18 Moisture, Clouds, and Precipitation

Big idea

Weather and Climate

Q: What processes are involved in cloud formation and precipitation?

VIRGINIA SCIENCE STANDARDS OF LEARNING

ES.1.a, ES.1.c, ES.11.c, ES.12.a, ES.12.b.
See lessons for details.

Low clouds cover mountain peaks in Great Smoky Mountains National Park.

INQUIRY TRY IT!

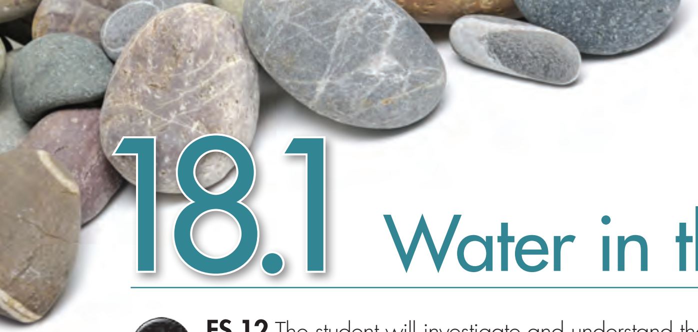
WHAT CAUSES CONDENSATION?

Procedure

1. Fill a 250-mL beaker about one-third full of tap water. Gradually add ice to the beaker. Gently stir the water-ice mixture with a thermometer.
2. Be sure to keep the thermometer in the water–ice mixture. Record the temperature at the moment water begins to form on the outside surface of the beaker.

Think About It

1. **Observe** At what temperature did water first appear on the outside of the beaker?
2. **Infer** Where did the water that formed on the beaker's outer surface come from?
3. **Apply Concepts** Describe a process in nature that results from condensation with a change in temperature.



18.1 Water in the Atmosphere

ES.12 The student will investigate and understand that energy transfer between the sun and Earth and its atmosphere drives weather and climate on Earth. Key concepts include **a.** observation and collection of weather data.

Key Questions

Which gas is most important for understanding atmospheric processes?

What happens during a change of state?

How do warm and cold air compare in their ability to hold water vapor?

What is relative humidity?

What can change the relative humidity of air?

Vocabulary

- precipitation
- latent heat
- evaporation
- condensation
- sublimation
- deposition
- humidity
- saturated
- relative humidity
- dew point
- hygrometer

Reading Strategy

Monitor Your Understanding Before you read, copy the table. List what you know about water in the atmosphere and what you would like to learn. After you read, list what you have learned.

What I Know	What I Would Like to Learn	What I Have Learned
a. ?	b. ?	c. ?
d. ?	e. ?	f. ?

AS YOU OBSERVE day-to-day weather changes, you can see the powerful role of water in the air. Water vapor is the source of all condensation and **precipitation,** which is any form of water that falls from a cloud. Snow, sleet, and hail, as well as the rain shown in **Figure 1,** are all examples of precipitation. **When it comes to understanding atmospheric processes, water vapor is the most important gas in the atmosphere.** Water vapor makes up only a small fraction of the gases in the atmosphere, varying from nearly 0 to about 4 percent by volume. But the importance of water in the air greatly exceeds what these small percentages would indicate.

Water's Changes of State

Water is the only substance that exists in Earth's atmosphere as a solid, liquid, and gas. Water can change from one state of matter to another—at temperatures and pressures experienced on Earth. This unique property allows Earth's water supply to circulate through the oceans, the atmosphere, solid Earth, and the biosphere in the water cycle. All water in the cycle eventually passes through the atmosphere as water vapor, even though the atmosphere only holds enough to make a global layer of water about 2 mm deep.

Reading Checkpoint *What is the range in volume percent of water in the atmosphere?*

FIGURE 1
Precipitation
This downpour shows how precipitation can affect daily activities.

