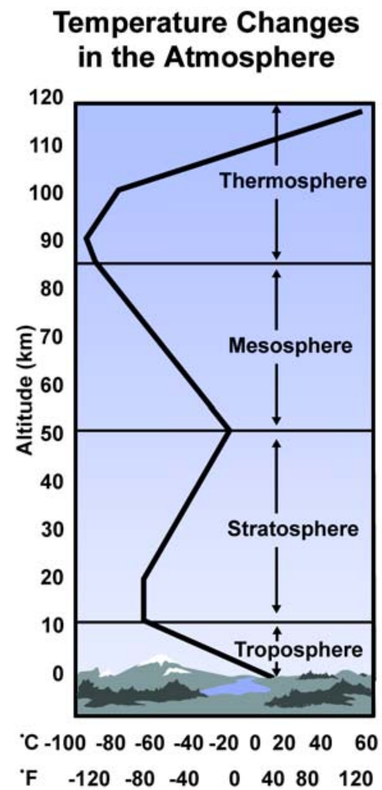


Figure 26.8: *The atmosphere is divided into layers based on temperature changes.*

In the mesosphere, the temperature falls as you go up

Above the stratosphere, the temperature begins to drop again. This marks the beginning of the **mesosphere**, which extends from 50 to 80 kilometers above Earth. The mesosphere is the coldest layer of the atmosphere, and at its outer reaches the temperature can be as low as -90°C. You may be surprised to learn that it is in this extremely cold layer that meteors burn up as they fall toward Earth. Friction created when air molecules rub against the meteor causes the meteor to burn, creating what we see as "shooting stars" in the night sky.

High temperatures in the thermosphere

The outer region of Earth's atmosphere is called the **thermosphere**. This part of the atmosphere is very thin. A cubic meter of air at Earth's surface contains 100,000 times as many molecules as a cubic meter of air in the thermosphere. The molecules in the thermosphere have a lot of kinetic energy, because the energy from the sun hits them first. Temperatures in this layer can reach 1,800°C.

Very little heat transfer

Interestingly, if you could hop out of a space shuttle into the thermosphere, you wouldn't feel hot. Temperature, as you remember, measures the average kinetic energy of the molecules of a substance. Heat, on the other hand, involves the transfer of energy from one object to another. Because the air molecules in the thermosphere are so far apart, very few of them would collide with you, so there would be very little heat transferred.

Divisions of the thermosphere

The thermosphere is further divided into two regions, the **ionosphere** and the **exosphere**. In the ionosphere (80-550 kilometers above Earth), the sun's ultraviolet light ionizes atoms and molecules. This process releases energy, which is why such high temperatures are recorded in the thermosphere. The ionosphere makes it possible for you to tune into AM radio stations that originate a hundred or more miles away. The radio signals are rebroadcast by the ions in the ionosphere back to Earth.

Satellites in the exosphere

The exosphere is the region extending from 550 kilometers above Earth. It does not have a specific outer limit. In this region, the atmosphere gets thinner and thinner. Lightweight atoms and molecules escape into space. Satellites orbit Earth in the exosphere, providing the photos used in television weather reports, transmitting long distance telephone calls, gathering intelligence information, and broadening our understanding of deep space through the use of special telescopes.

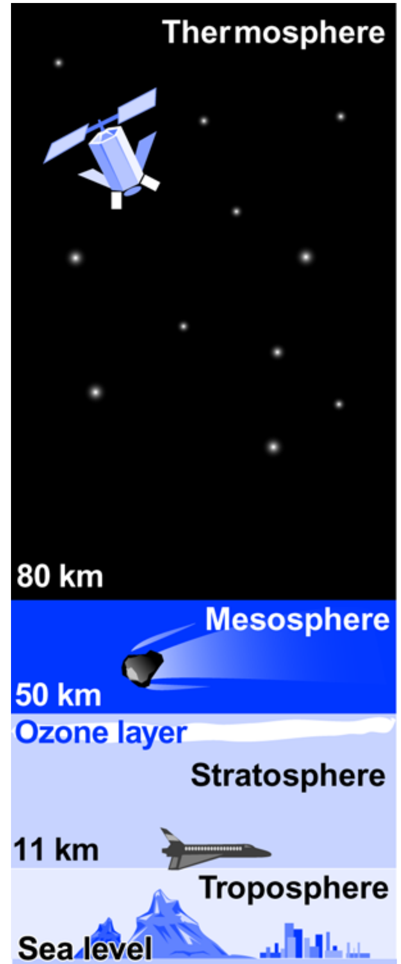
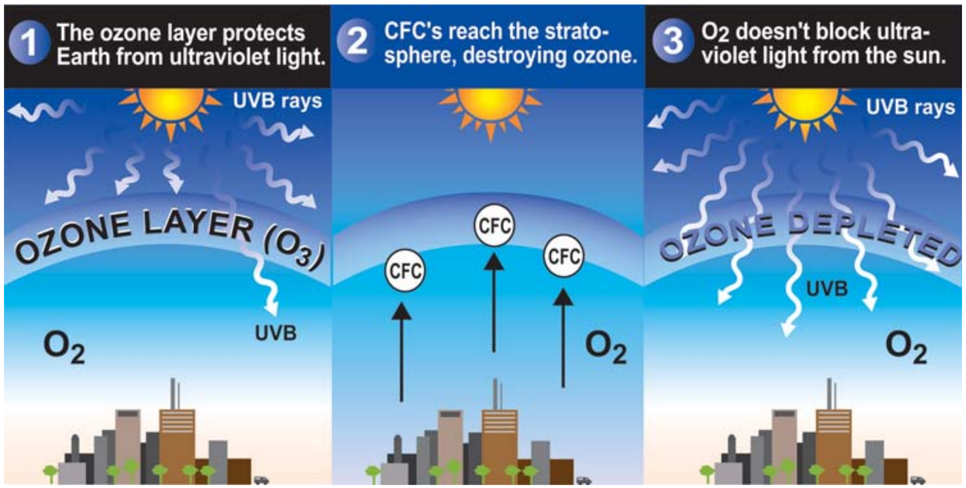


Figure 26.9: *The four layers of the atmosphere include the troposphere, where we live; the stratosphere, which contains the ozone layer; the mesosphere, where meteors burn; and the thermosphere, where satellites orbit Earth.*

Chlorofluorocarbons and ozone depletion

The thinning ozone layer

In the 1970s, scientists noticed that the ozone layer in the stratosphere above Antarctica was thinning. The detection of chlorine in the stratosphere led to the remarkable discovery that human activity is responsible for the loss of ozone. The culprit, it turns out, is a group of chemicals called **chlorofluorocarbons** (or CFC's). These chemicals were once commonly used in air conditioners, in aerosol spray cans, and for cleaning machine parts. While most airborne chemicals break down in the troposphere, chlorofluorocarbons stay intact until they travel up to the stratosphere (a journey taking anywhere from 6 to 26 years!), where they finally disintegrate, releasing chlorine. The chlorine reacts with ozone molecules, leaving behind ordinary diatomic oxygen, which does not block incoming ultraviolet radiation.



Repairing the damage

In the London Agreement of 1991, more than 90 countries banned the production and use of CFC's except for limited medical uses. This kind of international cooperation shows that we can make progress in repairing damage to our atmosphere. However, it will take several decades for the existing CFC's to break down. As a result, the problem of the "ozone hole" may get worse before it gets better.

The CFC-ozone reaction

Several processes destroy ozone in the stratosphere. Different processes operate under different atmospheric conditions. One common process starts when ultraviolet light (hv) hits a CFC molecule, and a chlorine atom breaks off:

$$CFCl_3 + hv \longrightarrow CFCl_2 + Cl$$

The Cl atom reacts with O_3, giving off O_2 and ClO. Two ClO molecules combine to form Cl_2O_2. When Cl_2O_2 encounters ultraviolet light, it disassociates, generating O_2 and two chlorine atoms.

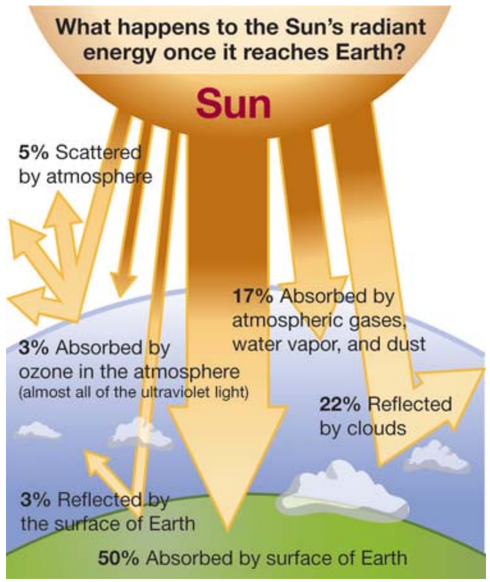
$$\begin{array}{ll} (1) & 2[Cl + O_3 \longrightarrow O_2 + ClO] \\ (2) & 2ClO \longrightarrow Cl_2O_2 \\ (3) & Cl_2O_2 + hv \longrightarrow 2Cl + O_2 \\ \hline & \text{Net: } 2O_3 + hv \longrightarrow 3O_2 \end{array}$$

As you can see, chlorine atoms are used in the first step but produced in the third. This means that a few chlorine atoms can repeat this sequence of reactions again and again, destroying a great many ozone molecules.

26.3 Energy in the Atmosphere

Our sun, through the process of nuclear fusion, converts 5 million tons of its own mass into energy every second. The sun broadcasts some of that energy as electromagnetic radiation. Earth receives only two-billionths of this radiation, but that is enough to sustain conditions needed for life here to exist.

What happens to solar energy once it enters Earth's atmosphere?



Outgoing radiation

So how does the energy that radiates from Earth get back out to space?

As Earth's surface absorbs incoming solar radiation, it gives off infrared radiation. Some of the infrared radiation is absorbed by air molecules and the energy is transferred through the atmosphere by convection, evaporation, condensation, and radiation. Eventually, the energy is transferred all the way back out to space.

Incoming radiation

Even though Earth intercepts only a tiny fraction of the radiation broadcast by the sun into space, this radiation provides most of Earth's thermal energy. About half is absorbed by Earth's surface, about a quarter is absorbed or scattered by the atmosphere, and about a quarter is reflected directly back to space.

Earth's average temperature stays constant

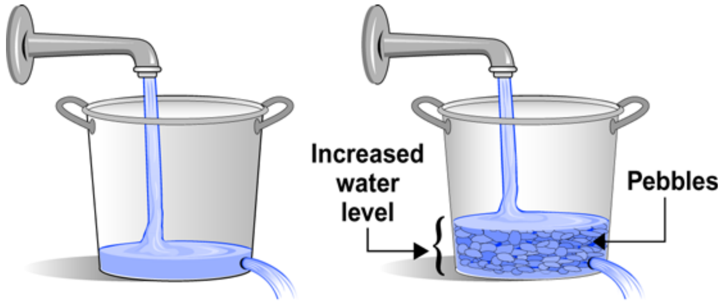
Every day, Earth absorbs more and more radiation from the sun. Why doesn't the planet just keep getting hotter? Earth's temperature remains at a relatively constant average of 27°C because the same amount of energy that is absorbed by Earth radiates out from Earth as infrared radiation. See the sidebar at right to find out more about how the energy radiating from Earth gets back to space.

The greenhouse effect and global warming

Greenhouse effect

You have probably heard of the greenhouse effect. This phrase, first used in 1937, describes the fact that molecules in the atmosphere keep Earth warmer than it would be without an atmosphere. How does this work?

Imagine an empty bucket with a hole near the bottom. If you pour water into that bucket at the same rate that the water spills out the hole, the bucket will never get full. However, if you fill the bucket partially with pebbles, it will take longer for the water to get through the bucket and out the hole. Even though the same amount of water still enters and exits the bucket, the water level in the bucket now stays at a constant *non-zero* level.

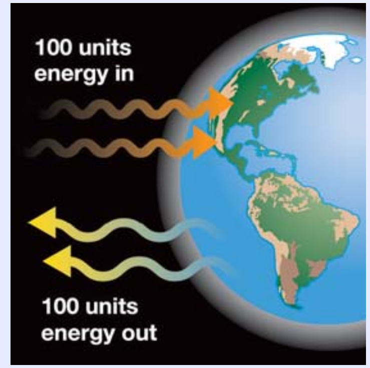


There are molecules in the atmosphere that act like the pebbles in the bucket. They make it take longer for the infrared radiation to escape back into space. Even though the same amount of energy (like the water in the bucket) is constantly coming into and leaving the planet, it takes time for the energy to pass through the atmosphere. While this energy remains in the atmosphere, it keeps Earth warm.

Greenhouse gases and global warming

Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water (H_2O), the so-called "greenhouse gases," are the molecules that act most like the pebbles in the bucket. Notice that all of the greenhouse gas molecules have at least three atoms joined together. They are larger than the nitrogen (N_2) and oxygen (O_2) molecules that make up most of Earth's atmosphere. Their large size makes them very good absorbers of infrared radiation. As a result, they are most responsible for increasing the time that the sun's energy remains in the atmosphere. The longer this energy remains in the atmosphere, the warmer Earth's average temperature will be. We call this process global warming.

Earth's "energy budget"



For every 100 units of radiation that enters Earth's atmosphere, 100 units exit. The incoming radiation is mostly in the form of visible and ultraviolet light. These light waves have higher frequency and shorter wavelength than the infrared waves that are emitted by Earth. They pass through the atmosphere faster than the infrared rays. The time lag between incoming and outgoing radiation means that there is energy in the atmosphere keeping Earth warm.

Some global warming occurs naturally

Some global warming due to greenhouse gases is normal on Earth. For centuries before the Industrial Revolution, the amount of carbon dioxide in the atmosphere was 0.028 percent, or 280 parts per million. This naturally produced CO_2 kept Earth at an average temperature about 30°C warmer than it would have been without any CO_2 in the atmosphere.

While some global warming occurs naturally, human activities add extra greenhouse gas molecules to the atmosphere, which may warm the planet further.

