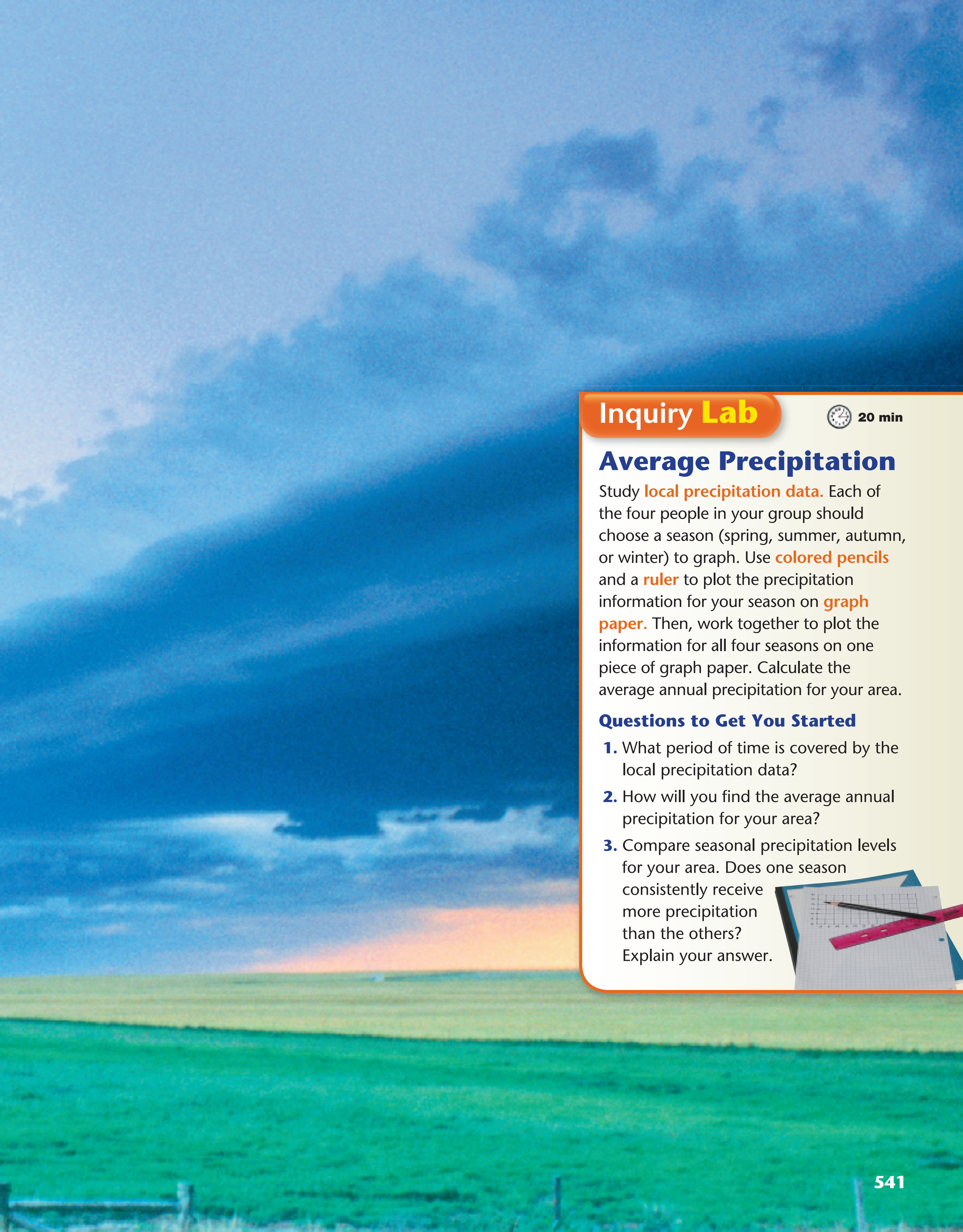
Chapter 20

Water in the Atmosphere

Chapter Outline

Why It Matters

Understanding how water moves through the atmosphere provides a basis for understanding how heat is transferred around the globe and for predicting the weather.



Inquiry **Lab**

20 min

Average Precipitation

Study **local precipitation data.** Each of the four people in your group should choose a season (spring, summer, autumn, or winter) to graph. Use **colored pencils** and a **ruler** to plot the precipitation information for your season on **graph paper.** Then, work together to plot the information for all four seasons on one piece of graph paper. Calculate the average annual precipitation for your area.

Questions to Get You Started

1. What period of time is covered by the local precipitation data?
2. How will you find the average annual precipitation for your area?
3. Compare seasonal precipitation levels for your area. Does one season consistently receive more precipitation than the others? Explain your answer.

READING TOOLBOX

These reading tools will help you learn the material in this chapter.

Word Parts

Suffixes The suffix *–ion* usually changes verbs into nouns to denote a process. For example, *combination* is a noun formed from the verb *combine*. It means "the result of combining." The suffix *-ly* changes a noun, an adjective, or a verb to an adverb. It means "in the manner of." *Slowly* means "in a slow manner." When you see a word that uses one of these suffixes, the root of the word can help you understand the word's meaning.

Your Turn On a sheet of paper, complete the table below with other words in the chapter that have the suffix *–ion*.

Word	Root	Suffix	Definition
sublimation	sublimate	- ion	the process by which a solid changes directly into a gas
		- ion	

Comparisons

Analyzing Comparisons Comparisons are often signaled by the use of a few key words. The words *like* and *unlike* can tell you whether a comparison is focused on similarities or differences. Comparative words can be formed by using the suffixes *-er* and *-est*. Comparative phrases can be formed by using the words *more* and *less*.

Your Turn As you read this chapter, fill out a table of comparisons like the one below. The entry is for the sentence "Unlike nimbostratus clouds, which produce heavy precipitation, altostratus clouds produce very little precipitation."

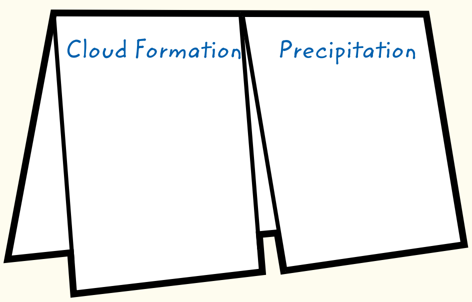
First thing	Second thing	Similarities or differences	Signal words or phrases
nimbostratus clouds	altostratus clouds	nimbostratus: heavy precipitation, altostratus: little precipitation	unlike

Fold Notes

Two-Panel Flip Chart FoldNotes help you learn and remember ideas that you encounter as you read. FoldNotes help you organize concepts and see the "big picture."

Your Turn Follow the instructions in **Appendix A** for making a two-panel flip chart. Label the panels as shown here.

Open the appropriate flap to take notes about each topic and draw a sketch.



For more information on how to use these and other tools, see **Appendix A.**

SECTION 1

Atmospheric Moisture

Key Ideas

- Explain how heat energy affects the changing phases of water.
- Explain what absolute and relative humidity are, and describe how they are measured.
- Describe what happens when the temperature of air decreases to the dew point or below.

Key Terms

latent heat
sublimation
dew point
absolute humidity
relative humidity

Why It Matters

When the air is humid, you feel warmer than you would if the air were dry, even if the temperature is the same. The humidity affects your body's ability to cool itself by sweating.

Water in the atmosphere exists in three states, or *phases*. One phase is a gas known as *water vapor*. The other two phases of water are the solid phase known as *ice* and the liquid phase known as *water*.

Changing Forms of Water

Water changes from one phase to another when heat energy is absorbed or released, as shown in **Figure 1.** Molecules of ice are held almost stationary in a definite crystalline arrangement. However, when energy is absorbed by the ice, the molecules move more rapidly. They break from their fixed positions and slide past each other in the fluid form of a liquid.

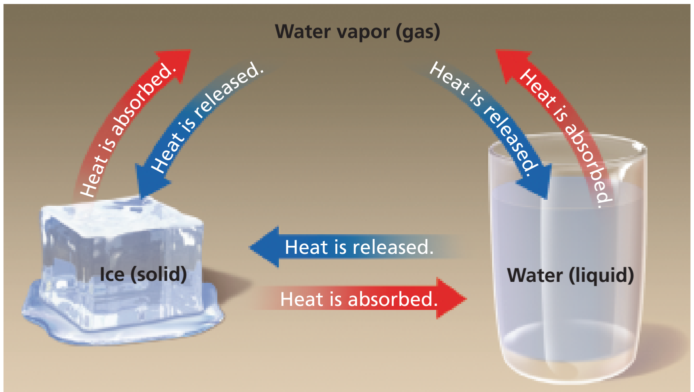
When more energy is absorbed by liquid water, the water changes from a liquid to a gas. Because the additional energy causes the movement of the molecules in liquid water to speed up, the molecules collide more frequently with each other. Such collisions can cause the molecules to move so rapidly that the fastest-moving molecules escape from the liquid to form invisible water vapor in a process called *evaporation*.

latent heat the heat energy that is absorbed or released by a substance during a phase change

Latent Heat

The heat energy that is absorbed or released by a substance during a phase change is called **latent heat.** When liquid water evaporates, the water absorbs energy from the environment. This energy becomes potential energy between the molecules. When water vapor changes back into a liquid through the process of *condensation,* energy is released to the surrounding air and the molecules move closer together. Likewise, latent heat is absorbed when ice thaws, and latent heat is released when water freezes.