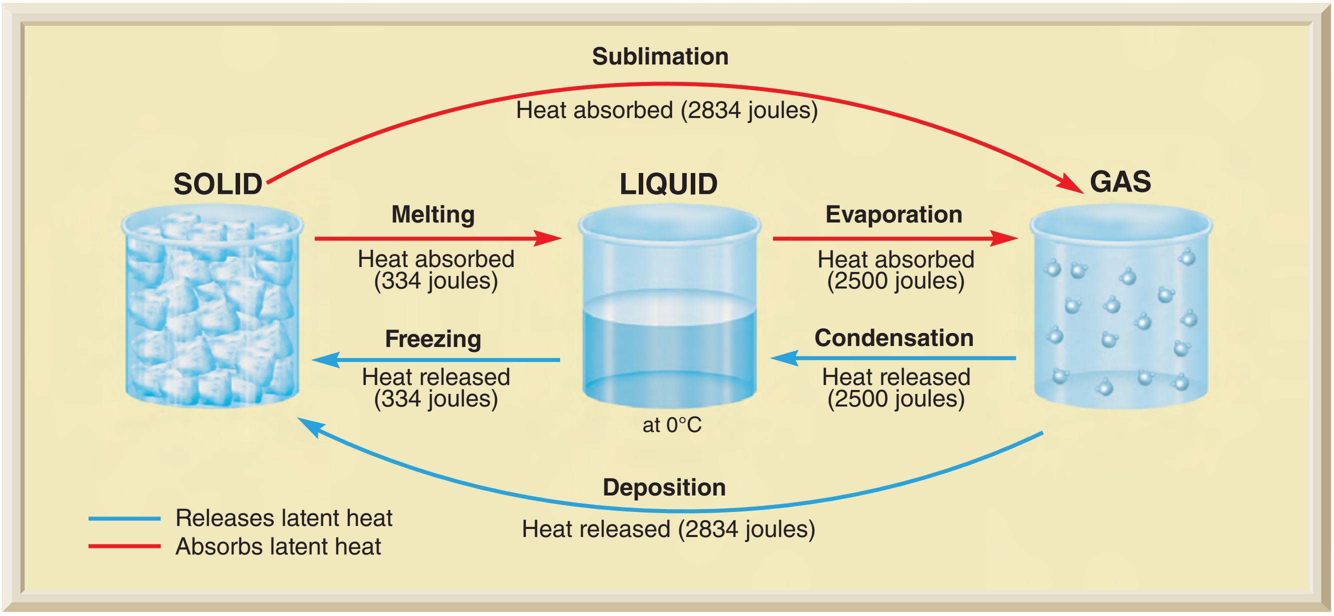


FIGURE 2 Changes of State The heat energy, in joules, is indicated for 1 gram of water.

Solid to Liquid **The process of changing state requires that energy is transferred in the form of heat.** When heat is transferred to a glass of ice water, the temperature of the ice water remains a constant 0°C until all the ice has melted. If adding heat does not raise the temperature, then where does this energy go? In this case, the added heat breaks apart the crystal structure of the ice cubes. The bonds between water molecules in the ice crystals are broken forming the noncrystalline substance liquid water. You know this process as *melting.*

The heat used to melt ice does not produce a temperature change, so it is referred to as **latent heat.** *Latent* means "hidden," like the latent fi gerprints hidden at a crime scene. This energy, measured in joules or calories, becomes stored in the liquid water and is not released as heat until the liquid returns to the solid state.

Latent heat plays a crucial role in many atmospheric processes. For example, the release of latent heat aids in forming the towering clouds often seen on warm summer days. It is the major source of energy for thunderstorms, tornadoes, and hurricanes.

Liquid to Gas The process of changing a liquid to a gas is called **evaporation.** You see in **Figure 2** that it takes approximately 2500 joules to convert 1 gram of liquid water at 0°C to water vapor. The energy absorbed by the water molecules during evaporation gives them the motion needed to escape the surface of the liquid and become a gas. This energy is referred to as *latent heat of vaporization.*

During the process of evaporation, the higher-temperature, faster-moving molecules escape the surface. As a result, the average molecular motion (temperature) of the remaining molecules is reduced. This is why evaporation is considered a cooling process. You might have experienced this effect when stepping dripping wet from a swimming pool or bathtub. It takes considerable energy to evaporate water. In this situation, the energy comes from your skin—hence you feel cool.

The opposite process where water vapor changes to the liquid state is called **condensation.** In the atmosphere, condensation generates clouds and fog. For condensation to occur, molecules of water vapor must release their stored heat energy, called *latent heat of condensation,* equal to what was absorbed during evaporation. This released energy plays an important role in producing violent weather and can transfer great quantities of heat from tropical oceans toward the poles.

Solid to Gas Water also can be transformed from a solid to a vapor state. **Sublimation** is the conversion of a solid directly to a gas, without passing through the liquid state. You may have observed this change in watching the sublimation of dry ice, or frozen carbon dioxide. Dry ice sometimes is used to generate "smoke" in theatrical productions. **Deposition** is the reverse process, the conversion of a vapor directly to a solid. This change happens when water vapor is deposited as frost on cold objects such as grass or windows.