CO_2 levels increasing

The present amount of CO_2 in the atmosphere is 370 ppm. Scientists project the level will rise to 700 ppm by 2100, due mainly to the burning of fossil fuels. Higher CO_2 levels may cause climate changes. Seven hundred parts per million would probably cause an increase in average global temperature of 1.5 to 3.5°C. Although this increase may seem insignificant, it could have far-reaching effects.

Ocean flooding and erosion

Scientists have already observed that the open waters amid the floating ice on the Arctic Ocean are expanding every year because the glaciers are melting. In the past century, ocean levels have risen between 10 and 25 centimeters, according to the Intergovernmental Panel on Climate Change. Along with the flooding that may occur if this trend continues, coastal areas would be subject to stronger wave action, resulting in greater erosion and large-scale destruction of both property and natural habitat.

Altered agricultural areas

Areas such as the Great Plains in the United States might become drier and dustier because of increased evaporation resulting from higher average temperatures. This could cause much of the rich topsoil to blow away, leaving desert-like conditions behind. However, areas of Canada, Northern Europe, and Siberia that are now too cold for significant farming could become suitable for agriculture.

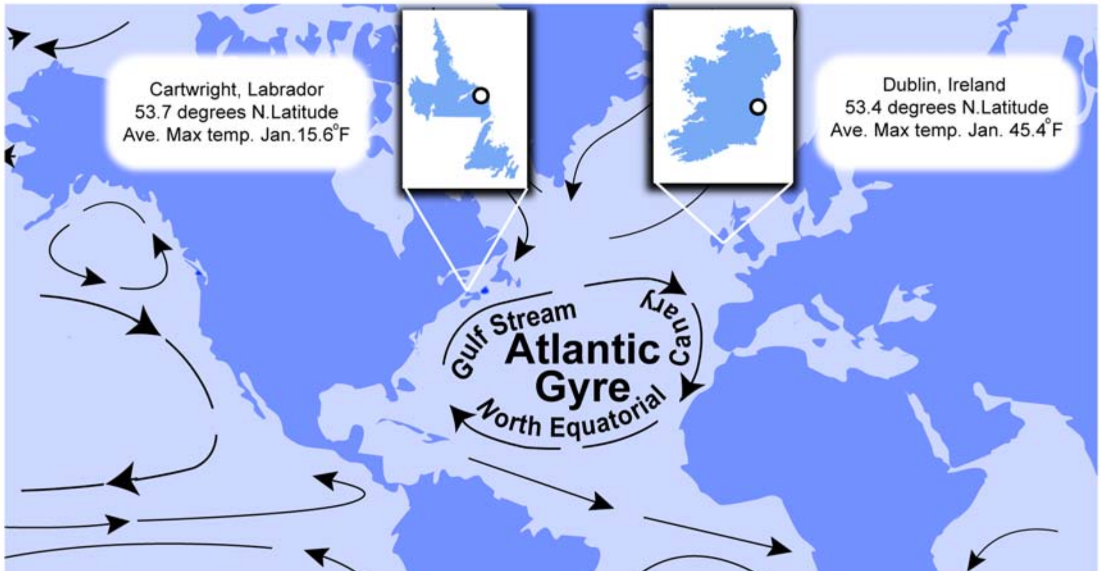
Figure 26.10: *Adding greenhouse gases to the atmosphere is like adding more pebbles to the bucket. It takes longer for radiation to escape from the atmosphere, so Earth's average temperature rises.*

Global warming on Venus

The planet Venus, as you may remember, has an atmosphere 90 times denser than Earth's. Most of Venus's atmosphere (96%) is made up of carbon dioxide, one of the greenhouse gases. The carbon dioxide slows the rate at which radiation escapes from the atmosphere. As a result, the average surface temperature on Venus is more than 500°C. Even though Mercury is closer to the sun, Venus is the hottest planet in the solar system, due to its thick atmosphere.

Change in ocean current paths

The increase in average global temperature could cause some shifting of big ocean currents, actually causing certain parts of the world to become cooler. For example, if the direction of the Gulf Stream current changed, the British Isles, which are at the same latitude as the northern portion of Canada's Labrador and Newfoundland province, would be much colder than they are now.



Reducing greenhouse gas emissions will require more than one solution

Lowering greenhouse gas levels will require more than one approach. Reducing power plant emissions and reducing the use of gasoline-powered cars and trucks are two important proposals. New technologies that produce fewer greenhouse gas emissions, such as the gas-electric hybrid car and hydrogen fuel cell, also play a significant role. Reviving some older methods of transport, such as using barges and trains for intercity transport of consumer goods, could also reduce greenhouse gas emissions.

For discussion:

1 Which of the changes listed above would be easiest to bring about?
2 How do you think governments should encourage and/or enforce these changes?
3 What additional steps should be taken to lower greenhouse gas levels?

Hydrogen-powered cars

Someday, you may drive a car with zero greenhouse gas emission. Hydrogen-fuel cell researchers are working with automobile manufacturers to design and test cars that run on a system of battery-like cells that convert hydrogen and oxygen to water, producing electricity and heat.

These hydrogen fuel cells are currently used by NASA to power the space shuttles' electrical systems. The only by-product of the fuel cells is water—which the astronauts use for drinking.

The biggest challenge facing researchers is finding the best source of hydrogen. Pure hydrogen is hard to store and transport. One proposal is to use methanol, which can be stored and delivered like gasoline. A device called a reformer removes hydrogen from methanol and delivers it to the fuel cell.

Chapter 26 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1.	atmosphere	a.	Most abundant gas in Earth's atmosphere
2.	atmospheric pressure	b.	Increases rapidly as altitude increases
3.	oxygen	c.	Measurement of force of air molecules in the atmosphere at a given altitude
4.	nitrogen	d.	Layer of gases surrounding a planet
5.	carbon dioxide	e.	Most abundant gas in atmosphere of Venus
		f.	21% of Earth's atmosphere

Set Two

1.	mercury barometer	a.	Standard air pressure at sea level
2.	aneroid barometer	b.	Air pressure at sea level is 29.2 ___________
3.	1atm	c.	Measures atmospheric pressure by the rise and fall of mercury in a tube
4.	inches of mercury	d.	The three-atom form of oxygen
5.	ozone	e.	A molecule that is harmful to humans when found in the stratosphere
		f.	Airtight cylinder made of thin metal, with walls that squeeze in or bulge out depending on atmospheric pressure

Set Three

1.	ionosphere	a.	Region of atmosphere 50 to 80 km above Earth's surface; meteoroids burn up here
2.	mesosphere	b.	Bottom layer of Earth's atmosphere; contains 90% of atmosphere's mass
3.	stratosphere	c.	Outer region of Earth's atmosphere; has very high temperatures
4.	thermosphere	d.	Region of the atmosphere where all of the oxygen is found
5.	troposphere	e.	Region of atmosphere in which the sun's ultraviolet rays ionize atoms and molecules
		f.	Layer of atmosphere from 11 to 50 km above Earth, with thin layer of ozone near the top

Set Four

1.	greenhouse gases	a.	The energy Earth receives from the sun
2.	global warming	b.	Chemicals formerly used in air conditioners and aerosol spray cans
3.	electromagnetic radiation	c.	Given off by Earth and its atmosphere as heat
4.	infrared radiation	d.	Large molecules that trap Earth's heat and are increasing the temperature of the planet
5.	chlorofluorocarbons	e.	An increase in Earth's temperature due mainly to increased CO_2 in the atmosphere
		f.	The three-atom form of oxygen

Concept review

1. What is in Earth's atmosphere? How has life on Earth changed Earth's atmosphere?
2. Explain how Earth's atmosphere formed.
3. Name one type of barometer and explain how it works.
4. Describe the four layers of Earth's atmosphere. Be sure to include the thermal characteristics of each layer.
5. Describe what would happen to Earth's water cycle if the top of the troposphere were as warm as the surface of Earth.
6. What is ozone? Where in Earth's atmosphere is it found? How does ozone affect your life?
7. If Earth constantly receives energy from the sun, why doesn't it keep getting hotter and hotter?
8. What would happen to Earth if there were no "greenhouse effect?"
9. What might happen to Earth if the amount of greenhouse gases in the atmosphere doubles? Name two possible outcomes.
10. List two ways that humans have increased the amount of greenhouse gases in the atmosphere. Suggest a means of reducing each.

Problems

1. Venus has an atmosphere that is much denser than Earth's, while Mars' atmosphere is much less dense than Earth's. Use the library or Internet to research how oceans on Venus and Mars may have affected the density of their atmospheres.
2. Carbon dioxide is the most abundant gas in the atmospheres of Venus and Mars. Why is this not true of Earth? Name at least one way that carbon is stored on Earth.
3. Would you expect a barometer to have a higher reading in Alaska's Denali national park or in Florida's Everglades national park? (Hint: An atlas may help you.)
4. Earth receives most of its energy from the sun. However, some of Earth's energy is internal energy. What is the primary source of this internal energy? What percentage of Earth's total energy comes from this source?
5. Scientists use computer models to predict the effect of the increase in greenhouse gases on the planet. What are some of the benefits and limitations of computer modeling systems?
6. The "ozone hole" above Antarctica varies in size over the course of a year. What causes the natural variation in the ozone layer?
7. Mexican chemist Mario Molina first wondered about the effects of chlorofluorocarbons in the atmosphere in 1973, when he was a graduate student in California. In 1996, he and two colleagues were awarded the Nobel prize in Chemistry for their discovery and exposure of the role of CFC's in ozone depletion. Research the life and work of Mario Molina. Develop an illustrated timeline of the twenty-three years he spent working on this project.

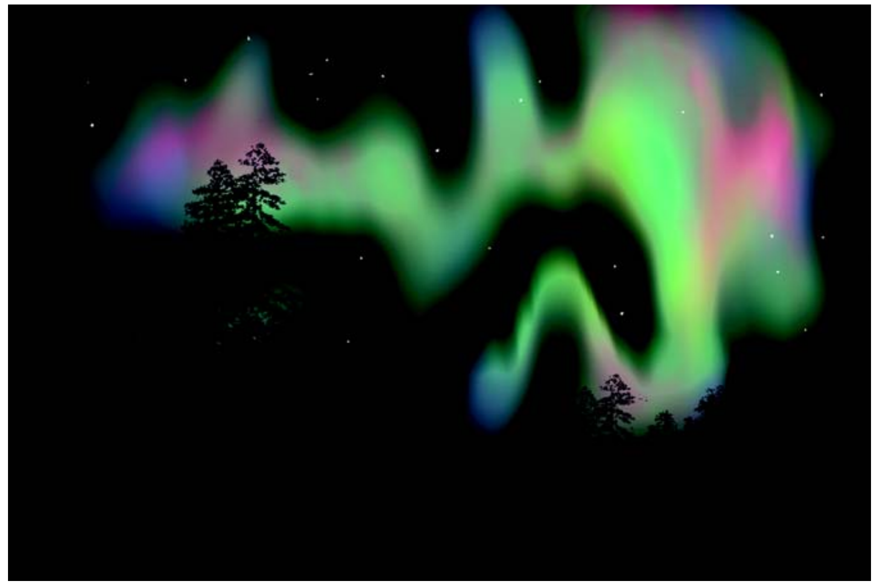
Applying your knowledge

1. Satellites are used for many different purposes, including weather monitoring, communications, intelligence gathering, and for collecting images of the universe through special telescopes. Research one type of satellite and provide a 5 minute report to your class about how it works, the shape and speed of its orbit, and how it affects your daily life.

2. Visitors to high-altitude regions may suffer from Acute Mountain Sickness (AMS) if they do not allow their bodies to acclimate to the new surroundings. Research guidelines for preventing this condition. Design a brochure for travelers that describes symptoms of AMS and provides recommendations for preventing and/or treating them.

3. The Kyoto Protocol is a 1997 document that came out of a United Nations-sponsored meeting to address the issue of reducing greenhouse gas emissions. Use a library or the Internet to research the Kyoto Protocol. What are some of the means it suggests for reducing greenhouse gas emissions? What are some of the arguments for and against putting these ideas into practice?

4. If you live in or visit high-latitude regions during the winter months, you may have the opportunity to observe an aurora in the nighttime sky. An aurora looks like a curtain of colored light flickering in the sky. Use a library or the Internet to find out what causes the auroras, which layer of the atmosphere is involved, and which locations on Earth provide the best viewing sites. You may wish to search the terms “aurora borealis,” as auroras are known in the northern hemisphere, “aurora australis,” as they are known in the southern hemisphere, or “northern lights,” the common term for this phenomenon.



UNIT 9
Energy in the Earth System

Chapter 27
Weather and Climate

Why does the temperature on Earth vary from place to place? What causes wind and ocean currents? How do you read a weather map? In this chapter you will find answers to these and other questions about weather, storms, and climate.

27.1	Variations in Earth's Heating and Cooling	*How can we demonstrate the seasonal changes in incoming solar radiation?*

In this Investigation you will use a globe, solar cell, and flashlight to model the seasonal changes in intensity of solar radiation due to the tilt of Earth's axis.

27.2	Global Winds and Currents	*How are currents, temperature, and ocean salt related?*

In this Investigation you will model how water temperature and saltiness change the density of ocean currents. These changes cause currents to float, sink, plunge to the ocean bottom and jet to the surface.

27.3	Weather patterns	*How is relative humidity measured?*

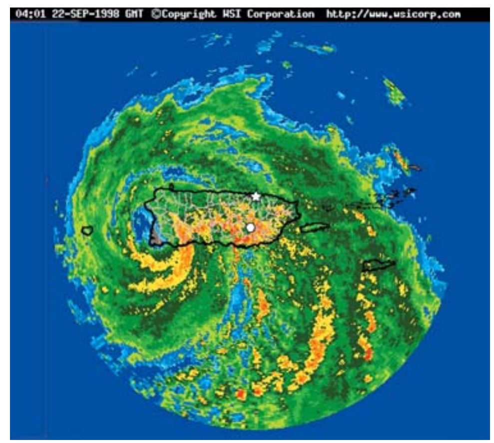
In this Investigation you will make and use a sling psychrometer to measure and graph water content in the atmosphere.