Figure 1 Water exists in three states, called *phases*. As it changes from one phase to another, water either absorbs or releases heat energy.



Evaporation

Most water enters the atmosphere through the process of evaporation. Because the largest amounts of solar energy reach Earth near the equator, most evaporation takes place over the oceans of the equatorial region. However, water vapor also enters the atmosphere by evaporation from lakes, ponds, streams, and soil. Plants release water into the atmosphere in a process called transpiration. Volcanoes and burning fuels also release small amounts of water vapor into the atmosphere.

Sublimation

sublimation the process in which a solid changes directly into a gas (the term is sometimes also used for the reverse process)

Ice commonly changes into a liquid before changing into a gas. However, in some cases, ice can change directly into water vapor without becoming a liquid. The process by which a solid changes directly into a gas is called **sublimation.** When the air is dry and the temperature is below freezing, ice and snow may sublimate into water vapor. Water vapor can also turn directly into ice without becoming a liquid.

Reading Check **Summarize the conditions under which sublimation commonly occurs.** (See Appendix G for answers to Reading Checks.)

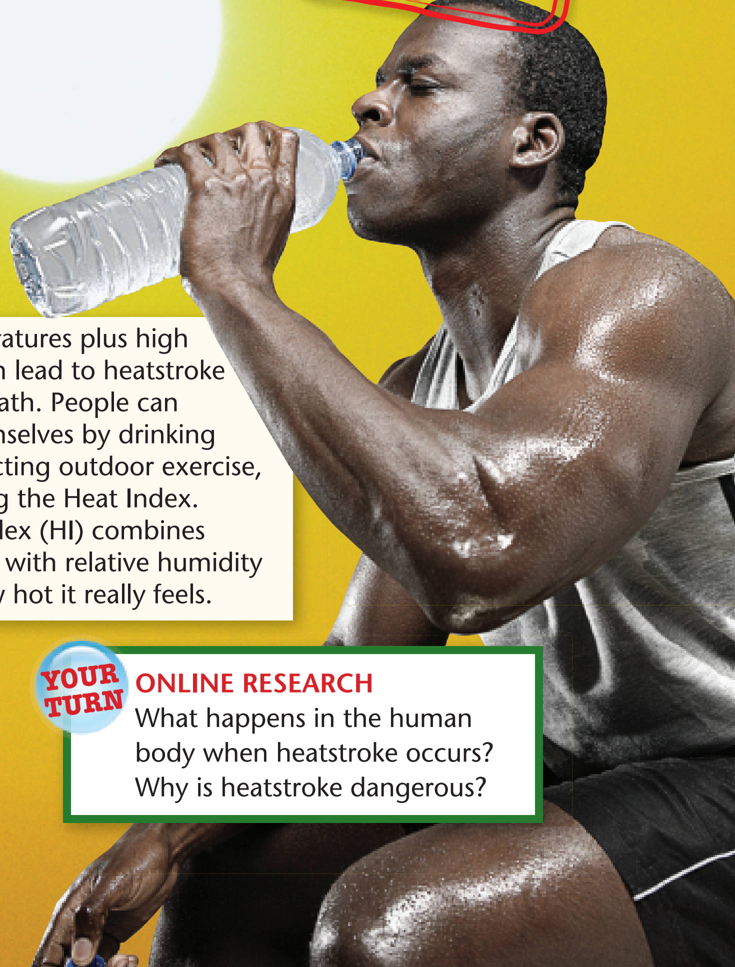
Why It Matters

Why Does Humid Air Feel Hotter?

REAL WORLD

You probably have heard people say, "It's not the heat—it's the humidity." When relative humidity is high, the day feels hotter than the temperature you read on the thermometer. Why? Evaporation of sweat is a main mechanism by which the body regulates temperature. Sweat does not evaporate when relative humidity is about 80 percent or higher. When sweat doesn't evaporate, the body does not cool as efficiently.

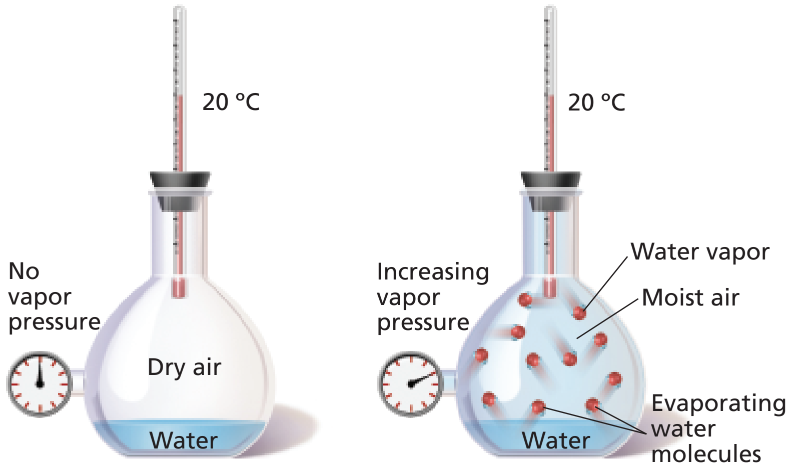
Smog is worsened by high humidity. Not only do you feel hotter, smog aggravates emphysema, asthma, and other respiratory problems. People can protect themselves by checking the pollution index before going outside.



High temperatures plus high humidity can lead to heatstroke and even death. People can protect themselves by drinking water, restricting outdoor exercise, and checking the Heat Index. The Heat Index (HI) combines temperature with relative humidity to show how hot it really feels.

YOUR TURN **ONLINE RESEARCH**

What happens in the human body when heatstroke occurs? Why is heatstroke dangerous?



THINK central
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Figure 2 When water comes into contact with dry air, some of the water molecules evaporate into the dry air. The addition of the water molecules to the air causes the air pressure to increase. This increase in pressure is due to vapor pressure.

Humidity

Water vapor in the atmosphere is known as *humidity*. Humidity is controlled by rates of condensation and evaporation. The rate of evaporation is determined by the temperature of the air. The higher the temperature is, the higher the rate of evaporation is. The rate of condensation is determined by *vapor pressure.* Vapor pressure is the part of the total atmospheric pressure that is caused by water vapor, as shown in **Figure 2.** When vapor pressure is high, the condensation rate is high.

When the rate of evaporation and the rate of condensation are in equilibrium, the air is said to be "saturated." The temperature at which the condensation rate equals the evaporation rate is called the **dew point.** At temperatures below the dew point, net condensation occurs, and liquid water droplets form.

dew point at constant pressure and water vapor content, the temperature at which the rate of condensation equals the rate of evaporation

absolute humidity the mass of water vapor per unit volume of air that contains the water vapor, usually expressed as grams of water vapor per cubic meter of air

Absolute Humidity

One way to express the amount of moisture in the air is by absolute humidity. **Absolute humidity** is the mass of water vapor contained in a given volume of air. In other words, absolute humidity is a measure of the actual amount of water vapor in the air. Absolute humidity is calculated by using the following equation:

$$\textit{absolute humidity} = \frac{\textit{mass of water vapor (grams)}}{\textit{volume of air (cubic meters)}}$$

However, as air moves, its volume changes as a result of temperature and pressure changes. Therefore, meteorologists prefer to describe humidity by using the mixing ratio of air. The *mixing ratio* is the mass of water vapor in a unit of air relative to the mass of the dry air. For example, the very moist air in tropical regions might have 18 g of water vapor in 1 kg of air, or a mixing ratio of 18 g/kg. On the other hand, the cold, dry air in polar regions commonly has a mixing ratio of less than 1 g/kg. Because this measurement uses only units of mass, it is not affected by changes in temperature or pressure.

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Topic: Atmospheric Moisture
Code: **HQX0113**

READING TOOLBOX

Two-Panel Flip Chart
Make a two-panel flip chart. Label the first panel "Humidity" and the second panel "Measuring Humidity." Inside each panel, write key ideas about the corresponding topics.

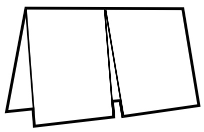

Figure 3 Dew forms on surfaces such as grass and spider webs when the temperature of the air drops lower than the dew point.

Relative Humidity

A more common way to express the amount of water vapor in the atmosphere is by *relative humidity*. **Relative humidity** is a ratio of the actual water vapor content of the air to the amount of water vapor needed to reach saturation. In other words, relative humidity is a measure of how close the air is to reaching the dew point. For example, at 25 °C, air is saturated when it contains 20 g of water vapor per 1 kg of air. If air that is 25 °C contains 5 g of water vapor, the relative humidity is expressed as 5/20, or 25%.

If the temperature does not change, the relative humidity will increase if moisture enters the air. Relative humidity can also increase if the moisture in the air remains constant but the temperature decreases. If the temperature increases as the moisture in the air remains constant, the relative humidity will decrease.

relative humidity the ratio of the amount of water vapor in the air to the amount of water vapor needed to reach saturation at a given temperature

Math Skills

Relative Humidity

Relative humidity can be calculated by using the following equation:

$$\text{relative humidity} = \left[\frac{\text{amount of water vapor in air}}{\text{amount of water vapor needed to reach saturation}}\right] \times 100$$

Air at 20 °C is saturated when it contains 14 g/kg of water vapor. What is the relative humidity of a volume of air that is 20 °C and contains 10 g/kg of water vapor?