Humidity

The general term for the amount of water vapor in air is **humidity.** Meteorologists use several methods to express the water-vapor content of the air. These include relative humidity and dew-point temperature.

Saturation Imagine a closed jar half full of water and half full of dry air. As the water begins to evaporate from the water surface, a small increase in pressure can be detected in the air above. This increase is the result of the motion of the water-vapor molecules that were added to the air through evaporation. As more and more molecules escape from the water surface, the pressure in the air above increases steadily. This forces more and more water molecules to return to the liquid. Eventually, the number of water-vapor molecules returning to the surface will balance the number leaving. At that point, the air is said to be **saturated.** The amount of water vapor required for saturation depends on temperature as shown in **Table 1.** **When saturated, warm air contains more water vapor than saturated cold air.**

Relative Humidity The most familiar and most misunderstood term used to describe the moisture content of air is relative humidity. **Relative humidity is a ratio of the air's actual water-vapor content compared with the amount of water vapor air can hold at that temperature and pressure.** Relative humidity indicates how near the air is to saturation, rather than the actual quantity of water vapor in the air.

Table 1 Water Vapor Needed for Saturation

Temperature		Water Vapor Content at Saturation (grams per kilograms of air)
°C	°F	
−40	−40	0.1
−30	−22	0.3
−20	−4	0.75
−10	14	2
0	32	3.5
5	41	5
10	50	7
15	59	10
20	68	14
25	77	20
30	86	26.5
35	95	35
40	104	47

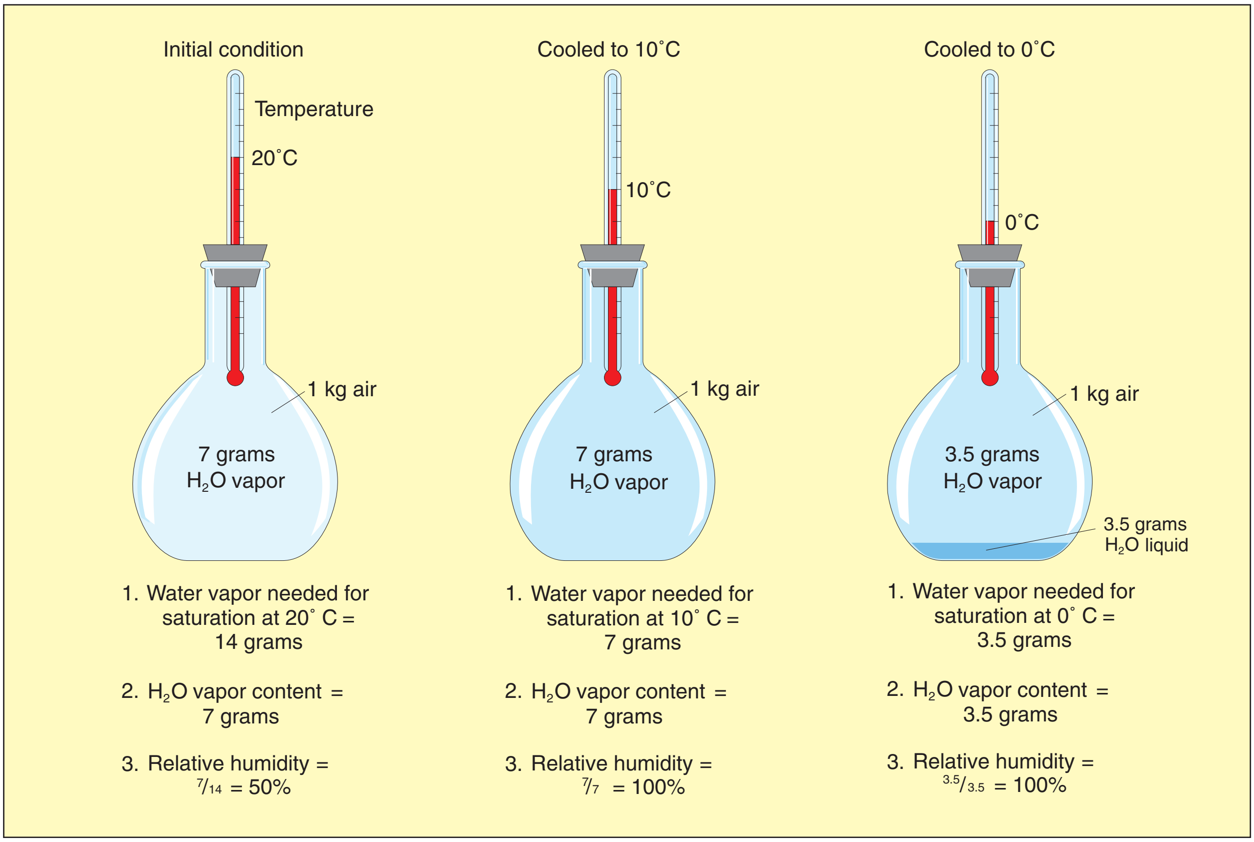


FIGURE 3 Relative Humidity Relative humidity varies with temperature. When the temperature in the flask decreased from 20°C to 10°C, the relative humidity increased to 100 percent. When the temperature was decreased further, some of the water vapor condensed to liquid water.