27.4	Storms	*How does Doppler radar work?*

In this Investigation you will learn how Doppler radar works and how it is used to track storms and other weather events.

27.5	Weather and Climate	*How do zoos model climates?*

In this Investigation you will research an animal living in a particular biome and design a suitable zoo habitat for the animal.



Learning Goals

In this chapter, you will:

- ✔ Learn how Earth's rotation, Earth's axial tilt, and distance from the equator cause variations in the heating and cooling of Earth.
- ✔ Learn how the heating of Earth's surface and atmosphere by the sun causes convection cycles in the atmosphere and oceans, producing winds and ocean currents.
- ✔ Learn about tools meteorologists use to predict weather, and how to read a weather map.
- ✔ Make and test your own weather instrument.
- ✔ Model a doppler radar system.
- ✔ Learn about the physical features that interact to form the climate of each of six important land biomes.

Vocabulary

air mass	El Niño-Southern Oscillation	longitude	temperate forest
biome	grassland	polar easterlies	temperature inversion
cold front	gyres	prevailing westerlies	trade winds
Coriolis effect	isobars	stratiform cloud	tropical rainforest
cumuliform cloud	jet stream	stratocumulus cloud	tundra
desert	latitude	taiga	warm front

27.1 Heating and Cooling of Earth

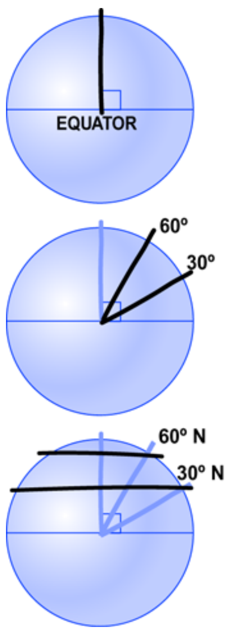
Why isn't Earth evenly heated by the sun? In this section you will learn how the heating and cooling of Earth is affected by several factors. These include Earth's tilt and position in space, global wind patterns, ocean currents, and the high specific heat of water. To understand this complex system, you will build on what you know about radiation, conduction, convection, and specific heat.

Identifying locations on Earth

Satellite data is used to map patterns of heating and cooling

Much of the data that scientists collect about patterns of heating and cooling on Earth comes from satellite images (Figure 27.1). The National Oceanic and Atmospheric Administration (or NOAA) uses infrared photography to map how much heat is reflected or emitted from different areas of Earth each day. Scientists who analyze this data need a way to pinpoint locations on the infrared photographs of Earth. One common system is with a man-made grid of latitude and longitude lines (Figure 27.2).

Latitude lines



Latitude lines measure distance from the equator. These lines run parallel to the equator and are labeled in degrees north or degrees south (Figure 27.3).

To figure out how the lines were originally labeled, draw a line on a globe from the north pole straight down to the equator. This line forms a 90-degree angle with the equator.

Next, draw 30- and 60-degree angles between the equator and the north pole.

Finally, draw lines parallel to the equator along these measured angles. These are the 30-degree north and 60-degree north latitude lines.

The same process is used to measure latitude in degrees south of the equator. You can find information about the latitude of a particular location by consulting an atlas or the Internet.

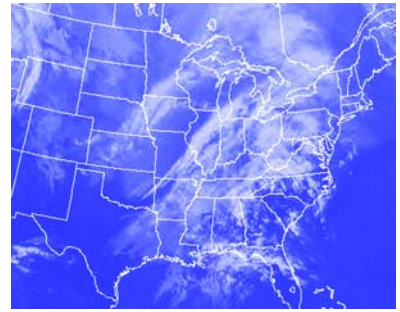


Figure 27.1: *This image shows infrared radiation emitted by cloud tops, land, oceans, ice, or snow. The coldest areas (usually high clouds in the atmosphere) appear the brightest white. NOAA photo.*

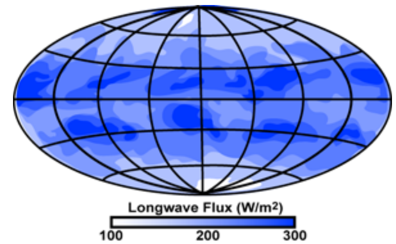


Figure 27.2: *Scientists use data from infrared photographs to map heat emitted from Earth's surface. NASA image.*

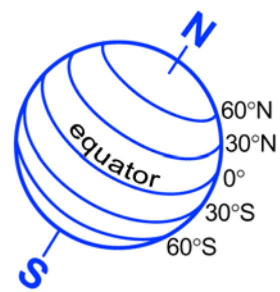


Figure 27.3: *Latitude lines.*

Longitude lines

Longitude lines run vertically from the north pole to the south pole. There are 360 equally-spaced longitude lines around the globe. The line that runs through Greenwich, England, is labeled 0 degrees longitude and is called the prime meridian. Lines *east* of the prime meridian are numbered from 1 to 179 degrees east, while lines *west* of the prime meridian are numbered from 1 to 179 degrees west. The 0- and 180-degree lines are not labeled east or west.

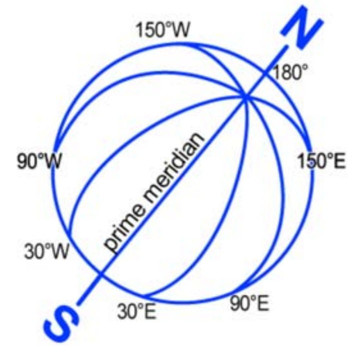


Figure 27.4: *Longitude lines.*

Latitude and longitude lines form a grid

Latitude and longitude lines form a grid that scientists use to locate various points on a satellite photo. This enables them to use the photos for climate research. For example, they can measure the spread of desert conditions across isolated parts of Africa, or compare the date each year when ice sheets melt in remote arctic locations.

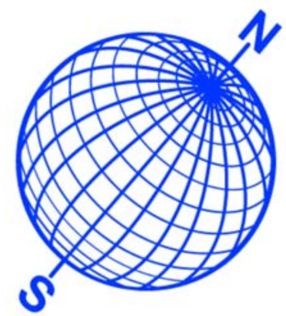


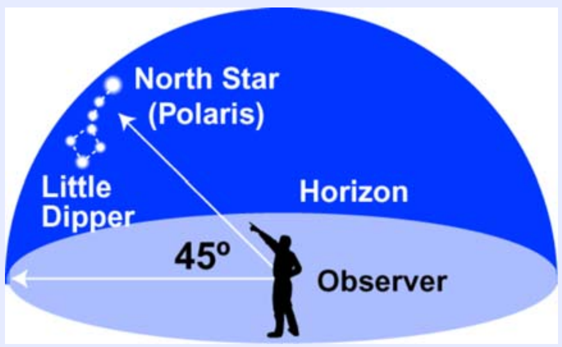
Figure 27.5: *Latitude and longitude lines form a grid.*

Try this!

On a clear night, you can use the North Star to estimate your own latitude.

The North Star is located at the end of the handle of the Little Dipper (the seven principal stars in the constellation Ursa Minor).

Once you locate the North Star, point to it with one outstretched arm. Extend your other arm toward the horizon.



Have a friend use a protractor to estimate the angle formed by your two arms.

The measure of the angle tells you your latitude. If the angle is 45 degrees, then you are located around 45° N latitude.

Temperature and latitude

Earth's temperature varies with latitude

In the northern hemisphere, we often associate "going south" with "getting warm." Birds, for example, fly south for the winter. States in the American South and Southwest are known as the sunbelt states. But in the southern hemisphere, the opposite is true. Birds fly north for the winter. The warmest part of Australia is the northern section. Generally, as latitude (or distance from the equator) increases, the amount of incoming solar radiation decreases.

At higher latitudes, solar radiation is less intense

The hottest part of Earth is near the equator, where the sun is closest to directly overhead year round. At the north and south poles, temperatures are much colder. To understand why, imagine shining a flashlight on a sheet of paper as in Figure 27.6. It makes a very bright, small spot. However, if the piece of paper is at an angle, the light is spread out over a larger spot and is less intense. The same thing happens to the sun's energy, which reaches the north and south poles at an angle. There, sunlight is spread out and thus less intense, while at the equator, the sunlight is direct and more intense (Figure 27.7). As a result, the average yearly temperature at the equator is 27°C (80°F), while at the north pole it is -18°C (0°F).

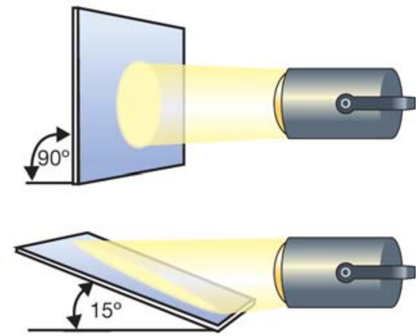


Figure 27.6: *If you hold a piece of paper at a 90-degree angle to a lamp and then at a 15-degree angle, where does the light have a larger area? Where is the light brightest and hottest?*

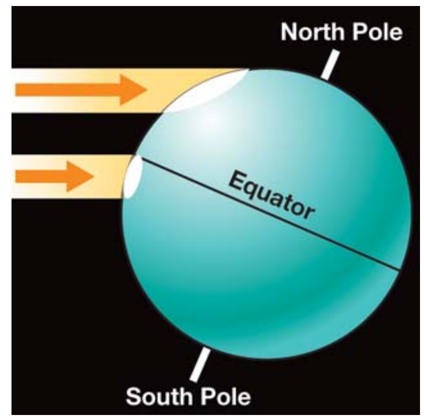
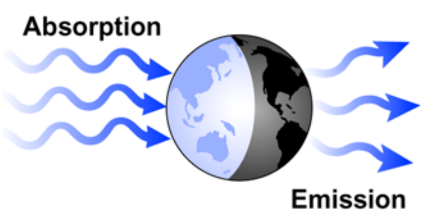


Figure 27.7: *This is how the sun's radiation reaches Earth. Sunlight is more intense at the equator.*

Temperature and Earth's rotation

Daytime heating and nighttime cooling



As Earth rotates, the portion of the globe facing the sun absorbs more solar radiation than it emits, and warms. Earth constantly emits some of the absorbed energy as infrared radiation. This emission of heat cools the dark side of the planet. Have you ever noticed that clear nights are often cooler than cloudy ones? That's because on a clear night, more of the emitted radiation escapes into space. Clouds absorb some of the radiation emitted by Earth's surface, keeping temperatures near the ground a little warmer.

Daytime heating in Arctic regions

You may know that in summer, the arctic regions experience daylight almost around the clock. With all that time to absorb heat, why don't they get very warm? There are two reasons. First, the sunlight is not intense, and second, snow reflects a great deal of the incoming radiation. Only a small percentage is absorbed.

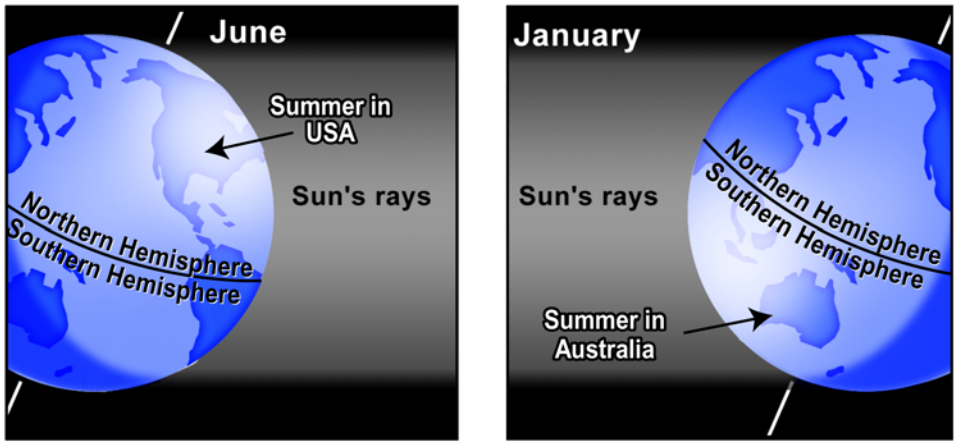
Why does Earth have seasons?

A common misunderstanding

Why is it cold in the winter and hot in the summer? Many people believe the answer is that Earth is closest to the sun in summer and farthest away in winter. In reality, distance from the sun has very little to do with seasons. Earth's orbit is almost circular. The difference between Earth's maximum and minimum distance from the sun is too small to cause changes in the seasons.

Earth's tilt causes seasons

The reason we have seasons is that Earth's axis is tilted at an angle. In January, the northern hemisphere is tilted away from the sun, and the southern hemisphere is tilted toward the sun. Rays of sunlight reaching the northern hemisphere are more spread out and less intense than those reaching the southern hemisphere. As a result, it is winter in the northern hemisphere and summer in the southern hemisphere.



As Figure 27.8 shows, in June, Earth has traveled halfway around its orbit and is on the opposite side of the sun. Now the northern hemisphere is tilted toward the sun. It receives more direct solar energy, and experiences summer conditions. The southern hemisphere is tilted away from the sun in June, and experiences winter.

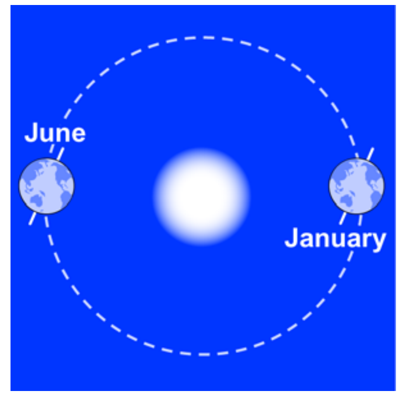


Figure 27.8: *Because of the tilt of Earth's axis, in June the northern hemisphere is tilted toward the sun. In January, the southern hemisphere is tilted toward the sun.*

27.2 Global Winds and Ocean Currents

Did you know that if Earth were heated evenly, there would be no wind? It's hard to imagine life without pleasant breezes or gigantic gales. In this section, you will learn why Earth is a windy planet, and how global winds create ocean currents.