Reaching the Dew Point

When the air is nearly saturated with a relative humidity of almost 100%, only a small temperature drop is needed for the air to reach its dew point. Air may cool to its dew point by conduction when the air comes in contact with a cold surface. During the night, grass, leaves, and other objects near the ground lose heat. Their surface temperatures often drop to the dew point of the surrounding air. Air, which normally remains warmer than surfaces near the ground do, cools to the dew point when it comes into contact with cooler objects, such as grass. When the temperature of air cools below the dew point, condensation, shown in **Figure 3,** called *dew* forms. Dew is most likely to form on cool, clear nights when there is little wind.

If the dew point falls below the freezing temperature of water, water vapor may change directly into solid ice crystals, or *frost*. Because frost forms when water vapor turns directly into ice, frost is not frozen dew. Frozen dew is relatively uncommon. Unlike frost, frozen dew forms as clear beads of ice.

Reading Check **How does dew differ from frost?**

Measuring Humidity

Meteorologists are interested in measuring humidity so that they can better predict weather conditions. Relative humidity can be measured by using a variety of instruments, such as an electrical hygrometer, a psychrometer, a dew cell, and a hair hygrometer.

Using an Electrical Hygrometer

Humidity is commonly measured by an electrical hygrometer that uses a *thin polymer film*. The relative humidity of the surrounding air affects the ability of the thin polymer film to absorb or release water vapor. The amount of water vapor that the thin polymer film contains changes the film's ability to conduct electricity. The polymer film's ability to conduct electricity is affected by the relative humidity of the surrounding air. Thus, by measuring the polymer film's ability to conduct electricity, relative humidity can be determined.

Using a Psychrometer

A *psychrometer*, shown in **Figure 4,** is another instrument that is used to measure relative humidity. It consists of two identical thermometers. The bulb of one thermometer is covered with a damp wick, while the bulb of the other thermometer remains dry. When the psychrometer is held by a handle and whirled through the air, the air circulates around both thermometers. As a result, the water in the wick of the wet-bulb thermometer evaporates. Evaporation requires energy, so energy as heat is released by the thermometer. Consequently, the temperature of the wet-bulb thermometer is lower than that of the dry-bulb thermometer. The difference between the dry-bulb temperature and the wet-bulb temperature is used to calculate relative humidity. If there is no difference between the wet-bulb temperature and dry-bulb temperature, no water evaporated from the wet-bulb thermometer. Thus, the air is saturated and the relative humidity is 100%.

Quick Lab

10 min

Dew Point

Procedure

1. Pour **room-temperature water** into a **glass container,** such as a drinking glass, until the water level is near the top of the cup.
2. Observe the outside of the glass container, and record your observations.
3. Add **one or two ice cubes** to the container of water.
4. Watch the outside of the container for 5 min for any changes.

Analysis

1. What happened to the outside of the container?
2. What is the liquid on the container?
3. Where did the liquid come from? Explain your answer.

Academic Vocabulary

instrument (IN struh muhnt) a mechanical or electronic measuring device

Figure 4 A psychrometer shows differences between wet-bulb and dry-bulb temperatures that can be used to determine relative humidity.

Figure 5 Scientists use weather balloons, such as this one in Antarctica, to send electrical hygrometers into the high altitudes of the atmosphere.

Other Methods for Measuring Humidity

Another instrument that has been used to measure relative humidity is a *dew cell*. A dew cell consists of a ceramic cylinder with electrodes attached to it and treated with lithium chloride, LiCl. When LiCl absorbs water from the air, the dew cell's ability to conduct electricity increases. By detecting the electrical resistance of LiCl as it is heated and cooled, the dew cell can determine the dew point.

A *hair hygrometer* determines relative humidity based on the principle that hair becomes longer as relative humidity increases. As relative humidity decreases, hair becomes shorter.

Measuring Humidity at High Altitudes

To measure humidity at high altitudes, scientists use an electrical hygrometer. The hygrometer may be carried up into the atmosphere in an instrument package known as a *radiosonde*. The radiosonde is attached to a weather balloon, such as the one shown in **Figure 5.** The electrical hygrometer is triggered by passing an electric current through a moisture-attracting chemical substance. The amount of moisture changes the electrical conductivity of the chemical substance. The change can then be expressed as the relative humidity of the surrounding air.

Section 1 Review

Key Ideas

1. **Explain** how most water vapor enters the air.
2. **Identify** the principal source from which most water vapor enters the atmosphere.
3. **Identify** the process by which ice changes directly into a gas.
4. **Define** *humidity*.
5. **Compare** relative humidity with absolute humidity.
6. **Describe** what happens when the temperature of air decreases to the dew point or below the dew point.
7. **Identify** four instruments that are used to measure relative humidity.

Critical Thinking

8. **Predicting Consequences** Explain what would happen to a sample of air whose relative humidity is 100% if the temperature decreased.
9. **Identifying Relationships** Which region of Earth would you expect to have a higher absolute humidity: the equatorial region or the polar regions?

Concept Mapping

10. Use the following terms to create a concept map: *humidity, water vapor, dew point, absolute humidity, dew cell, psychrometer, hygrometer, evaporation, condensation,* and *relative humidity.*

SECTION 2

Clouds and Fog

Key Ideas	Key Terms	Why It Matters
❯ Describe the conditions that are necessary for clouds to form. ❯ Explain the four processes of cooling that can lead to the formation of clouds. ❯ Identify the three major types of clouds, noting their characteristic shapes and the altitudes at which they generally form. ❯ Describe four ways in which fog can form.	**cloud** **condensation nucleus** **adiabatic cooling** **advective cooling** **stratus cloud** **cumulus cloud** **cirrus cloud** **fog**	Often you do not have access to the local weather report. Understanding how clouds form and being able to recognize different cloud types will help you make your own weather predictions and might save you from a drenching.

A **cloud** is a collection of small water droplets or ice crystals in the air. People commonly think that clouds are high in the sky and fog is close to the ground. However, clouds are not limited to high altitudes. Fog is actually a cloud that forms near or on Earth's surface.

Cloud Formation

For water vapor to condense and form a cloud, a solid surface on which condensation can take place must be available. The lowest layer of the atmosphere, the *troposphere*, contains millions of particles of ice, salt, dust, and other materials that serve as solid surfaces. These particles are so small—less than 0.001 mm in diameter—that they remain suspended in the atmosphere for a long time. The suspended particles that provide the surfaces necessary for water vapor to condense are called **condensation nuclei.** As water molecules collect on the nuclei, water droplets form, as **Figure 1** shows.

In addition, for clouds to form, the air must be "saturated" with water vapor. When the temperature of the air drops, condensation occurs more rapidly than evaporation does. As a result of this net condensation, clouds begin to form. Because the rate of evaporation decreases as temperature decreases, the cooling of air may lead to net condensation.

cloud a collection of small water droplets or ice crystals suspended in the air, which forms when the air is cooled and condensation occurs

condensation nucleus a solid particle in the atmosphere that provides the surface on which water vapor condenses

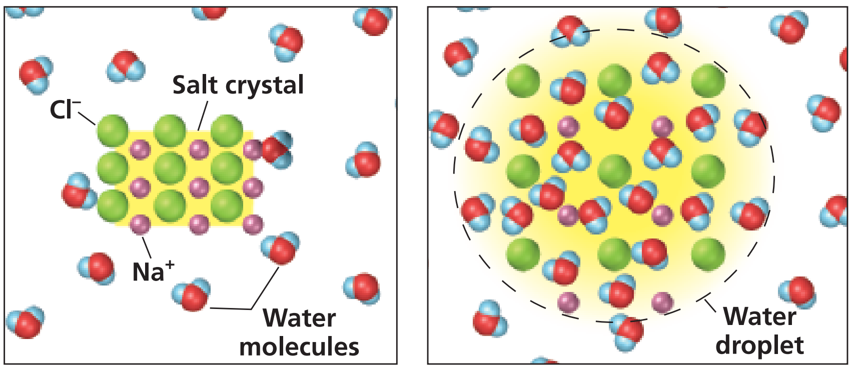

Figure 1 Water molecules are attracted to the sodium and chloride ions in a salt crystal, forming a solution. Additional water molecules are attracted to the solution and the droplet gets bigger.

Adiabatic Cooling

As a mass of air rises, the surrounding atmospheric pressure decreases. Because of the lower pressure, the molecules in the rising air move farther apart. Thus, fewer collisions between the molecules happen. The resulting decrease in the amount of energy that is transferred between molecules decreases the temperature of the air. The process by which the temperature of a mass of air decreases as the air rises and expands is called **adiabatic cooling** (AD ee uh BAT ik KOOL ing).

adiabatic cooling the process by which the temperature of an air mass decreases as the air mass rises and expands

Adiabatic Lapse Rate

The rate at which the temperature of a parcel of air changes as the air rises or sinks is called the *adiabatic lapse rate*. The adiabatic lapse rate for clear air is about –1 °C for every 100 m that the air rises. Air that is below the dew point—and thus is cloudy—cools more slowly, however. The average adiabatic lapse rate for cloudy air varies between –0.5 °C and –0.9 °C per 100 m that the air rises. The slower rate of cooling of moist air results from the release of latent heat as the water condenses.

Academic Vocabulary

expand (ek SPAND) to enlarge

Condensation Level

The process through which clouds form by adiabatic cooling is shown in **Figure 2.** Earth's surface absorbs energy from the sun and then reradiates that energy as heat. The air close to Earth's surface absorbs the heat. As the air warms, it rises, expands, and then cools. When the air cools to a temperature that is below the dew point, net condensation causes clouds to form. The altitude at which this net condensation begins is called the *condensation level*. The condensation level is marked by the base of the clouds. Further condensation allows clouds to rise and expand above the condensation level.

Reading Check **What is the source of energy that warms the air and leads to cloud formation?**

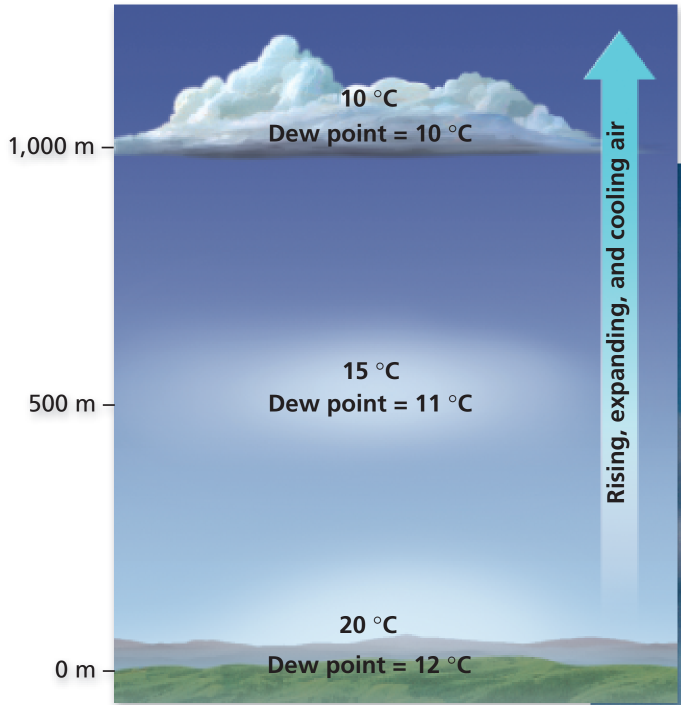

Figure 2 Notice in this illustration that temperature and dew point are the same at an altitude of 1,000 m. Above that altitude, condensation begins and clouds, such as the clouds in the image on the right, form.

Figure 3 Clouds can form as air is pushed up along a mountain slope and is cooled to below the dew point.

Mixing

Some clouds form when one body of moist air mixes with another body of moist air that has a different temperature. The combination of the two bodies of air causes the temperature of the air to change. This temperature change may cool the combined air to below its dew point, which results in cloud formation.

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Lifting

The forced upward movement of air commonly results in the cooling of air and in cloud formation. Air can be forced upward when a moving mass of air meets sloping terrain, such as a mountain range. As the rising air expands and cools, clouds form. As **Figure 3** shows, entire mountaintops can be covered with clouds that formed in this way.

The large cloud formations that are associated with storm systems also form by lifting. These clouds form when a mass of cold, dense air enters an area and pushes a less dense mass of warmer air upward.

Advective Cooling

Another cooling process that is associated with cloud formation is advective cooling. **Advective cooling** is the process by which the temperature of an air mass decreases as the air mass moves over a cold surface, such as a cold ocean or land surface. As air moves over a surface that is colder than the air is, the cold surface absorbs heat from the air and the air cools. If the air cools to below its dew point, clouds form.

advective cooling the process by which the temperature of an air mass decreases as the air mass moves over a cold surface

Quick Lab

15 min

Cloud Formation

Procedure

1. Use a **bottle opener** to puncture one or two holes into the **metal lid** of a **glass jar.**
2. Pour **1 mL of hot water** into the jar, then secure the lid on the jar.
3. Place an **ice cube** over the holes in the lid of the jar. Make sure that the holes are completely covered.
4. Observe the changes that occur within the jar.

Analysis

1. Draw a diagram of the jar. Label the areas of the diagram where evaporation and condensation take place. Also, label areas where latent heat is released and absorbed.

2. Explain why latent heat was released and absorbed in the areas that you labeled on your diagram.

stratus cloud a gray cloud that has a flat, uniform base and that commonly forms at very low altitudes

Classification of Clouds

Clouds are classified by their shape and their altitude. The three basic cloud types are stratus clouds, cumulus clouds, and cirrus clouds. There are also three altitude groups: low clouds (0 to 2,000 m), middle clouds (2,000 to 6,000 m), and high clouds (above 6,000 m). This classification system is shown in **Figure 4.**

Stratus Clouds

Clouds that have a flat, uniform base and that begin to form at very low altitudes are called **stratus clouds.** *Stratus* means "sheet-like" or "layered." The base of stratus clouds is low and may almost touch Earth's surface. Stratus clouds form where a layer of warm, moist air lies above a layer of cool air. When the overlying warm air cools below its dew point, wide clouds appear. Stratus clouds cover large areas of sky and often block out the sun. Usually, very little precipitation falls from most types of stratus clouds.

Two variations of stratus clouds are known as *nimbostratus* and *altostratus*. The prefix *nimbo-* and the suffix *-nimbus* mean "rain." Unlike other stratus clouds, the dark nimbostratus clouds can cause heavy precipitation. Altostratus clouds form at the middle altitudes and usually produce very little precipitation.

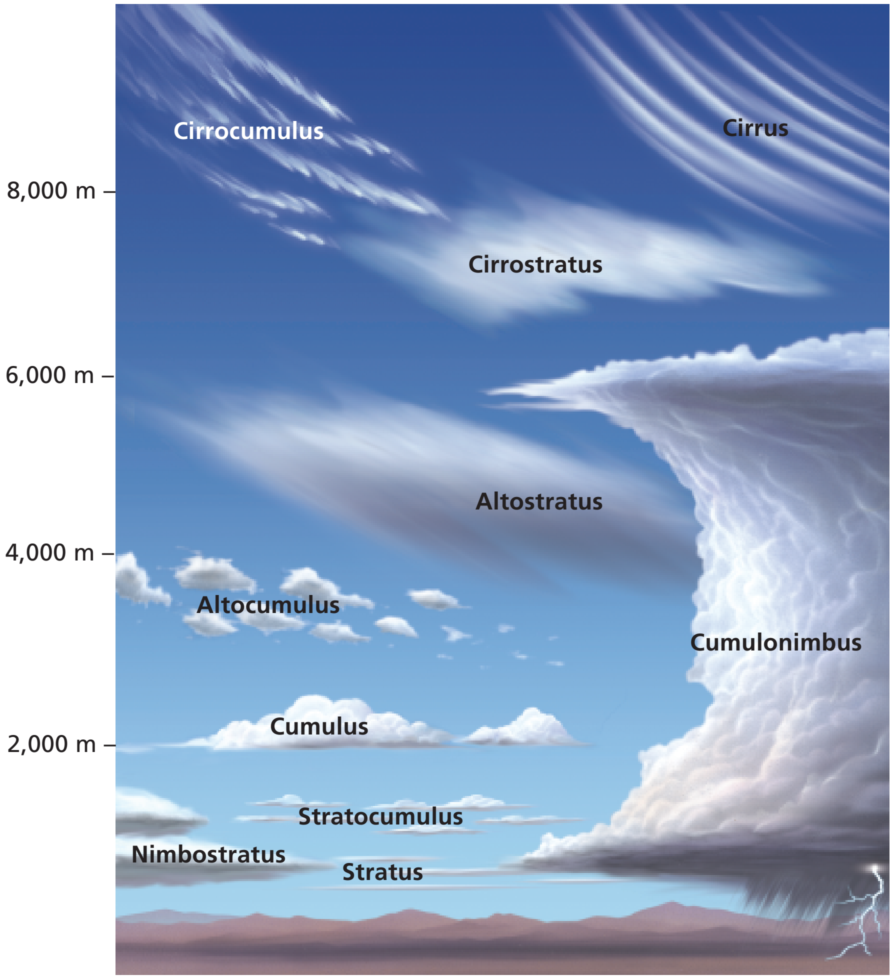


Figure 4 A variety of cloud types can be identified by their altitude and shape. ***What cloud types form at or above 6,000 m?***

Figure 5 Cumulus clouds (left) are puffy, vertically growing clouds, while cirrus clouds (right) are wispy.

Cumulus Clouds

Low-altitude, billowy clouds that commonly have a top that resembles cotton balls and a dark bottom are called **cumulus clouds.** *Cumulus* means "piled" or "heaped." Cumulus clouds usually look fluffy, as shown in **Figure 5.** These clouds form when warm, moist air rises and cools. As the cooling air reaches its dew point, the clouds form. The flat base that is characteristic of most cumulus clouds represents the condensation level.

The height of a cumulus cloud depends on the stability of the troposphere, which is the layer of the atmosphere that touches Earth's surface, and on the amount of moisture in the air. On hot, humid days, cumulus clouds reach their greatest heights. High, dark storm clouds known as *cumulonimbus clouds*, or thunderheads, are often accompanied by rain, lightning, and thunder. If the base of cumulus clouds begins at middle altitudes, the clouds are called *altocumulus clouds*. Low clouds that are a combination of stratus and cumulus clouds are called *stratocumulus clouds*.

cumulus cloud a low-level, billowy cloud that commonly has a top that resembles cotton balls and a dark bottom

cirrus cloud a feathery cloud that is composed of ice crystals and that has the highest altitude of any cloud in the sky

Cirrus Clouds

Feathery clouds that are composed of ice crystals and that have the highest altitude of any cloud in the sky are **cirrus clouds.** Cirrus clouds are also shown in **Figure 5.** *Cirro-* and *cirrus* mean "curly." Cirrus clouds form at altitudes above 6,000 m. These clouds are made of ice crystals because the temperatures are low at such high altitudes. Because these clouds are thin, light can easily pass through them.