Convection in the atmosphere

Thermals are small convection currents in the atmosphere

Have you ever seen a hawk soaring above a highway and wondered how it could fly upward without flapping its wings? The hawk is riding a *thermal*—a convection current in the atmosphere. A thermal forms when a surface like a blacktop highway absorbs solar radiation and emits energy as heat. That heat warms the air near the surface. The warmed air molecules gain kinetic energy and spread out. As a result, the heated air near the highway becomes less dense than the colder air above it. The heated air rises, forcing the colder air to move aside and sink toward the ground. Then this colder air is warmed by the heat from the blacktop, and it rises. A convection current is created. Hawks and other broad-winged birds often ride the rising warm air several hundred meters high!

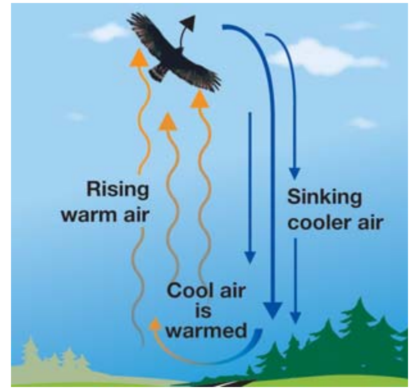


Figure 27.9: *Hawks ride convection currents called thermals.*

Giant convection currents

While thermals form on a local level, there are also giant convection currents in the atmosphere. These form as a result of the temperature difference between the equator and the poles. Warm air at the equator tends to rise and flows toward the poles. Cooler, denser air from the poles sinks and flows back toward the equator. When air flows horizontally from an area of high density and pressure into an area of low density and pressure, we call the flowing air wind.

Global wind cells

While it might seem logical that air would flow in giant circles from the equator to the poles and back, the reality is more complicated than that. The warm air from the equator doesn't make it all the way to the poles because of Earth's rotation. In fact, the combination of global convection and Earth's rotation sets up a series of wind patterns called *global wind cells* in each hemisphere (Figure 27.10). These cells play a large role in shaping weather patterns on Earth.

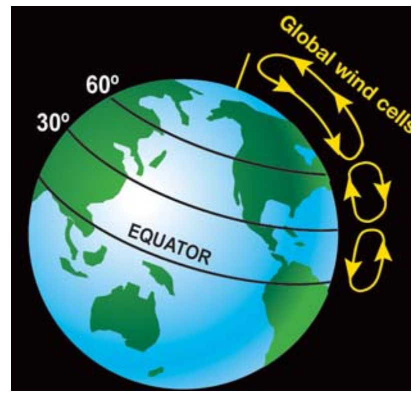


Figure 27.10: *These smaller circular wind patterns exist in both the northern and southern hemispheres. We call them global wind cells.*

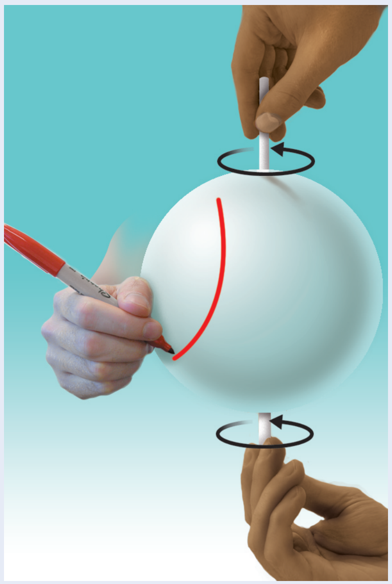
The Coriolis effect

Why does Earth's rotation affect the path of air currents?

To understand why Earth's rotation affects the path of air currents, imagine the following situation: You are a pilot who wants to fly an airplane from St. Paul, Minnesota, 700 miles south to Little Rock, Arkansas. If you set your compass and try to fly straight south, you will probably end up in New Mexico! Why? As you are flying overhead, Earth is rotating counterclockwise beneath you. This makes it appear that you have bent your path westward.

How air currents bend

The same thing happens with air currents. Because of Earth's rotation, cold air from the north pole flowing south seems to bend to the west, while warm air from the equator flowing north seems to bend to the east (Figure 27.12).



To understand why air currents seem to bend, try this demonstration:

Place a large Styrofoam ball on a skewer. Ask a partner to rotate the skewer so that the ball turns in a counterclockwise direction. Using a permanent marker, try to draw a line from the top of the ball toward an imaginary equator.

Next, start at the center and try to draw a line straight up. What happened?

Now turn the ball over and switch roles. Your partner should demonstrate the way air currents would flow in the southern hemisphere.

The Coriolis effect

This bending of currents is called the Coriolis effect, after the French engineer-mathematician Gaspard Gustave de Coriolis (1792-1843), who first described the phenomenon in 1835.

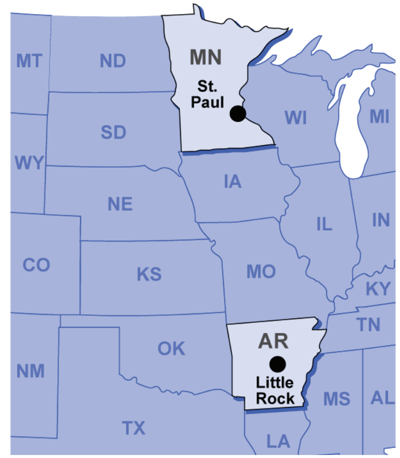


Figure 27.11: *Pilots planning to fly from St. Paul, Minnesota, to Little Rock, Arkansas, must take the Coriolis effect into account.*

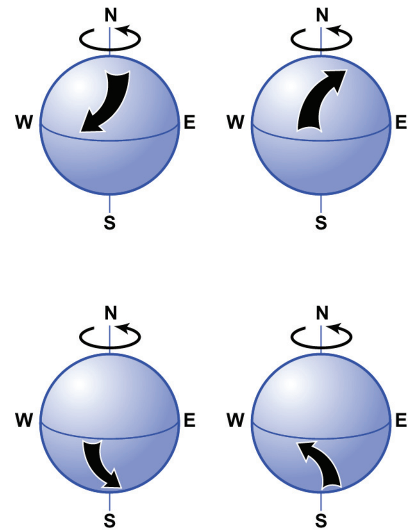


Figure 27.12: *Because of the Coriolis effect, global air currents seem to bend.*

Global wind patterns

There are three important global surface wind patterns in each hemisphere. These wind patterns have been very important to the history of civilizations, because cultures were spread across the globe by sailors following wind currents.

Describing wind Winds are described by the direction from which they originate. A west wind blows from the west toward the east. A southwest wind blows from the southwest toward the northeast. In the northern hemisphere, a southwest wind is associated with pleasant, warm breezes. Would the same be true in the southern hemisphere?

Trade winds The **trade winds** are surface wind currents that move between 30° latitude and the equator. You learned earlier that the air around the equator warms, rises, and flows toward the poles. At about 30°N and 30°S, it cools, sinks, and flows toward the equator again. The Coriolis effect bends the trade winds moving across the surface so that they flow from northeast to southwest in the northern hemisphere and from southwest to northeast in the southern hemisphere (Figure 27.13).

Polar easterlies Another major wind pattern is called the **polar easterlies**. Polar easterlies form when the air over the poles cools, sinks, and spreads along the surface to about 60° latitude. Like the other global winds, this polar wind is bent by the Coriolis effect. The air flows from northeast to southwest in the northern hemisphere, and from southeast to northwest in the southern hemisphere.

Prevailing westerlies Since the trade winds set up a high pressure area at about 30°N latitude and the rising air of the polar easterlies sets up a low at 60°N, air along the surface between 30° N and 60°N moves northward, from high to low pressure. The air bends to the right due to the Coriolis effect, creating the **prevailing westerlies**. Most of the United States is between 30°N and 60°N, so most of our weather patterns move from west to east. Using Figure 27.13 as a guide, can you describe how the prevailing westerlies move in the southern hemisphere?

The polar front At about 60 degrees latitude, the polar easterlies meet the prevailing westerlies, at a boundary called the polar front. Here the dense polar air forces the warmer westerly air upward. Some warmer air flows toward the poles, and some flows back toward the 30 degree latitude line, completing the middle global wind cell.

Sailing with the wind

The trade winds were named by sailors who crossed the North Atlantic in the 17th and 18th centuries in search of goods to bring back to Europe. The trade winds provided a helpful push on their journey west.

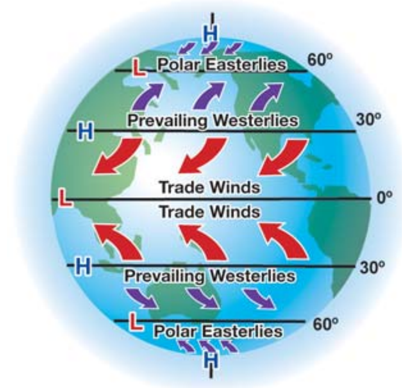


Figure 27.13: *Notice how the global surface wind patterns in the northern and southern hemispheres bend due to Earth's rotation. Can you see that the wind always flows from high pressure to low pressure?*

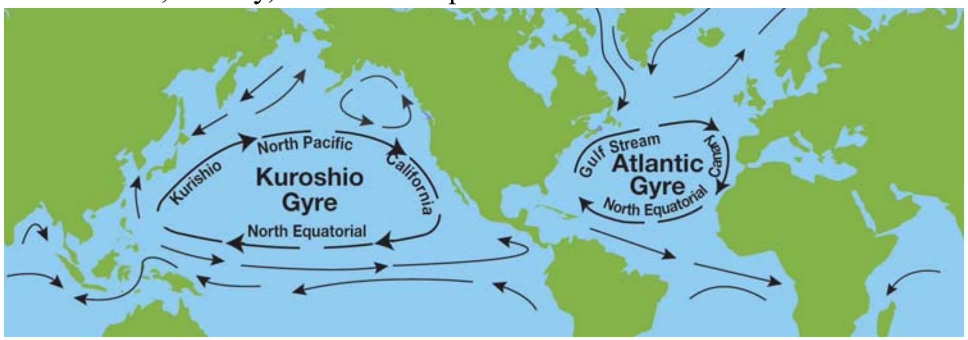
Surface ocean currents

What are surface ocean currents?

When a global wind moves over the surface of the ocean, it pushes the ocean water along its path. The global winds move ocean water in recognizable patterns that we call *surface ocean currents*. The Gulf Stream is one well-known example of a surface ocean current. The Gulf Stream moves northward from Mexico's Yucatan Peninsula, around the coast of Florida, and northeast to Nantucket Island, Newfoundland's Grand Banks, and then off toward the British Isles.

How surface ocean currents move

The global wind patterns and Earth's rotation cause surface ocean currents to move in large circular patterns called **gyres**. The gyres move clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. The major clockwise gyres are Kuroshio gyre in the Pacific, and the Atlantic gyre, formed by the Gulf Stream, Canary, and North Equatorial currents.



Deep ocean currents

Ocean currents can also occur deep within the ocean. These currents, called *thermohaline currents*, move slower than surface currents and are driven by temperature and density differences in the ocean. Surface and thermohaline currents work together to move huge masses of water around the globe.

Ocean currents and climate

Ocean currents play a big role in heating and cooling some parts of Earth. Did you know that you can find palm trees on the northeast coast of Scotland? This part of Scotland is on the same latitude as southern Norway and the northern tip of Newfoundland. But because the Gulf Stream surrounds Great Britain with warm water from the Caribbean, Scotland has much milder winters than other places at the same latitude.

Tracking ocean currents

Oceanographers often study ocean currents using high-tech methods like satellite infrared photographs that map ocean temperature. Since 1991, Oregon researcher Curtis Ebbesmeyer has been supple-menting this research with a low-tech but very effective method: studying cargo spilled from ships. His research has followed spills of 60,000 running shoes into the North Pacific, 29,000 bathtub toys into the waters near the International Date Line, and over 4.5 million plastic toy bricks off the coast of Britain. By mapping where these items wash ashore, researchers can make better mathematical models to predict the motion of objects in ocean currents and waves. These models can help predict the movement of oil spills and of lost ships, making cleanup or rescue easier and faster.

27.3 Weather Patterns

How do meteorologists predict the weather? What factors influence whether you will see sunshine, clouds, or precipitation on any given day? In this section, you will learn how air temperature, pressure, and water content in the atmosphere work together to produce different kinds of weather. You will explore cloud formation, precipitation, air masses, and fronts. You will learn what the symbols on a weather map mean, and how different kinds of storms develop.

What factors influence the weather?

Air temperature and pressure

You have already learned about two important factors that shape the weather in a given region: temperature and pressure. Higher temperatures cause air near the equator to expand and rise, initiating the processes that produce wind and ocean currents. Pressure differences between warm and cold air masses cause air to flow from regions of high to low pressure. The greater the difference in pressure, the greater the speed of the air flow, or wind.

Water in the atmosphere

A third important factor that shapes weather patterns is, of course, water. You cannot have rain, snow, sleet, or hail without water in the atmosphere. Even when the skies are totally blue, there is some water present in the atmosphere. The amount varies widely, from just 0.1 percent in the atmosphere above Antarctica to as much as 3 percent above a tropical rain forest. Why do clouds and precipitation sometimes form from this water, while at other times the skies are blue? It depends on the rate of phase changes happening in the atmosphere.

Temperature, air pressure, and water content in the atmosphere are the three most important factors that influence weather patterns.

Joanne Simpson

Joanne Simpson was born in Boston in 1923. As a child, she loved to watch clouds. She was fascinated with airplanes and earned her pilot's license at age 16. As a student pilot, Simpson had to take a meteorology course. She was fascinated by the processes that caused weather patterns. She enrolled in the University of Chicago's meteorology program.