Cirrocumulus clouds are high-altitude, billowy clouds composed entirely of ice crystals. Cirrocumulus clouds commonly appear just before a snowfall or a rainfall. Long, thin clouds called *cirrostratus clouds* form a high, transparent veil across the sky. A halo may appear around the sun or moon when either is viewed through a cirrostratus cloud. This halo effect is caused by the bending of light rays as they pass through the ice crystals.

READING TOOLBOX

Analyzing Comparisons
As you read about cumulus clouds and cirrus clouds, look for comparisons between them. Create a table of their similarities and differences.

Reading Check **Why are cirrus clouds commonly composed of ice crystals?**

Figure 6 Steam fog covers the Yakima River in Washington.

Fog

Like clouds, **fog** is the result of the condensation of water vapor in the air. The obvious difference between fog and clouds is that fog is very near the surface of Earth. However, fog also differs from clouds because of how fog forms.

Radiation Fog

One type of fog forms from the nightly cooling of Earth. The layer of air in contact with the ground becomes chilled to below the dew point, and the water vapor in that layer condenses into droplets. This type of fog is called *radiation fog* because it results from the loss of heat by radiation. Radiation fog is thickest in valleys and low places because dense, cold air sinks to low elevations. Radiation fog is often quite thick around cities, where smoke and dust particles act as condensation nuclei.

fog water vapor that has condensed very near the surface of Earth because air close to the ground has cooled

Other Types of Fog

Another type of fog, *advection fog*, forms when warm, moist air moves across a cold surface. Advection fog is common along coasts, where warm, moist air from above the water moves in over a cooler land surface. Advection fog forms over the ocean when warm, moist air is carried over cold ocean currents.

An *upslope fog* forms by the lifting and cooling of air as the air rises along land slopes. *Steam fog* is a shallow layer of fog that forms when cool air moves over an inland warm body of water, such as a river, as shown in **Figure 6.**

Section 2 Review

Key Ideas

1. **Describe** the conditions that are necessary for clouds to form.
2. **Explain** the four processes of cooling that can lead to cloud formation.
3. **Identify** the cloud types that form at 8,000 m.
4. **Compare** cirrus, cumulus, and stratus clouds.
5. **Identify** the type of cloud that is known for causing thunderstorms.
6. **Compare** clouds with fog.
7. **Describe** four ways in which fog can form.

Critical Thinking

8. **Applying Ideas** Explain why air expands when it rises.
9. **Making Predictions** How might an increase in pollution affect cloud formation?
10. **Making Comparisons** Which type of cloud has the lowest condensation level? Which type has the highest condensation level?

Concept Mapping

11. Use the following terms to create a concept map: *cloud, cirrus, condensation level, advective cooling, adiabatic cooling, stratus, cumulus,* and *fog.*

ENVIRONMENTAL CONNECTION

SECTION 3

Precipitation

Key Ideas	Key Terms	Why It Matters
❯ Identify the four forms of precipitation. ❯ Compare the two processes that cause precipitation. ❯ Describe two ways that precipitation is measured. ❯ Explain how rain can be produced artificially.	**precipitation** **coalescence** **supercooling** **cloud seeding**	You may not appreciate the rain when you need to go outside. But rain and other forms of precipitation are an essential part of the water cycle.

Any moisture that falls from the air to Earth's surface is called **precipitation.** The four major types of precipitation are rain, snow, sleet, and hail.

Forms of Precipitation

Rain is liquid precipitation. Normal raindrops are between 0.5 and 5 mm in diameter. They may vary from a fine mist to large drops in a torrential rainstorm. If the raindrops are smaller than 0.5 mm in diameter, the rain is called *drizzle*. Drizzle results in only a small amount of total precipitation.

The most common form of solid precipitation is *snow*, which consists of ice particles. These particles may fall as small pellets, as individual crystals, or as crystals that combine to form snowflakes. Snowflakes tend to be large at temperatures near 0°C and become smaller at lower temperatures.

precipitation any form of water that falls to Earth's surface from the clouds; includes rain, snow, sleet, and hail

When rain falls through a layer of freezing air near the ground, clear ice pellets, called *sleet*, can form. In some cases, the rain does not freeze until it strikes a surface near the ground. There, it forms a thick layer of ice called *glaze ice*, as shown in **Figure 1.** The condition in which glaze ice is produced is commonly referred to as an *ice storm*.

Hail is solid precipitation in the form of lumps of ice. The lumps can be either spherical or irregularly shaped. Hail usually forms in cumulonimbus clouds. Convection currents within the clouds carry raindrops to high levels, where the raindrops freeze before they fall. If the frozen raindrops are carried upward again, they can accumulate additional layers of ice until they are too heavy for the convection currents to carry them. Then they fall to the ground. Large hailstones can damage crops and property.

Figure 1 Glaze ice forms as rain freezes on surfaces near the ground, such as on these flowers.

Figure 2 During coalescence, cloud droplets collide and combine with smaller droplets as they fall. The resulting larger droplets fall as rain.

Causes of Precipitation

Most cloud droplets have a diameter of about 20 μm (micrometers), which is smaller than the period at the end of this sentence. Droplets of this size fall very slowly through the air. A droplet must increase in diameter by about 100 times to fall as precipitation. Two natural processes cause cloud droplets to grow large enough to fall as precipitation: coalescence and supercooling.

Coalescence

The formation of a large droplet by the combination of smaller droplets is called **coalescence** (KOH uh LES uhnts) and is shown in **Figure 2.** Large droplets fall much faster through the air than small droplets do. As these larger droplets drift downward, they collide and combine with smaller droplets. Each large droplet continues to coalesce until it contains a million times as much water as it did originally.

Supercooling

Precipitation also forms by the process of supercooling. **Supercooling** is a condition in which a substance is cooled to below its freezing point, condensation point, or sublimation point without changing state. Supercooled water droplets may have a temperature as low as –40 ºC. Yet even at this low temperature, the water droplets do not freeze. They cannot freeze because too few *freezing nuclei* on which ice can form are available. Freezing nuclei are solid particles that are suspended in the air and that have structures similar to the crystal structure of ice. Most water from the supercooled water droplets evaporates. The water vapor then condenses on the ice crystals that have formed on the freezing nuclei. The ice crystals rapidly increase in size until they gain enough mass to fall as snow, as shown in **Figure 3.** If the ice crystals melt and turn into rain as they pass through air whose temperature is above freezing, they form the big raindrops that are common in summer thunderstorms.

coalescence the formation of a large droplet by the combination of smaller droplets

supercooling a condition in which a substance is cooled below its freezing point, condensation point, or sublimation point without going through a change of state

Figure 3 Most of the rain and snow in the middle and high latitudes of Earth are the result of the formation of ice crystals in supercooled clouds.

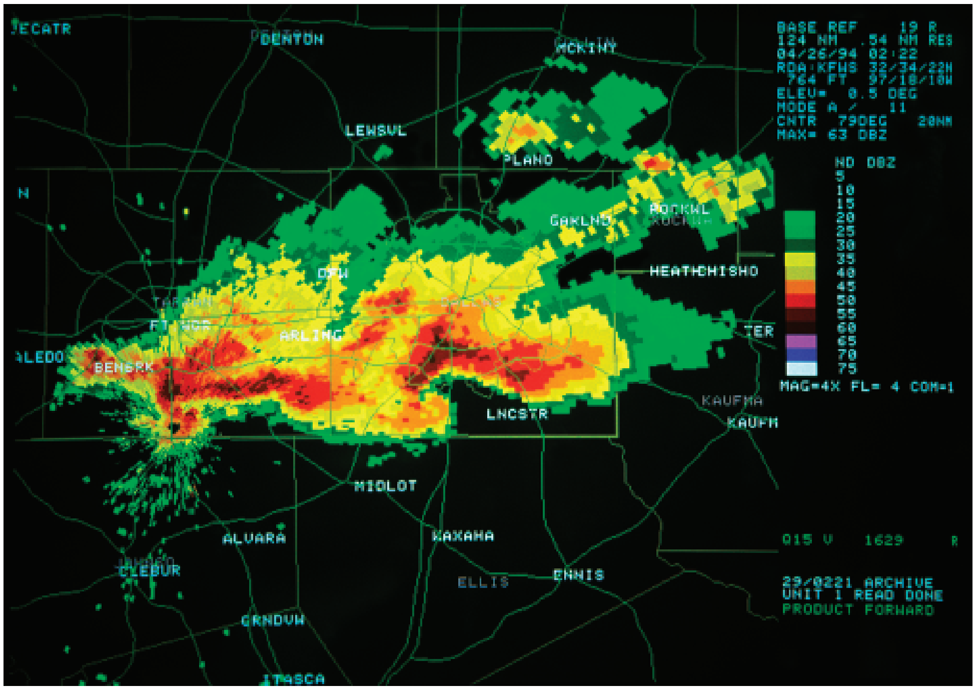


Figure 4 Doppler radar helps meteorologists track storms, such as this large thunderstorm system over North Texas. The colors represent the intensity of rainfall. Reds and yellows indicate areas of heaviest rainfall, while blues and greens denote areas of lighter rainfall.

Measuring Precipitation

Meteorologists use a variety of instruments to measure precipitation. For example, a *rain gauge* may be used to measure rainfall.