Simpson completed a master's degree and wanted to earn her Ph.D. But the all-male faculty felt that women were unable to do the work, which included night shifts and flying planes. Simpson refused to give up. She became the first woman to receive a Ph.D in meteorology. Simpson went to Woods Hole Oceanographic Institute to study how tropical cumulus clouds called "hot towers" carry moisture, transfer heat, and release energy. She found that these hot towers release energy to the hurricane eye and act as a hurricane's engine.

Simpson is currently a NASA chief scientist at Goddard Space Flight Center, studying rainfall, satellite images, and hurricanes.

Phase changes in the atmosphere

Temperature and pressure influence phase changes

Recall from your study of properties of matter that the state of water (whether it is a solid, liquid, or gas) depends on both temperature and atmospheric pressure. As temperature increases, the random motion of the water molecules increases, and more of the bonds holding water molecules together are overcome (Figure 27.14). Therefore, as temperature increases, the rate of evaporation increases. But that's not the whole story. Pressure also affects changes of state. As atmospheric pressure decreases, it becomes easier for water molecules to escape from the liquid to the gas state (Figure 27.15). Therefore, a decrease in pressure also increases the rate of evaporation.

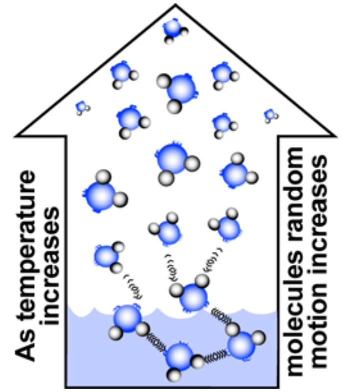


Figure 27.14: *As temperature increases, more bonds between water molecules are overcome.*

The three phases of water in the atmosphere

Water in the atmosphere exists in all three states. High in the troposphere, there are ice crystals. Tiny water droplets, much too small to see, are suspended throughout the troposphere virtually all the time. They are considered liquid water and not gas because they are made of microscopic "clumps" of water molecules. Other water molecules in the atmosphere are truly in the gas state, separate from all other molecules.

Water constantly changes phase

Because the combination of temperature and pressure in the atmosphere is constantly changing, water is constantly changing state. When the rate of evaporation in the atmosphere is greater than the rate of condensation, we see clearing skies.

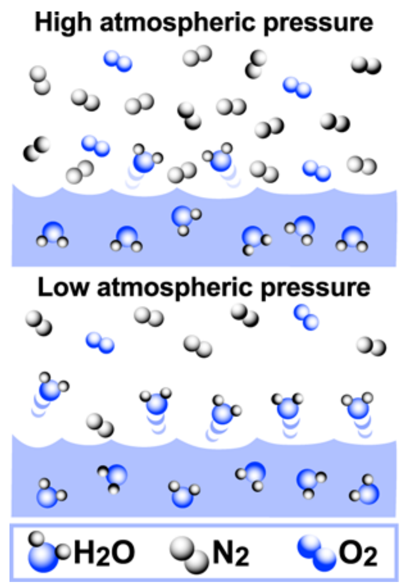


Figure 27.15: *Under low atmospheric pressure, water molecules more easily enter the gas state.*

Dew point

If the amount of water in the air remains constant, but the temperature decreases, the random motion of the water molecules will decrease. As a result, the rate of evaporation will decrease also. When the rate of condensation exceeds the rate of evaporation, we say that the air's **dew point temperature** has been reached.

When more water is condensing than evaporating, the air's dew point temperature has been reached.

Cloud formation

Different conditions cause different clouds

When more water in the atmosphere is condensing than evaporating, we begin to see the condensing water as clouds. Different kinds of clouds form under different conditions.

Cumuliform clouds

For example, **cumuliform clouds**, which look like heaps of popcorn with flat bottoms, form when pockets of air rise because of convection. These pockets of rising air usually form over land, especially an area like a blacktop road, which absorbs a great deal of heat. Why, then, don't we typically see a line of cumulus clouds right above a highway? It's because wind currents in the atmosphere blow the pockets of rising air around before they condense and form clouds.

Cumuliform clouds form when convection causes rising pockets of air in the atmosphere.

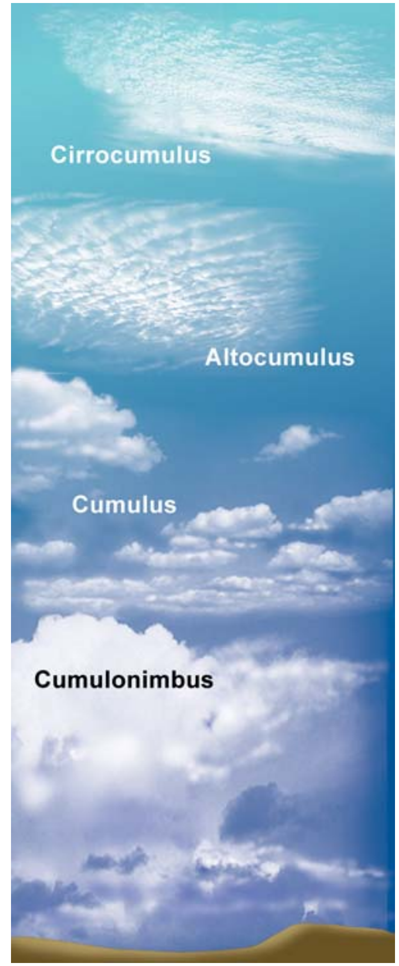


Figure 27.16: *Cumuliform clouds.*

Cirrocumulus

As these air pockets cool, the water evaporation rate decreases and more condensation is evident. The flat bottom of the cloud marks the level of the atmosphere where condensation first exceeds evaporation. Small, puffy "cotton ball" type clouds high in the atmosphere (above 6,000 meters) are called *cirrocumulus*. They usually indicate fair weather.

Altocumulus

Altocumulus clouds form between 2,000 and 6,000 meters high. They usually form larger, darker puffs than cirrocumulus clouds. Sometimes they appear in rows. If the altocumulus clouds have turret-like tops, they are called "altocumulus castellatus." These clouds often appear before a storm.

Cumulus

The base of a *cumulus* cloud is usually around 1,000 meters high, but it can extend to 5,800 meters. Cumulus clouds are the tall, puffy clouds that form when air over land is strongly heated. When the sun begins to set, cumulus clouds often dissipate.

Cumulonimbus

When a cumulus cloud grows dark and stormy looking, it is given a new name: *cumulonimbus*. Later, you will learn more about how thunderstorms develop from cumulonimbus clouds.

Stratiform clouds

Stratiform clouds form when a large mass of stable air gradually ascends over a mass of colder air or a gentle incline of land. As this air ascends, it expands and cools, allowing condensation to spread evenly throughout the layer. Stratiform clouds look like smooth, flattened blankets. They can cover as much as 300,000 square miles! A sky covered with stratiform clouds will appear uniformly gray.

Stratiform clouds form when a large mass of stable air gradually rises, expands, and cools.

Cirrostratus clouds look like a translucent white coating across the sky. They are high clouds, located at least 6,000 meters above the ground. Cirrostratus clouds are made of ice crystals. As a result, the sun shining through the crystals is refracted. The refracted light looks like a "halo" around the sun.

Altostratus clouds are the most easily recognizable stratiform clouds. If the sky looks like a smooth gray sheet and no shadows form on the ground, you are seeing altostratus clouds located between 2,000 and 6,000 meters high.

Below 2,000 meters, stratiform clouds are called simply *stratus* clouds. Stratus clouds look like fog that doesn't quite reach the ground. When a stratus cloud turns dark gray, it signals the approach of a weather front and rain to go with it. These rain clouds are called *nimbostratus*.

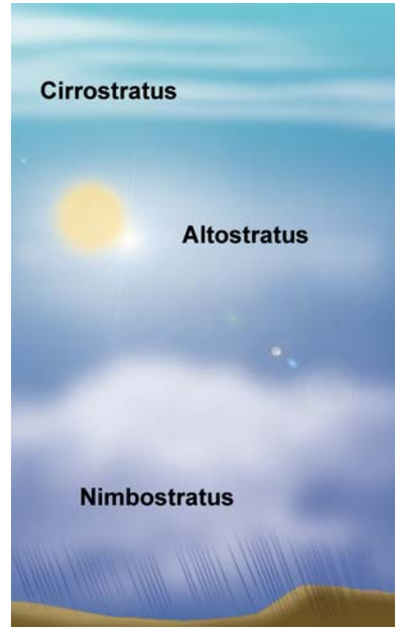


Figure 27.17: *Stratiform clouds.*

Figure 27.18: *Stratocumulus clouds.*

Figure 27.19: *Cirrus clouds.*

Stratocumulus clouds

Sometimes a cloud formation combines aspects of both cumuliform and stratiform clouds. We call these clouds **stratocumulus clouds.** They form when conditions in the atmosphere cause pockets of convection to occur within a stratiform cloud. As the rising air cools, the water in the pocket condenses, creating a cumuliform cloud within the stratiform cloud. This causes the formerly smooth cloud to look lumpy.

The last type of cloud doesn't look much like the other clouds—it is just a thin streak of white across a blue sky. **Cirrus clouds** are thin lines of ice crystals high in the sky, above 6,000 meters. If a cirrus cloud curves, it is commonly called a "mare's tail." The curving is due to a change in wind direction, and as a result may indicate that the weather is going to change.

Precipitation

How does rain form?

If you cool air to a temperature lower than the dew point, and the pressure remains constant, some water vapor condenses into liquid. At first, the water molecules condense on particles of dust called *condensation nuclei*. Once a few water molecules condense, they create a site for other molecules to condense too. What starts as just a few water molecules on a speck of dust quickly grows to millions of molecules that form a water droplet with the dust in the center. If the droplets reach about 1 to 10 microns in size, they form visible clouds. So if all clouds are liquid water, why don't all clouds produce rain? It all depends on the droplets' size. Small droplets are kept aloft by wind forces and air friction. If the droplets reach about 1,000 microns (1 millimeter), they become heavy enough that the wind forces and air friction cannot keep them aloft and they fall as raindrops.

Snow and sleet

Snow usually forms when both ice crystals and water droplets are present in the sky. The water droplets tend to attach to ice crystals and freeze there. When the ice crystals are large enough, they will fall to the ground as snow. However, if the air temperature near the ground is warm, the crystals will melt and the precipitation will fall as rain. Sometimes very cold air lies below warmer air, causing the water to refreeze and hit the ground as sleet.

Condensation warms the air

Condensation is actually a warming process. Why? Energy was needed to break the bonds holding molecules together when the water completed the phase change from liquid to gas. This energy (called latent heat) is released when the water changes back into the liquid form. As a result, if it is not too windy, you can sometimes feel the air warm up a few degrees when precipitation begins to fall.

Why does dew form?

Because the ground cools quickly, late at night or early in the morning the temperature of the ground is often below the dew point. Air near the ground gets cooled and some water vapor condenses in the form of dew. If the temperature is low enough, the dew freezes and we get frost.

Where does fog come from?

If air within a few hundred meters of the ground is cooled below the dew point, fog will form. Fog can form under several conditions. Warm moist air could move over a cooler surface. The ground below could cool below the dew point at night. Either way, fog consists of suspended water droplets. Fog is a ground-level cloud.

Meredith Charles Gourdine

Meredith Gourdine was born in Newark, New Jersey in 1929. During high school, Meredith spent many hours helping his father, a painter and janitor, at work. Meredith paid his own expenses for most of his first two years at Cornell University. There, Gourdine discovered he had a knack for track and field. He went on to win a silver medal in the long jump at the 1952 Olympics in Helsinki, Finland.

Gourdine earned his Ph.D. in Engineering from the California Institute of Technology. He showed that if you apply a negative charge to particles in the air, they become electromagnetically attracted to the ground, and drop down. This allows fresh air to move in to the space the particles had occupied. Gourdine used this process to invent a way to clear smoke from buildings, and fog from runways. Gourdine founded a research lab and a multimillion dollar corporation that developed commercial uses for his scientific research.

Gourdine lost his sight due to diabetes, but remained an active, creative scientist and entrepreneur until his death in 1998.

Air masses and fronts

What is an air mass? An air mass is a large body of air with consistent temperature and moisture characteristics throughout. Air masses can cover areas as large as 750,000 square miles. These air masses form when air remains stationary over an area long enough to take on the characteristics of the surface below. Two common air masses affecting the United States are the continental polar air mass, which forms over the Canadian plains, and the maritime tropical air mass, which forms over the Gulf of Mexico (Figure 27.20). The continental polar air mass contains cold, dry air. In contrast, the maritime tropical air mass contains warm, moist air.

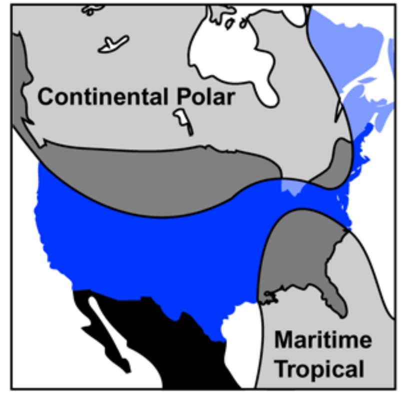


Figure 27.20: *Two major air masses that affect the weather across the United States.*

Air masses move Changing atmospheric conditions and global wind currents eventually cause these air masses to move. The continental polar air mass tends to slide south or southeast, while the maritime tropical air mass tends to slide north or northwest.

Cold fronts When two air masses collide, the result is called a *front.* Sometimes, cold air will move in and replace warm air at Earth's surface. This is known as a cold front. The warm air is forced sharply upward as the cold, denser air moves in. The cold air acts somewhat like a wedge, sliding under the warm air and pushing it up.

Cold fronts can produce rain or snowstorms As the warm air rises, it cools. This causes condensation (and often a band of rain or snow showers) to accompany the cold front. As a cold front moves through an area, the temperature and water content of the air decrease rapidly. The air sometimes cools as much as 15°F in the first hour!

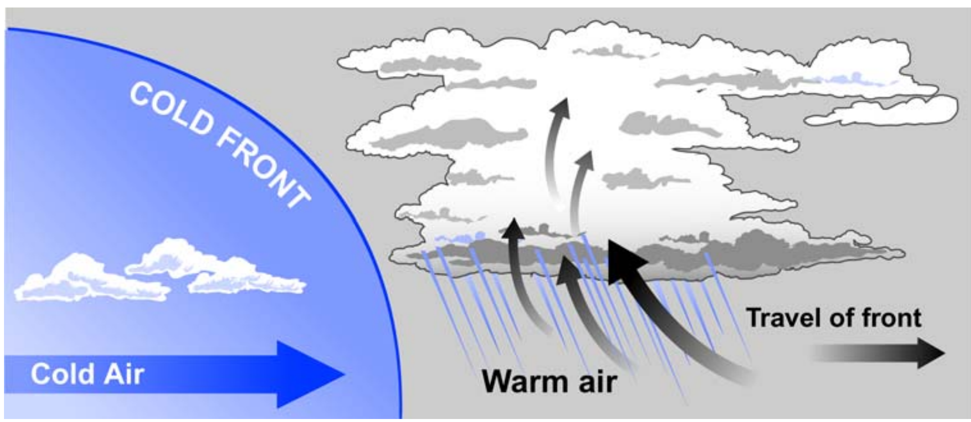


Figure 27.21: *On a weather map, a cold front is shown using a line marked with triangles. The triangles point in the direction the front is moving.*

Warm fronts

At other times, warm air advances, overtaking cooler air in a region. This is known as a **warm front**. The warm air slides up over the colder air. The warm air rises and cools, but in this case the lifting is very gradual and steady. As a result, long bands of light precipitation often move ahead of the warm front. As the warm front moves through an area, there will be a noticeable increase in temperature and moisture in the air.

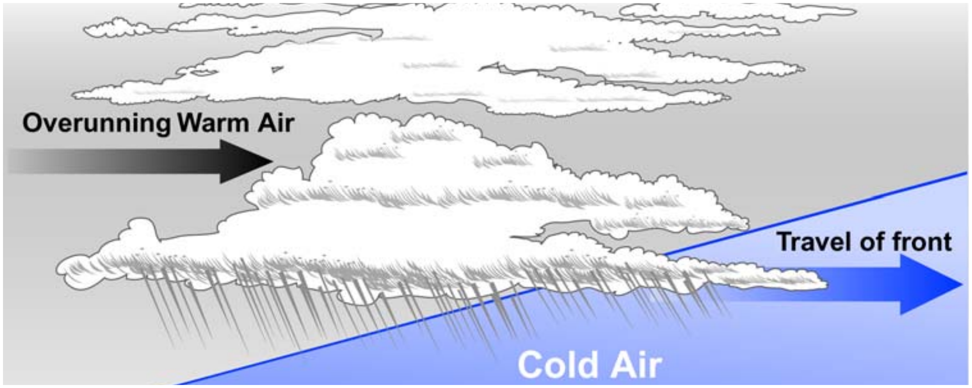


Figure 27.22: *On a weather map, a warm front is shown using a line marked with semicircles.*

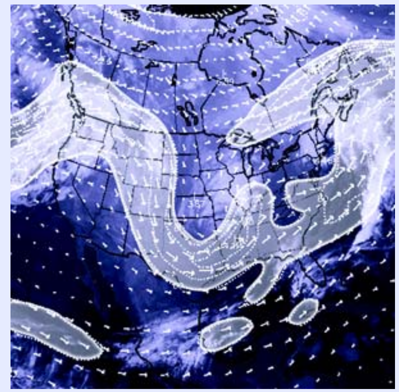
Jet streams and weather fronts

The movement of these large air masses is affected by high-altitude fast moving winds called the **jet streams**. There are two big jet streams in each hemisphere, formed where there are sharp boundaries between cold and warm temperatures. The jet stream winds are found near the top of the troposphere, and have speeds of at least 87 kilometers (54 miles) per hour, and sometimes as great as 320 kilometers (200 miles) per hour. The jet streams wind around the globe from west to east. In the winter, when the temperature difference between the poles and the equator is greatest, the jet streams attain their fastest speeds. The path of a jet stream can be altered by land features such as mountain ranges, or by giant cumulus clouds that act like boulders in a rushing river, changing the speed and direction of the flow. The rushing jet stream acts like a border between cold and warm air masses, so when it changes course, the air masses tend to move as well.

How were jet streams discovered?

Jet streams were discovered by World War II pilots attempting to cross the Pacific Ocean for the first time. On occasion, the plane's progress would come to a halt, because the jet stream was pushing the plane backward as fast as the engines were moving it forward! Today, pilots traveling west to east often try to ride the jet stream, while pilots flying east to west try to avoid it.

Satellite photos map the jet stream's path



This photo was taken by the GOES-8 satellite in orbit 36,000 kilometers above Earth. It shows the path of the jet stream, which helps meteorologists predict the path of weather fronts. NOAA photo.

Low and high pressure areas

How does a low pressure area develop?

When a cold front moves into a region and warm air is forced upward, an area of low pressure is created near Earth's surface at the boundary between the two air masses. Cold air rushes in to fill that low pressure region. This cold air forces more warm air to be pushed upward, and more cold air moves in. A cycle begins to develop. Due to the Coriolis effect, the air masses move in curved, rather than straight paths. As a result the moving air begins to rotate around the low pressure center. In the northern hemisphere, the moving air rotates counterclockwise around a low pressure center, while in the southern hemisphere, the air rotates clockwise. In both hemispheres, strong winds and precipitation are associated with these rotating systems.

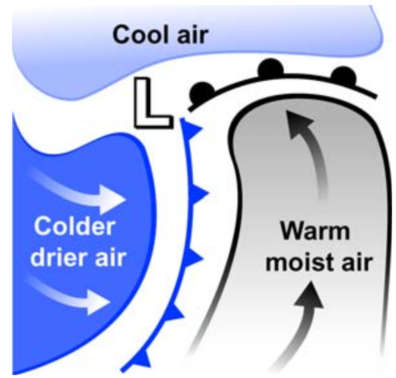


Figure 27.23: *A low pressure system as shown on a weather map.*

High pressure centers

A center of high pressure tends to be found where a stable cold air mass has settled in a region. Remember that colder air is denser than warm air, and therefore creates higher atmospheric pressure. Sinking air in a high pressure region inhibits the development of the upward air movement needed to create clouds and precipitation. High pressure areas, therefore, are associated with fair weather.

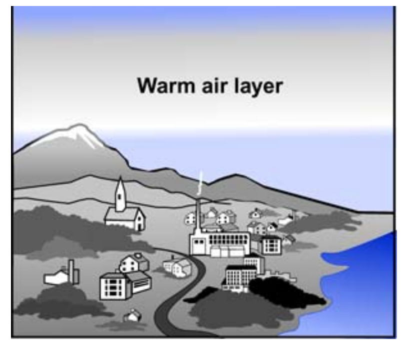


Figure 27.24: *An inversion traps airborne pollutants near the ground.*

What is a temperature inversion?

Although high pressure is usually associated with clear skies, a condition known as a **temperature inversion** can lead to haze or smog. A temperature inversion occurs when the temperature near the ground is actually colder than the temperature higher in the troposphere. For example, if cold air settles in a valley and warm air moves in above, the warm air caps the lower atmosphere like a ceiling. As a result, the warm pollutants that rise through the relatively cool lower atmosphere stop rising when they move into the warmer upper-level air. When these trapped pollutants are exposed to sunlight, smog is formed.

Isobars

Weather maps often contain information about areas of low and high pressure. The letters H and L are used to mark centers of high and low pressure. You may also see wavy lines or circles surrounding the letters. These lines are called **isobars**. To create the isobars, meteorologists collect atmospheric pressure data from weather stations throughout the regions. Then they draw a line to connect the places that have the same atmospheric pressure. Drawing isobars helps them pinpoint the location of high and low pressure centers, and provides information about the movement of weather systems.

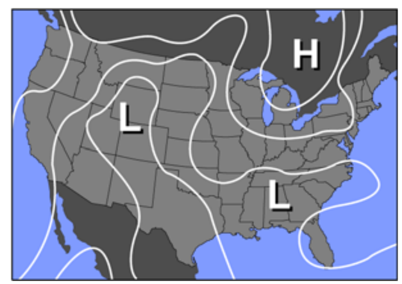


Figure 27.25: *Isobars show areas with the same atmospheric pressure.*

27.4 Storms

In the previous section, you learned that air temperature, atmospheric pressure, and water content in the atmosphere are the three ingredients that most influence the weather. In this section, you will explore how those three ingredients interact to create thunderstorms, hurricanes, and tornados.

Thunderstorms

How storm cells form

Thunderstorms arise when air near the ground is strongly warmed and rises high into the troposphere. As the air rises, it cools and condenses, forming a towering cumulonimbus cloud. Eventually some of the cloud droplets become large enough to fall as rain. Some of the colder air from high regions is dragged along with the falling rain, causing a downdraft of cooler, denser air. This downdraft, along with the updraft of rising warm air, forms a type of convection cell called a *storm cell* within the cloud.

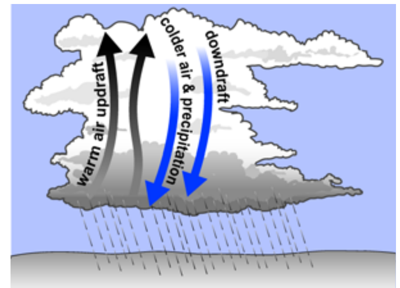


Figure 27.26: *A storm cell.*

Lightning and thunder

The process that causes lightning and thunder begins when vapor particles within the storm cell collide, and electrical charges are transferred from one particle to another. Positive charges tend to build up on smaller particles and negative charges on bigger ones. The forces of gravity and wind cause the particles to separate. Positively charged particles accumulate near the top of the cloud and negatively charged particles fall toward the bottom. The negatively charged particles at the bottom of the cloud repel negative charges in the ground, causing the ground to become positively charged. This positive charge is why people who have been struck by lightning sometimes say they first felt their hair stand on end.

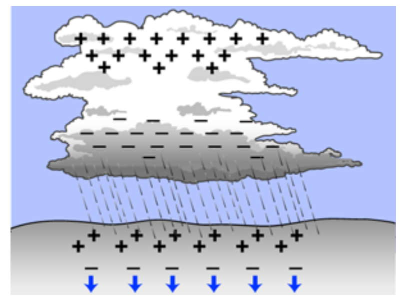


Figure 27.27: *Electrical charges build up in storm cells, causing flashes of lightning.*

The negative charges in the cloud are attracted to the positively charged ground. When enough charges have been separated by the storm, the cloud, air, and ground act like a giant circuit. All the accumulated charges flow from the cloud to the ground, heating the air along the path so that it glows like a bright streak of light. When the heated air expands, we hear thunder.

A thunderstorm's end

Eventually, the downdrafts in the storm cell bring enough cool, drier air to ground level that the supply of warm, moist air is depleted. The updraft stops flowing, the rain tapers off, and the thunderstorm ends.

Hurricanes

What is a cyclone?

Hurricanes are a type of *cyclone*—a low pressure center surrounded by rotating winds. Remember that the Coriolis effect causes these winds to rotate counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. The Coriolis effect is minimal along the equator, and as a result, the lack of rotating winds prevents cyclones from forming there.

How hurricanes form

Hurricanes form over ocean water that is at least 26.5°C (81°F). Warm, moist air over the tropical ocean provides the initial energy source for a hurricane. As the warm air rises, the water vapor in it condenses. Clouds and thundershowers form. The condensation releases latent heat, warming the surrounding air even more. As all of this air expands and rises, it creates an area of low pressure at the surface of the water. This pressure difference causes the surrounding air to rush toward the center. The path of this rushing air curves due to the Coriolis effect, and a rotating system forms.

What conditions are needed for a hurricane to develop?

Several conditions must be present for a rotating system to become a hurricane, which is defined as a tropical cyclone with wind speeds of at least 74 miles (119 kilometers) per hour. First, the warm ocean water must be at least 46 meters deep. Otherwise, when the storm stirs up the water, cooler water brought to the surface slows the rise of warm, moist air and the storm's strength dissipates. Second, the air must be warm and moist to a point at least 5,500 meters above sea level. As this upper-level air is pulled into the storm, it provides the water vapor that must condense and release latent heat in order to strengthen the storm even further.

The wind conditions must also be right. If preexisting winds are blowing from different directions or speeds, they can push the rising warm air in different directions and break the storm apart.

How common are hurricanes?

An average of 96 tropical cyclones form across the globe each year. More arise in the Western North Pacific and the Indian Ocean than any other area. An average of 10 tropical cyclones develop over the Atlantic, Caribbean, and Gulf of Mexico each year. Five or six of these usually reach hurricane status.

Figure 27.28: *Image of a hurricane as seen by space shuttle astronauts. The blue spot in the image's center is the low pressure center, called the eye. Here, winds are calm and blue skies can be seen. However, the surrounding bands of wind and rain are fierce. NASA photo.*

Category five hurricanes

Meteorologists use the Saffir/Simpson Hurricane scale to rate hurricanes. The most severe type, a category five, has wind speeds of at least 155 mph, air pressure in the eye less than 920 mb, and a storm surge of 18 or more feet. Three category five hurricanes hit the United States in the twentieth century.

Tornadoes

Comparing hurricanes and tornadoes

A tornado, like a hurricane, is a system of rotating winds around a low pressure center. An average tornado is less than 200 meters in diameter—tiny, compared with the 640 kilometer (640,000 meter) average diameter of a hurricane! However, the wind speeds of a tornado are much greater than those of a hurricane. A tornado's wind speed can reach 400 kilometers per hour.

How tornadoes form

Both tornadoes and hurricanes form from thunderstorms. A tornado begins to form when the updrafts in a storm cell reach over 160 kilometers per hour. Winds near the top of the cloud begin rotating at a very high speed. As more air flows in, the rotation extends downward. The diameter of the rotating wind pattern narrows, causing the wind to speed up like a spinning ice skater who draws her arms and legs inward.