Amount of Precipitation

In one type of rain gauge, rainwater passes through a funnel into a calibrated container, where the amount of rainfall can then be measured. In another type of rain gauge, rain caught in a funnel fills a bucket. Each time the bucket fills with a given amount of rainwater, the bucket tips and sets off an electrical device that records the amount. As the bucket tips, it activates a switch that releases the water from the bucket.

Snow depth is simply determined with a measuring stick. The water content of the snow is determined by melting a measured volume of snow and by measuring the amount of water that results. On average, 10 cm of snow will melt to produce about 1 cm of water.

Doppler Radar

The intensity of precipitation can be measured using Doppler radar. Doppler radar images, such as the one in **Figure 4,** are commonly used by meteorologists for communicating weather forecasts. Doppler radar works by bouncing radio waves off rain or snow. By timing how long the wave takes to return, meteorologists can detect the location, direction of movement, and intensity of the precipitation. This information is extremely valuable for saving lives because people can be warned of an approaching storm.

Reading Check **What aspects of precipitation can Doppler radar measure?**

READING TOOLBOX

Suffixes

Find two adverbs that end in the suffix *-ly* on this page. Identify which adjective forms the root of each adverb, and give the meaning of the adverb.

SCILINKS.

www.scilinks.org
Topic: Precipitation
Code: HQX1202

Academic Vocabulary

detect (dee TEKT) to discover the presence of something

Figure 5 Special equipment attached to the wings of cloud-seeding planes releases freezing nuclei into clouds. Meteorologists hope that cloud seeding will induce rain to fall on drought-stricken areas.

Weather Modification

In areas suffering from drought, scientists may attempt to induce precipitation through cloud seeding, as shown in **Figure 5.** **Cloud seeding** is the process of introducing freezing nuclei or condensation nuclei into a cloud to cause rain to fall.

cloud seeding the process of introducing freezing nuclei or condensation nuclei into a cloud in order to cause rain to fall

Methods of Cloud Seeding

One method of cloud seeding uses silver iodide crystals, which resemble ice crystals, as freezing nuclei. The silver iodide is released from burners on the ground or from flares dropped from aircraft. Another method of cloud seeding uses powdered dry ice, which is dropped from aircraft to cool cloud droplets and to cause ice crystals to form. As the ice crystals fall, they may melt to form raindrops.

Improving Cloud Seeding

In some cases, seeded clouds produce more precipitation than unseeded clouds do. In other cases, cloud seeding does not cause a significant increase in precipitation. Sometimes, cloud seeding appears to cause less precipitation. Thus, meteorologists have concluded that cloud seeding may increase precipitation under some conditions but decrease it under others. Research is underway to identify the conditions that cause increased precipitation. Eventually, cloud seeding may become a way to overcome many drought-related problems. In theory, cloud seeding could also help to control a severe storm by releasing precipitation from clouds before the storm can become too large. But scientific experiments have so far failed to prove this.

Section 3 Review

Key Ideas

1. **Identify** four forms of precipitation.
2. **Compare** coalescence and supercooling.
3. **Identify** the instrument that measures amounts of rainfall.
4. **Describe** how the amount of snowfall can be measured.
5. **Explain** how Doppler radar can be used to measure the intensity of precipitation.
6. **Describe** how precipitation can be induced or increased artificially.

Critical Thinking

7. **Predicting Consequences** If water could not remain liquid during supercooling, how would the potential for precipitation in colder climates be affected?
8. **Making Inferences** Explain how cloud seeding could be dangerous if it is not done properly.

Concept Mapping

9. Use the following terms to create a concept map: *precipitation, rain, snow, glaze ice, hail, coalescence, supercooling, freezing nucleus, sleet,* and *drizzle.*

Why It Matters

Ice Storms

SCIENCE & SOCIETY

Beautiful but dangerous, ice storms are one of weather's most sudden phenomena. Ice storms occur when falling snow, passing through a layer of warmer air, melts into rain. At ground level, the rain then passes through a layer of colder air and freezes when it makes contact with a solid object, coating the object in ice. The rain does not have time to form sleet or snow before it hits Earth's surface because the layer of cold air is very close to the ground.

Ice storms can cover roads with ice in a matter of minutes, causing traffic accidents, as surprised motorists are unable to control their cars. Ice coats power lines and utility poles, which can break when the ice becomes too heavy, causing massive power outages that deprive homes of heat during the coldest part of the year.

People can prepare for ice storms by listening to the radio or watching television for news of winter storm watches, warnings, and advisories. They should have extra food and water at home, plus other supplies such as flashlights, batteries, and a first aid kit.

YOUR TURN

UNDERSTANDING CONCEPTS

Why does freezing rain coat Earth's surface with ice instead of falling as sleet?

WRITING IN SCIENCE

Create a pamphlet that explains what people should do in the event of an ice storm.

45 min

Relative Humidity

What You'll Do

- **Measure** humidity in the classroom.
- **Determine** relative humidity.

What You'll Need

cloth, cotton, at least 8 cm × 8 cm
container, plastic
piece of paper
ring stand with ring
rubber band
string
thermometer, Celsius (2)
water

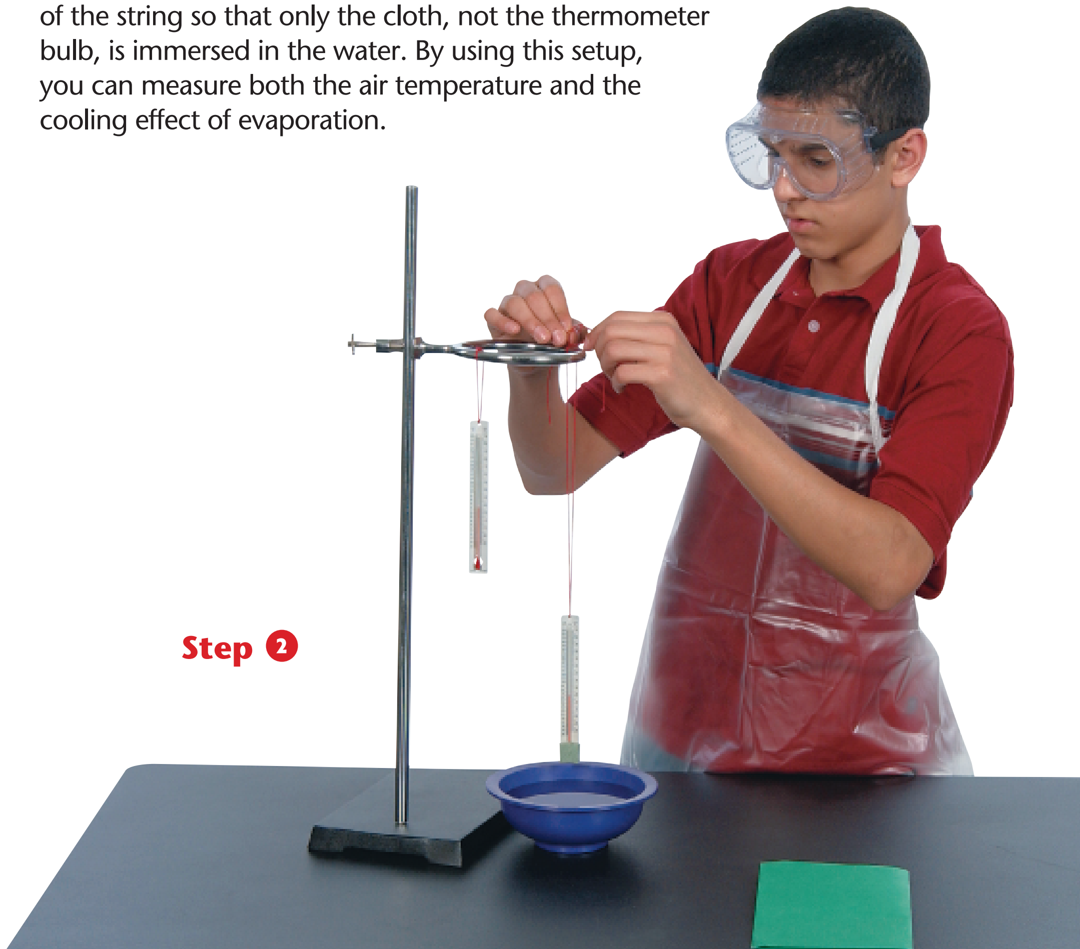
Safety

Earth's atmosphere acts as a reservoir for water that evaporates from Earth's surface. However, the amount of water vapor in the atmosphere depends on the relative rates of condensation and evaporation. When the rates of condensation and evaporation are equal, the air is said to be "saturated." When the rate of condensation exceeds the rate of evaporation, water droplets begin to form in the air or on nearby surfaces. The point at which the condensation rate equals the evaporation rate is called the *dew point* and depends on the temperature of the air and on the atmospheric pressure.

Relative humidity is the ratio of the amount of water vapor in the air to the amount of water vapor that is needed for the air to become saturated. This ratio is most commonly expressed as a percentage. When the air is saturated, the air is said to have a relative humidity of 100%. In this lab, you will use wet-bulb and dry-bulb thermometer readings to determine the relative humidity of the air in your classroom.

Procedure

1. Hang two thermometers from a ring stand, as shown in the photo below.
2. Using a rubber band, fasten a piece of cotton cloth around the bulb of one thermometer. Adjust the length of the string so that only the cloth, not the thermometer bulb, is immersed in the water. By using this setup, you can measure both the air temperature and the cooling effect of evaporation.