As the rotating wind pattern narrows and lengthens, it forms what is known as a funnel cloud. If the funnel cloud reaches the ground, it is called a tornado (Figure 27.29).

High wind speeds cause damage

The high wind speed of the tornado is the real culprit that causes damage, not the low pressure "vacuum" at the center of the funnel. The rushing wind can flatten houses to their foundation and even lift cars completely off the ground. A tornado in Broken Bow, Oklahoma, once carried a motel sign 48 kilometers and dropped it in Arkansas! Most tornadoes last around 10 to 20 minutes, although the strongest tornadoes can last an hour or more. They travel along the ground at speeds of about 40 to 60 kilometers per hour.

Figure 27.29: *When a funnel cloud reaches the ground, it is called a tornado.*

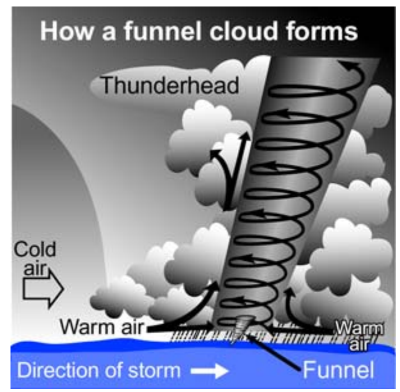


Figure 27.30: *A funnel cloud forms when updrafts in a storm cell reach high speed and begin to rotate. As the diameter of the rotation narrows and extends downward, a funnel cloud takes shape.*

The El Niño Southern Oscillation

Patterns in storm activity across the globe

Scientists studying decades of storm patterns across the globe have noticed cyclical patterns in storm activity. One such pattern is the rise and fall of thunderstorm activity in the tropical Pacific. Usually, the trade winds blow warm water from east to west across the Pacific, from Peru on the ocean's eastern edge toward Indonesia on the western side. As a result, the average water temperature off the coast of Indonesia is 6°C warmer than the average water temperature off the coast of Peru. The warm water of the western Pacific generates thunderstorms of greater frequency and intensity than what is normally seen nearer Peru.

The Southern Oscillation

For reasons not fully understood, every so often the trade winds weaken and the warm water reverses direction, flowing from the western Pacific toward South America. Along with that warm water comes greater thunderstorm activity across the Pacific. Indonesia and other western Pacific nations experience drier than normal conditions, while the eastern Pacific countries get more precipitation. This change in wind flow, air pressure, and thunderstorm activity is known as the Southern Oscillation. Nine of these events occurred between 1954 and 1994.

El Niño

Peruvian fisherman were among the first to notice the change in water temperature along their shores. They call the arrival of the warm water El Niño (or "the child," meaning the Christ child). When the warm water from the west flows back toward their shores, it cuts off a normal pattern in which cold water from the ocean depths flows up to the surface along the coast of Peru. The cold water brings many nutrients necessary for fish and other aquatic life to flourish. During an El Niño event, the warm water flowing over the cold water acts like a lid. It prevents the cold water from reaching the surface. As a result, nutrients are not available for aquatic life and the fish population declines.

Shifting jet streams

The shift in thunderstorm activity causes another El Niño Southern Oscillation (or ENSO) effect. The towering thunderstorm clouds act like big boulders in the upper atmosphere. When they move across the Pacific, they actually change the course of the fast moving upper-atmosphere winds that we know as the jet streams. As a result, entire air masses shift and the weather in places as far away as Canada and Africa are affected.

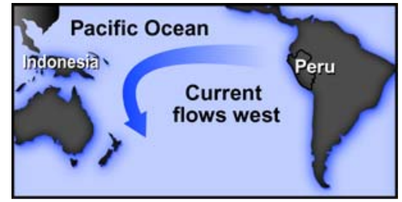


Figure 27.31: *This is the usual pattern of current flow.*

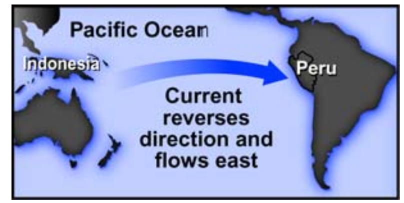


Figure 27.32: *During an El Niño Southern Oscillation event, the current reverses direction.*

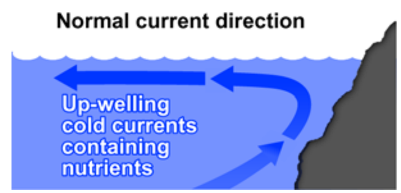


Figure 27.33: *Usually, cold water from ocean depths flows up to the surface along the coast of Peru.*

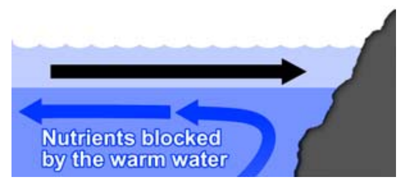
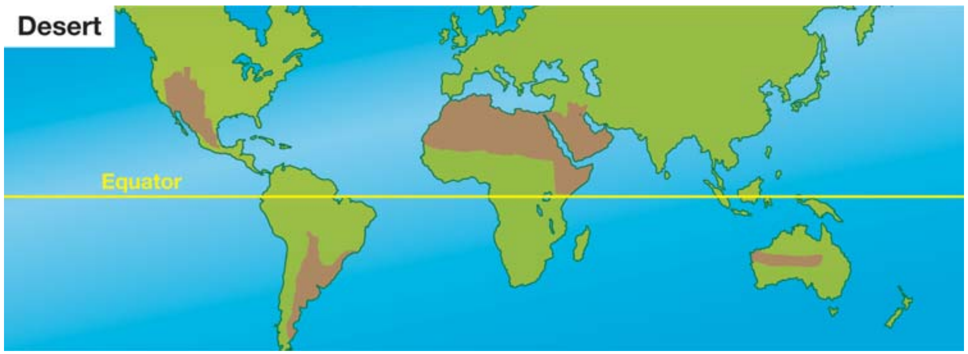


Figure 27.34: *During an El Niño event, the warm water current acts like a lid over the cold water.*

27.5 Weather and Climate

You have been studying about seasonal changes, wind and ocean currents, and weather patterns. All of these elements work together to produce different climates in different parts of the world. Climate is defined as the long-term average of a region's weather. If you wanted to know about the climate of a place you were about to visit, you might ask questions like "How hot and how cold does it usually get? What is the yearly rainfall pattern? How often is the temperature below freezing?" Climate depends on many factors, including latitude, precipitation, elevation, topography, and distance from large bodies of water. Scientists divide the planet into climate regions called biomes. Each biome has a unique set of plants and animals that thrive in its climate. Read on to find out more about six important Earth biomes.

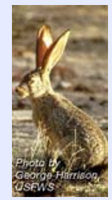
Desert biome



Desert regions Deserts are regions that average less than 35 centimeters of rainfall per year. Most deserts are found between 30° N and 30° S latitude. Because of the lack of cloud cover, deserts receive more than twice as much incoming solar radiation as humid regions. They also emit almost twice as much radiation at night. As a result, deserts have large variations in daily high and low temperatures.

How do animals survive in the desert?

The desert biome is home to more species of plants and animals than any other biome except the rain forest. Desert creatures have some remark-able features that help them survive without an abundant water supply.



Desert jackrabbits have enormous ears with many blood vessels near the surface. When the rabbit is in a shady spot, the blood running through the vessels is cooled, lowering the animal's body temperature. Use a library or the Internet to learn more about desert animals' adaptations.

How deserts form You may wonder why there is so little rain in the desert. The answer depends on which desert you are talking about. The Sahara and Australian deserts are caused by regions of high atmospheric pressure found near 30° latitude lines. As you have learned, high pressure prevents air near the ground from rising and cooling. As a result, not much condensation takes place. When the condensation rate is lower than the evaporation rate, skies are usually clear and very little precipitation falls.

Rainshadow deserts Other deserts, such as the one found in eastern Washington state, are caused by the "rainshadow effect" (Figure 27.35). Prevailing westerly winds blow moisture-filled air from the Pacific Ocean over the Washington coast. This air rises as it travels up the western slope of the Cascade Range and cools, causing condensation and lots of rain. By the time the air blows over the mountains to the eastern side, there is very little moisture left. Olympia, Washington, on the western side of the Cascades, receives an average of 201 centimeters of rain per year. Yakima, on the eastern side, receives only 32 centimeters per year (Figure 27.36).

Fog deserts A third type of desert is known as a "fog desert." Fog deserts are found on the west coasts of continents between 20° and 30° latitude. Here the prevailing winds are easterly, so moisture-filled air does not blow in from the ocean. Cold water currents run along many of these coastlines. The cold water causes air to condense as fog over the ocean. The small amount of precipitation received in these areas is from fog drifting over the land. The Baja desert of California and the Atacama desert in South America are fog deserts.

Desert life It might seem that few plants and animals could survive the harsh desert conditions, but actually many different kinds of plants and animals have adapted to desert life. In fact, only the tropical rain forest biome contains a greater number of plant and animal species.

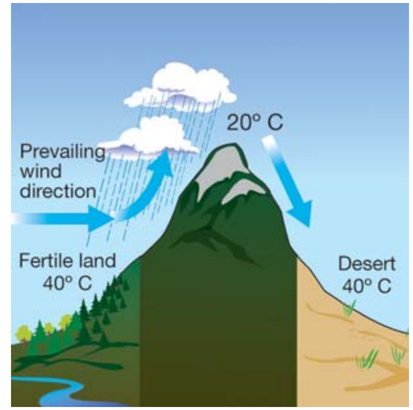
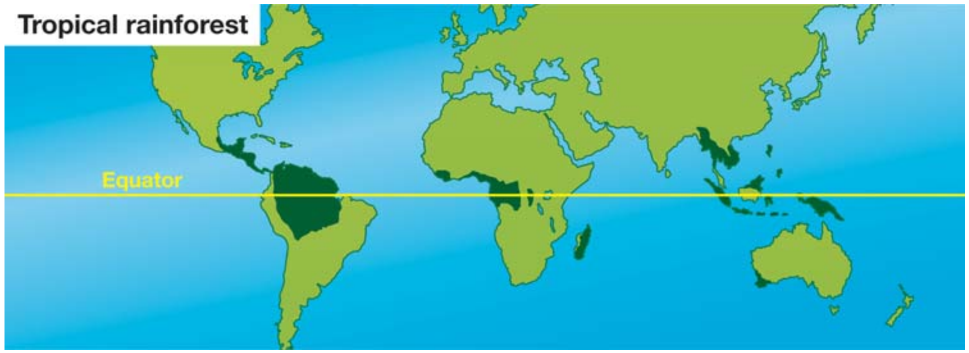


Figure 27.35: *The rainshadow effect.*

Figure 27.36: *Olympia, Washington, on the western side of the Cascade Range, receives an average of 201 centimeters of rain per year. On the eastern side, Yakima receives only 32 centimeters.*

Tropical rain forest biome



Tropical rain forests Tropical rain forests are found near the equator—between 23.5° N latitude and 23.5° S latitude. They have an average rainfall of at least 200 centimeters per year. This large amount of precipitation occurs in the area where the northern and southern hemisphere trade winds meet. The intense sun and warm ocean water cause this converging air to rise. As the air rises, it cools, condensing into clouds and rain. This cycle happens over and over, causing a period of thundershowers in the warmest part of the afternoon almost every day. Because the tropical rain forests are near the equator, the temperature varies little year round, averaging about 20° to 25° Celsius.

Rain forest life Although tropical rain forests cover less than 6 percent of Earth's land, half of all animal and plant species are found there. There can be as many as 100 different species of plants per hectare (2.47 acres). The most abundant type of plants are tall trees that form a dense canopy. Many foods we enjoy, including Brazil nuts, bananas, pineapple, cocoa, coffee, vanilla and cinnamon flavorings, and coconut originated in tropical rain forests.

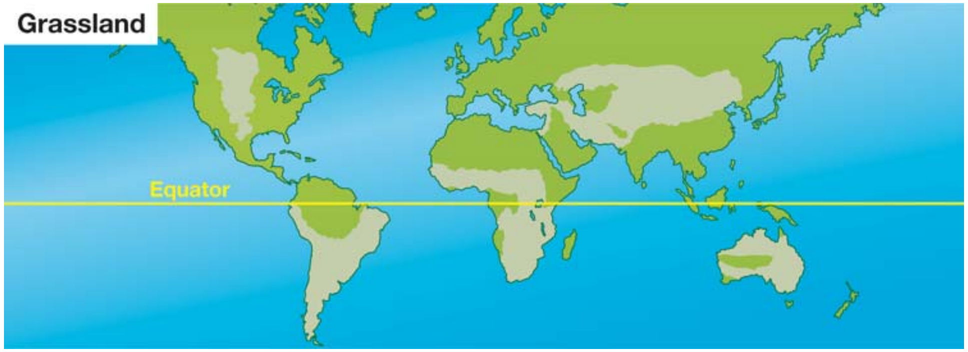
Trees and global climate

According to NASA data, an area of tropical rain forest the size of North Carolina is destroyed each year. Land is cleared for crops, grazing land, lumber, or firewood. When clear cutting occurs, the thin topsoil soon washes away, exposing thick clay that is almost useless for agriculture.

This clay absorbs the sun's energy and then emits infrared radiation, which is strongly absorbed by greenhouse gases. This process warms the atmosphere.

Trees prevent some of this warming. Leaves appear green because they reflect green light. Light at this wavelength is not as readily absorbed by greenhouse gases as infrared radiation. In a forested area, more of the suns's energy is reflected directly back to space without first being absorbed by greenhouse gases. In this way, trees keep Earth cooler.

Grassland biome



Grasslands are found on every continent except Antarctica. There are two types of grasslands: Tropical grasslands, known as savannas, and temperate grasslands.

Savannas Savannas are found in parts of the tropics where there is not enough rainfall throughout the year to create a rain forest. Savannas are characterized by two seasons: rainy and dry. During the rainy season, which lasts for six to eight months each year, 50 to 127 centimeters of rain falls. This season is followed by a drought, which in many areas culminates with wildfires. The fires and the poor soil conditions prevent the growth of most trees. In fact, in some areas, trees grow only on termite mounds. The isolated trees found in savannas have cork-like bark or an outer coating that is able to withstand some fire damage.