3. Predict whether the two thermometers will have the same reading or which thermometer will have the lower reading.
4. Using a piece of paper, fan both thermometers rapidly until the reading on the wet-bulb thermometer stops changing. Read the temperature on each thermometer.
   a. What is the temperature on the dry-bulb thermometer?
   b. What is the temperature on the wet-bulb thermometer?
   c. What is the difference in the two temperature readings?
5. Use the table entitled "Relative Humidity" in the Reference Tables section of the Appendix to find the relative humidity based on your temperature readings in step 4. Look at the left-hand column labeled "Dry-Bulb Temperature." Find the temperature that you recorded in step 4a. Then, find the difference in temperature that you recorded in step 4c along the top row of the table. Locate the intersection of the row and column you have identified. The number shown, expressed as a percentage, is the relative humidity. What is the relative humidity of the air in your classroom?

Step 4

Analysis

1. **Drawing Conclusions** On the basis of the relative humidity you determined, is the air in your classroom close to or far from the dew point? Explain your answer.
2. **Applying Conclusions** If you wet the back of your hand, would the water evaporate and cool your skin?

Extension

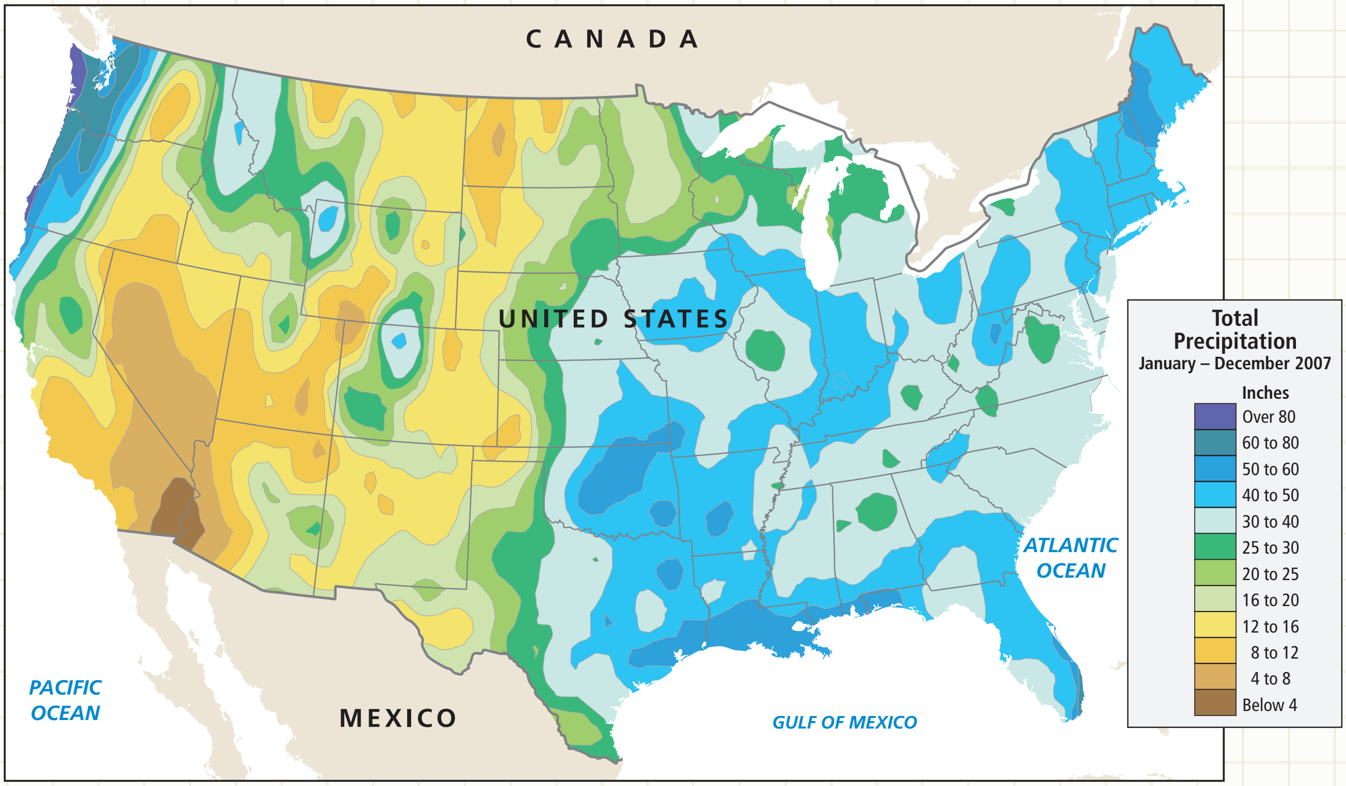
Making Inferences Suppose that you exercise in a room in which the relative humidity is 100%.

a. Would the moisture on your skin from perspiration evaporate easily?
b. Would you be able to cool off readily? Explain your answer.

Applying Ideas Suppose that you have just stepped out of a swimming pool. The relative humidity is low, about 30%. Would you feel warm or cool? Explain your answer.

MAPS in Action

Annual Precipitation in the United States



Map Skills Activity

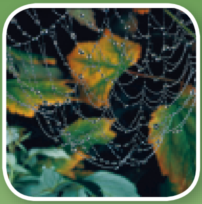
This map shows the total precipitation for the continental United States in 2007. Use the map to answer the questions below.

1. **Using a Key** What is the highest total amount of precipitation for any area in your state?
2. **Making Comparisons** Which area of the United States has the highest total annual precipitation?
3. **Analyzing Methods** Using what you have learned about the formation of precipitation, explain why one area of the United States might have a higher total annual precipitation than another area has.
4. **Making Inferences** List the forms of precipitation that occur in the United States. Identify areas of the United States where you would likely encounter each form.
5. **Evaluating Data** Describe the area of the United States that might be classified as desert.
6. **Making Comparisons** Describe the area of the United States that might have the highest rate of evaporation.
7. **Making Comparisons** Describe the area of the United States that you think might have the highest relative humidity.

THINK central
SUPER SUMMARY
Keyword: HQXWIAS

Key Ideas

Section 1



Atmospheric Moisture

- Latent heat is released or absorbed when water changes from one state to another.
- Absolute humidity is the mass of water vapor contained in a given volume of air. Relative humidity is a ratio of the actual amount of water vapor in the air to the amount of water vapor needed to reach saturation. Humidity can be measured using a variety of instruments, including an electrical hygrometer, a psychrometer, a dew cell, and a hair hygrometer.
- When air reaches the dew point, the rate of condensation equals the rate of evaporation. Below the dew point, net condensation or deposition causes dew or frost to form.

Key Terms

latent heat, p. 543
sublimation, p. 544
dew point, p. 545
absolute humidity, p. 545
relative humidity, p. 546

Section 2

Clouds and Fog

- Clouds form when water vapor cools and condenses on condensation nuclei.
- Water vapor can cool and condense by adiabatic cooling, by the mixing of two bodies of moist air that have different temperatures, by the lifting of air, and by advective cooling.
- The three major types of clouds are stratus clouds, cumulus clouds, and cirrus clouds.
- Fog forms when air near Earth's surface is chilled below the dew point. Fog can form due to heat loss through radiation, advective cooling, the lifting and cooling of air along land slopes, or when cool air moves over an inland body of warm water.

Key Terms

cloud, p. 549
condensation nucleus, p. 549
adiabatic cooling, p. 550
advective cooling, p. 551
stratus cloud, p. 552
cumulus cloud, p. 553
cirrus cloud, p. 553
fog, p. 554

Section 3

Precipitation

- The major forms of precipitation are rain, snow, sleet, and hail.
- Coalescence and supercooling are two processes by which cloud droplets become large enough to fall as precipitation.
- A rain gauge is used to measure liquid precipitation. Snow is measured by its depth and water content.
- Meteorologists utilize cloud seeding to try to induce precipitation.

Key Terms

precipitation, p. 555
coalescence, p. 556
supercooling, p. 556
cloud seeding, p. 558

Chapter 20 Review

1. **Comparisons** Create a table of the similarities and differences among the different types of precipitation.

READING TOOLBOX

USING KEY TERMS

Use each of the following terms in a separate sentence.

2. *latent heat*
3. *condensation nucleus*
4. *precipitation*

For each pair of terms, explain how the meanings of the terms differ.

5. *coalescence* and *supercooling*
6. *stratus cloud* and *cumulus cloud*
7. *adiabatic cooling* and *advective cooling*
8. *relative humidity* and *absolute humidity*
9. *cloud* and *fog*

UNDERSTANDING KEY IDEAS

10. When the temperature of the air decreases, the rate of evaporation
    a. increases.
    b. varies.
    c. stays the same.
    d. decreases.
11. The type of fog that results when moist air moves across a cold surface is
    a. radiation fog.
    b. ground fog.
    c. advection fog.
    d. steam fog.
12. Changes in temperature that result from the cooling of rising air or the warming of sinking air are
    a. adiabatic.
    b. relative.
    c. advective.
    d. latent.
13. Clouds form when the water vapor in air condenses as
    a. the air is heated.
    b. the air is cooled.
    c. snow falls.
    d. the air is superheated.
14. The prefix *nimbo-* and the suffix *-nimbus* mean
    a. high. **c.** rain.
    b. billowy. **d.** layered.
15. The fog that results from the nightly cooling of Earth is called
    a. steam fog. **c.** radiation fog.
    b. upslope fog. **d.** advection fog.
16. Rain that freezes when it strikes a surface produces
    a. sleet. **c.** hail.
    b. glaze ice. **d.** frost.
17. Clouds in which the water droplets remain liquid below 0 °C are said to be
    a. saturated. **c.** superheated.
    b. supersaturated. **d.** supercooled.
18. In one method of cloud seeding, silver iodide crystals are used as
    a. freezing nuclei. **c.** dry ice.
    b. cloud droplets. **d.** latent heat.
19. An instrument that uses the electrical conductance of the chemical lithium chloride to measure relative humidity is the
    a. hygrometer. **c.** psychrometer.
    b. rain gauge. **d.** dew cell.

SHORT ANSWER

20. Explain how the transfer of energy affects the changing forms of water.
21. Explain how a psychrometer measures humidity.
22. Describe how frost forms.
23. Describe how precipitation is measured.
24. Describe how cloud seeding may increase precipitation.
25. Explain how clouds are classified.

CRITICAL THINKING

26. Making Inferences Where would air contain more water vapor: over Panama or over Antarctica? Explain your answer.

27. Identifying Relationships One body of air has a relative humidity of 97%. Another has a relative humidity of 44%. At the same temperature, which body of air is closer to its dew point? Explain your answer.

28. Applying Ideas Why would polluted air be more likely to form fog than clean air would?

29. Analyzing Relationships In tropical regions, surface temperatures are very high. However, some precipitation in these regions forms by supercooling. Why might this happen?

30. Predicting Consequences How would a significant decrease in condensation nuclei in the world's atmosphere affect cloud formation and climate?

CONCEPT MAPPING

31. Use the following terms to create a concept map: *hygrometer, condensation nucleus, stratus, cirrus, cloud, cumulus, precipitation, relative humidity, saturated, rain, supercooling, snow, sleet, coalescence, dew cell,* and *psychrometer.*

MATH SKILLS

Math Skills

32. Applying Quantities One day in January, 6 cm of snow falls on your area. If all this snow melts quickly, how deep will the water from the melted snow be? Explain your answer.

33. Making Calculations At 15 °C, air reaches saturation when it contains 10 g of water vapor per 1 kg of air. What is the relative humidity of air at 15 °C if the air contains 7 g of water vapor per 1 kg of air?

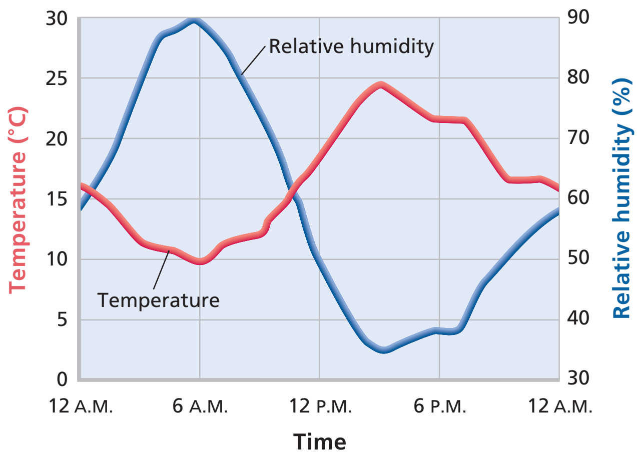
WRITING SKILLS

34. Writing from Research Write a report that describes weather conditions necessary to form each type of cloud. Propose regions and describe climates where each cloud type is most likely to be found.

35. Outlining Topics Create an outline of how clouds form and a separate outline of how precipitation forms. Then, explain how the two differ.

INTERPRETING GRAPHICS

The graph below shows variations in temperature and humidity over a 24 h period. Use this graph to answer the questions that follow.



36. Estimate the relative humidity at 6:00 A.M.

37. Estimate the temperature at 6:00 A.M.

38. Explain why relative humidity might be the highest at 6:00 A.M.

39. When is relative humidity the lowest?

40. How does humidity vary relative to temperature?

Chapter 20 Standardized Test Prep

Understanding Concepts

Directions (1–4): For each question, write on a separate sheet of paper the letter of the correct answer.

1. Which type of fog is formed when cool air moves across a warm river or lake?
   A. radiation fog
   B. advection fog
   C. upslope fog
   D. steam fog
2. Which of the following processes produces most of the water vapor in the atmosphere?
   F. sublimation
   G. evaporation
   H. advective cooling
   I. convective cooling
3. Which of the following is the main source of moisture in Earth's atmosphere?
   A. lakes
   B. rivers
   C. polar icecaps
   D. oceans
4. What is relative humidity?
   F. a ratio comparing the mass of water vapor in the air at two different locations
   G. a ratio comparing the mass of water vapor in the air at two times during the day in the same location
   H. a ratio comparing the actual amount of water vapor in the air with the capacity of the air to hold moisture at a given temperature
   I. a ratio comparing the mass of water vapor that air can hold at two different altitudes at noon and at midnight

Directions (5–7): For each question, write a short response.

5. What instrument is used to measure atmospheric pressure?
6. Particles called condensation nuclei, which are suspended in the atmosphere, are necessary in allowing what process to take place?
7. What does water vapor turn into when the dew point falls below the freezing point of water?

Reading Skills

Directions (8–9): Read the passage below. Then, answer the questions.

Acid Precipitation

Thousands of lakes thoughout the world are affected by acid precipitation, often known simply as acid rain. Acid precipitation is precipitation, such as rain, sleet, or snow, that contains high concentrations of acids. When fossil fuels are burned, they release oxides of sulfur and nitrogen. When the oxides combine with water in the atmosphere, they form sulfuric acid and nitric acid, which fall as precipitation. This acidic water flows over and through the ground, and then flows into lakes, rivers, and streams. Acid precipitation can kill living things and can result in the decline or loss of some local animal and plant populations.

A pH (power of hydrogen) number is a measure of how acidic or basic a substance is. The lower the number on the pH scale is, the more acidic a substance is; the highter a pH number is, the more basic a substance is. Each whole number on the pH scale indicates a tenfold change in acidity.

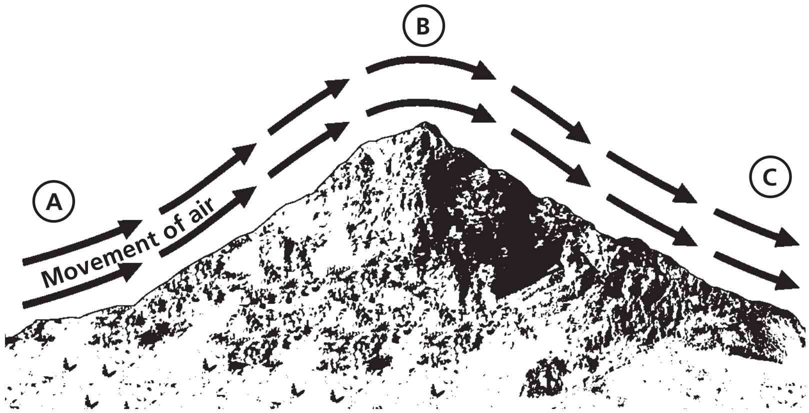
8. According to the passage, which of the following statements is true?
   A. Acid precipitation always falls as rain.
   B. Acid precipitation seeps into local water supplies and may pose a danger to living things in the area.
   C. Sulfur and nitrogen mix with oxygen in the atmosphere and become acids.
   D. The amount of acidic precipitation is balanced in nature by an equal amount of basic precipitation.
9. Which of the following statements can be inferred from the information in the passage?
   F. A reduction in the use of fossil fuels may help to alleviate the problem of acid rain.
   G. Local animal and plant species will most likely adapt to acid rain.
   H. The acid in precipitation is effectively neutralized once it is in a lake or stream.
   I. The amount of acid in a substance can be measured by using a 10-point scale.

Interpreting Graphics

Directions (10–14): For each question below, record the correct answer on a separate sheet of paper.

The diagram below shows the direction of air movement over a mountain. Use this diagram to answer questions 10 through 12.

Movement of Air over a Mountain



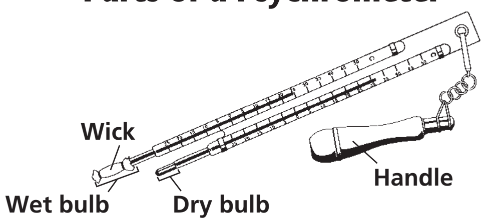
10. As air moves from point A to point B, the air temperature
- **A.** increases.
- **B.** decreases.
- **C.** stays the same.
- **D.** is impossible to predict.

11. Air moving from point B to point C will become compressed and gain energy as it moves down the mountain, which will cause the air to undergo
- **F.** adiabatic warming.
- **G.** adiabatic cooling.
- **H.** condensation.
- **I.** sublimation.

12. If moist air moves up the mountain from point A, what process is likely to occur when the moist air moves near point B?

The diagram below shows the parts of a psychrometer. Use this diagram to answer questions 13 and 14.

Parts of a Psychrometer



13. How does a meteorologist use a psychrometer, such as the one shown in the diagram above?
- **A.** It is placed in a pan of water and exposed to the air for 1 h.
- **B.** The handle is used to dip it into a body of water, such as a lake.
- **C.** It is held by the handle and twirled in the air.
- **D.** It is held until the readings on both thermometers are equal.

14. Why is it necessary to obtain two readings? What measurements of atmospheric moisture can be determined from these readings?

Test Tip

If you are not sure of an answer, go to the next question, but remember to skip that number on your answer sheet.