Temperate grasslands Temperate grasslands grow in the middle latitude regions and are called prairies and plains in North America, pampas in Argentina and Uruguay, veldts in South Africa, and steppes in Russia and Eastern Europe. Temperate grasslands receive most of their precipitation in late spring and early summer. Most temperate grassland is found in the interior of continents, far from large bodies of water. The average yearly rainfall is between 51 and 89 centimeters. Summer temperatures can reach over 38°C, while in the winter they can plummet below -40°C. The soil is rich in nutrients, and much of this biome has been cleared for farmland. Trees are uncommon except along river valleys.

How do savanna animals survive the periodic fires?

Many large mammals of the savanna, including the wildebeest pictured above, have long legs that enable them to outrun fires. Smaller mammals burrow under the ground and stay there until the fire has passed over them. Most birds fly away from the fire, but several species, including the Fork-tailed Drongos, actually fly *toward* the fires so that they can feast on the hoards of insects trying to escape the heat.

Temperate forest biome

Temperate forests

Temperate forests are found in middle-latitude regions, where there are four distinct seasons. The winter temperatures in some places dip as low as -30°C, and in the summer they can be as warm as 30°C. There are between four and six frost-free months each year. Average yearly rainfall is 75 to 150 centimeters, enough to support the growth of broad-leafed trees like oak, beech, maple, basswood, cottonwood, and willow.

Why do temperatures vary more in inland regions?

Have you ever wondered why cities near the ocean don't get as hot in the summer or as cold in the winter as inland cities at the same latitude? Portland, Oregon, and Minneapolis, Minnesota, are two cities near the same latitude. Portland's average daily low and high temperature for July is 14-27°C, while in Minneapolis, it is 17-29°C. In January, Portland averages a comfortable 1-7°C, while Minneapolis averages only -16 to -6°C.

Portland's climate is milder because it is close to the ocean. Water has a high specific heat, so it warms up slowly in the spring and summer. Land has a low specific heat, so it warms up quickly. Breezes blowing off the ocean keep Portland cooler in the summer. The difference in specific heat also means that land cools off quickly, while water cools off slowly. Portland is located next to relatively warm water in the winter, so it doesn't get as cold as an inland city like Minneapolis.

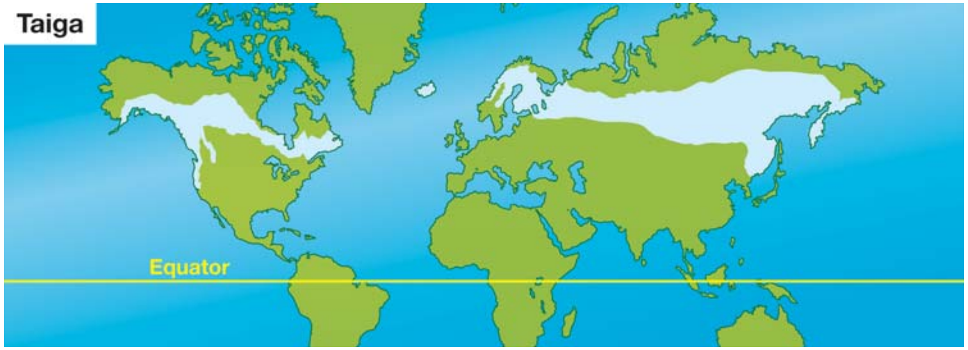
Wangari Maathai

Wangari Maathai was born in Kenya in 1940. She enjoyed school and earned a scholarship to study biology in the United States. When Maathai returned to her homeland, she was shocked by what she saw. In six years, water had become scarce and forests were gone. What caused this drastic change?

Forests had been clear-cut for timber. Native plants were replaced by fast-growing cash crops that stripped nutrients from the soil. Businesses made money on these products but local people did not benefit. Villagers couldn't grow food in the spoiled soil.

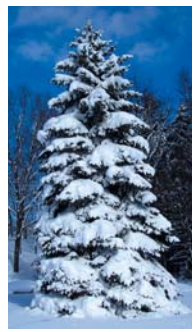
Maathai founded the Green Belt Movement (GBM) in an effort to restore the land and the livelihood of native Kenyans. She taught women to plant and grow trees in the barren landscape. Fruit trees provide food and firewood and prevent erosion. GBM has has now branched out to other African nations. In 2004, Maathai won the Nobel Peace Prize for her work. She is currently the Assistant Minister for the Environment, Natural Resources, and Wildlife in Kenya's parliament.

Taiga biome



Taiga **Taiga**, otherwise known as boreal or coniferous forest, is the largest land biome. Taiga can be found between 50° and 70° N latitude in North America and Eurasia, including Canada and Russia. The average temperature in the taiga is below freezing for at least six months of the year. Annual precipitation averages 40 to 100 centimeters. Much of this falls during the short growing season (approximately 130 days). Summer temperatures rarely reach above 21°C.

Taiga life Evergreen trees with needle-like leaves are the most common type of vegetation found in the taiga, which is the Russian word for forest. These include pine, fir, and spruce trees. All of these trees are cone-shaped, which helps them shed snow so its weight doesn't break their branches. The needle shape of the leaves helps prevent moisture loss in the winter. This is important because trees can't take in water from frozen soil. The fact that they don't lose their needles in the fall means that they don't have to waste time in the early spring growing new ones, and can get started on photosynthesis as soon as it is warm enough. The roots of these trees are shallow and spread out wide. This makes it possible for them to take in surface water from melting snow and ice even though much of the ground underneath them is still frozen.



Snow keeps things warm!

Did you know that snow is a great insulator? In the taiga biome, a thick layer of snow (often several meters deep) falls before the coldest part of the winter. The air spaces between snow crystals prevent the ground underneath from losing more and more heat as the winter progresses.

While air temperatures may be well below zero Celsius for weeks on end, the ground temperature will remain right around freezing. Mice and other small mammals make tunnels in the snow that link their burrows and food stashes. The temperature in the burrows remains fairly constant, even when the outside air temperature plummets.

Tundra biome

Tundra Tundra is the coldest biome on Earth. The word tundra comes from a Finnish word for treeless land. There are two types of tundra—arctic tundra, found in a band around the arctic ocean, and alpine tundra, found high in mid-latitude mountains.

Arctic tundra Arctic tundra has a growing season of only 50 to 60 days. The average winter temperature is -34°C. Summer temperatures rarely exceed 12°C. As a result of these cold temperatures, the ground is permanently frozen from 25 centimeters to about 100 centimeters below the surface. This ground is called permafrost. There is a thin layer of soil above the permafrost that does thaw in summertime, but it is not deep enough to support the growth of trees. Lichens, mosses, grasses, and a few woody shrubs are the most common plants in the arctic tundra.

Permafrost stores carbon dioxide Permafrost has a very important function on our planet: It stores carbon dioxide. Here's how the process works: Usually, when plants die, they decompose into soil. This process releases carbon dioxide into the air. However, when an arctic tundra plant dies, the cold temperatures prevent it from rapidly decaying into soil. Instead, at least part of its structure remains intact until it is frozen in the permafrost. In fact, remains of plants 1,000 years old have been found in the permafrost. Since the plant structures don't completely decay, carbon that would have been released into the atmosphere as carbon dioxide stays in the ground.

Alpine tundra Alpine tundra occurs in middle latitude regions, but at very high altitudes. Cold temperatures, windy conditions, and thin soil create an environment where only plants similar to those in the arctic regions can survive. In rocky alpine regions, lichens and mosses are the dominant plants, but in alpine meadows, grasses and small woody shrubs can be found.

What is a "carbon sink"?

Permafrost is known as a "carbon sink." A sink is an area where more carbon is stored than is released into the atmosphere. Some scientists are concerned that if Earth warms up several degrees, the permafrost will begin to melt. If this happens, the frozen plants would decompose and release carbon dioxide into the air. The permafrost would no longer serve a "sink." It would become a source of carbon dioxide (a greenhouse gas) in the atmosphere.

Chapter 27 Review

Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

Set One

1. Coriolis effect	a. Global wind pattern formed when air over the poles cools, sinks, and spreads over the surface
2. trade winds	b. Large circular patterns of surface ocean currents
3. prevailing westerlies	c. Global wind pattern named for the fact that sailors used these winds to travel to new lands, where they interacted with other cultures
4. polar easterlies	d. Cold winds that blow in early spring
5. gyres	e. Global wind pattern that flows over most of the continental United States
	f. The bending of wind and ocean currents due to Earth's rotation

Set Two

1. cirrus	a. Cloud that looks like popcorn with flat base
2. cumuliform	b. Cloud type that looks like wispy white streaks high in the sky
3. stratiform	c. Cloud type that looks like a lumpy blanket
4. stratocumulus	d. Cloud type that looks like a smooth gray sheet
5. dew point temperature	e. Air temperature in which more water in atmosphere is evaporating than condensing
	f. Air temperature where condensation rate first exceeds evaporation rate

Set Three

1. cold front	a. Energy stored when water changes from liquid to gas and released when water condenses
2. warm front	b. High altitude fast-moving wind
3. jet stream	c. When a cold air mass moves in and replaces warm air at Earth's surface
4. temperature inversion	d. When temperatures near the ground are cooler than the air temperature up high
5. latent heat	e. Fast-moving winds near Earth's surface
	f. When a warm air mass overtakes cooler air in a region

Set Four

1. El Niño	a. Climate region which contains plants and animal uniquely adapted to this environment
2. southern oscillation	b. Distance from equator, measured in degrees
3. climate	c. Area of Earth that stores more carbon than it releases into the atmosphere; found in tundra
4. biome	d. Peruvian fisherman's name for the arrival of warm water currents along their shores
5. permafrost	e. The long-term average of a region's weather
	f. Description of change in wind flow, air pressure, and thunderstorm activity occurring in Pacific ocean, from Indonesia to Peru

Concept review

1. If Earth were heated evenly, every location would be at the same temperature all the time. Obviously, this is not the case! How does Earth's rotation affect its heating and cooling?
2. Explain why cooler climates are found at high latitudes and warmer climates are found near the equator.
3. What is a thermal?
4. What would you call wind that is blowing from the northeast to the southwest?
5. Name the three most important global surface wind patterns and describe where each is found.
6. What causes surface ocean currents like the Gulf Stream? How does the Gulf Stream affect the climate of Great Britain?
7. What are the three most important factors that shape a region's weather?
8. What is an air mass and how does it form?
9. Is a warm front more likely to be accompanied by fast-moving thunderstorms or long bands of light precipitation? Why?
10. How do mountains or very tall cumulus clouds shift the path of the jet stream? Why does a shift in the jet stream often cause a change in the weather?
11. If you heard a weather report that said high pressure was moving into your region, would you expect clear skies or clouds and precipitation? Why?
12. There are several important factors that shape climates. Name four of these.

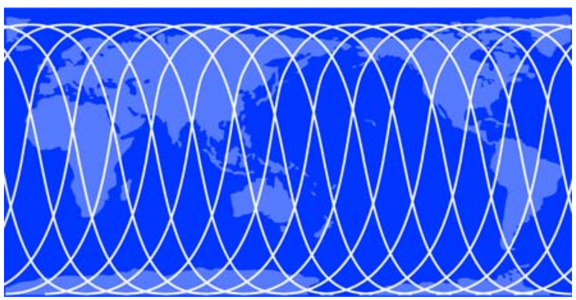
Problems

1. Draw a diagram and write a paragraph to explain why the northern hemisphere experiences winter in January and summer in July.
2. Draw a diagram and write a paragraph to explain why global wind patterns are bent to the right in the northern hemisphere.
3. Describe how cumuliform, stratiform, and stratocumulus clouds form.
4. Which of these conditions is NOT necessary for rain to fall?
   a. The dew point temperature has been reached.
   b. Dust is present as a site for water condensation.
   c. Large cumulonimbus clouds develop.
   d. Water droplets grow to a size of at least 1,000 microns.
5. Describe what happens when a cold front moves through a region.
6. How does a low pressure center develop? What kind of weather do you expect from a low pressure system?
7. Describe what happens to surface ocean currents, water temperatures, and thunderstorm activity during an El Niño-Southern oscillation event.
8. Draw a diagram and write a paragraph to explain what is meant by a "rainshadow" desert.

Applying your knowledge

1. Create a three-dimensional model that you could use to teach a class of fourth graders about why Earth has seasons.

2. Polar orbiting satellites travel in the same elliptical orbit over and over again, taking photographs and collecting data about Earth. The satellite shown at right completes one orbit approximately every two hours. Below you will see a map of the satellite's "ground path," showing the locations covered by the satellite each day. Using what you have learned about the Coriolis effect, explain why the ground path of the satellite doesn't go straight north and south. How is it possible for the satellite to photograph the entire Earth in one day without changing its orbit?



3. Hurricane Andrew was one of the strongest storms to hit the United States in the previous century. Use the Internet to research the development and path of Hurricane Andrew. What conditions caused this storm to grow so intense?

4. Use the Internet to research the National Weather Service's recommendations for staying safe during a tornado. Write an action plan for your school or home that describes the safest place to seek shelter during a tornado in your area.

5. Wilson "Snowflake" Bentley (1865-1931) was a self-educated farmer from Jericho, Vermont. He was a pioneer in the use of photomicrography—taking photographs of images seen through a microscope. Bentley took the first photomicrograph of an individual snowflake and went on to produce more than 5,000 snowflake images. By keeping detailed weather records for decades, Bentley made several important findings about the relationship between snowflake crystal structure and atmospheric conditions. Research and prepare a five minute presentation on Bentley's contributions to the field of meteorology.

6. Find out how an El Niño event affects the area where you live. Make a poster which shows what you can expect during an El Niño event, and why.

7. Permafrost is an important "carbon sink," or area that stores more carbon than it releases as carbon dioxide. Use a library or the Internet to find out what other important "carbon sinks" are found on Earth.