Relative humidity can be changed in two ways. First, it can be changed by adding or removing water vapor. In nature, moisture is added to air mainly by evaporation from the oceans and smaller bodies of water.

Second, because the amount of moisture needed for saturation depends on temperature, relative humidity varies with temperature. Notice in **Figure 3** that when the flask is cooled from 20°C to 10°C, the relative humidity increases from 50 to 100 percent. However, once the air is saturated, further cooling does not change the relative humidity. Further cooling causes condensation, which keeps the air at its saturation level for the temperature. When air far above Earth's surface is cooled below its saturation level, some of the water vapor condenses to form clouds. Because clouds are made of liquid droplets, this moisture is no longer part of the water-vapor content of the air. **To summarize, when the water-vapor content of air remains constant, lowering air temperature causes an increase in relative humidity, and raising air temperature causes a decrease in relative humidity.**

FIGURE 4 Dew The water droplets on this spider web formed when the air temperature dropped below the dew point.

Dew Point Another important measure of humidity is the dew-point temperature. The dew-point temperature or simply the **dew point** is the temperature to which a parcel of air would need to be cooled to reach saturation. If the same air was cooled further, the air's excess water vapor would condense, typically as dew, fog, or clouds. During evening hours, objects near the ground often cool below the dew-point temperature and become coated with water. This is known as dew, shown on the spider web in **Figure 4.**

For every 10°C increase in temperature, the amount of water vapor needed for saturation doubles. Therefore, relatively cold saturated air at 0°C contains about half the water vapor of saturated air at a temperature of 10°C, and roughly one-fourth that of hot saturated air with a temperature of 20°C as shown in Table 1. Because the dew point is the temperature at which saturation occurs, high dew-point temperatures indicate moist air, and low dew-point temperatures indicate dry air.

Measuring Humidity Relative humidity is commonly measured by using a **hygrometer.** One type of hygrometer, called a psychrometer, consists of two identical thermometers mounted side by side. One thermometer, the dry-bulb thermometer, gives the present air temperature. The other, called the wet-bulb thermometer, has a thin cloth wick tied around the end.

To use the psychrometer, the cloth wick is saturated with water and air is continuously passed over the wick. In a sling psychrometer like the one shown in **Figure 5,** air is passed over the wick by swinging the instrument. Water evaporates from the wick, and the heat absorbed by the evaporating water makes the temperature of the wet bulb drop. The loss of heat that was required to evaporate water from the wet bulb lowers the thermometer reading. This temperature is referred to as the wet-bulb temperature.

The amount of cooling that takes place is directly proportional to the dryness of the air. The drier the air, the more moisture evaporates, and the lower is the temperature of the wet bulb. The larger the difference is between temperatures observed on the thermometers, the lower the relative humidity. If the air is saturated, no evaporation will occur, and the two thermometers will have identical readings. To determine the precise relative humidity and to calculate the dew point, standard tables are used.

A psychrometer would not be all that useful in a weather balloon used to monitor conditions in the upper atmosphere. A different type of hygrometer is used in instrument packages that transmit data back to a station on the ground. The electric hygrometer contains an electrical conductor coated with a chemical that absorbs moisture. The passage of current varies with the amount of moisture absorbed.

INQUIRY APPLY IT!

Q: *Why is the air in buildings so dry in the winter?*

A: If the water-vapor content of air stays constant, an increase in temperature lowers the relative humidity, and a drop in temperature raises the relative humidity. During winter months, outside air is comparatively cold. When this air is drawn into a building, it is heated to room temperature. This causes the relative humidity to drop, often to uncomfortably low levels of 10 percent or lower. Living with dry air can mean static electrical shocks, dry skin, sinus headaches, or even nosebleeds.

FIGURE 5
Sling Psychrometer
This psychrometer is used to measure both relative humidity and dew point.
Interpret Photographs *Identify the wet bulb and the dry bulb in this photograph.*

18.1 Assessment

Review Key Concepts

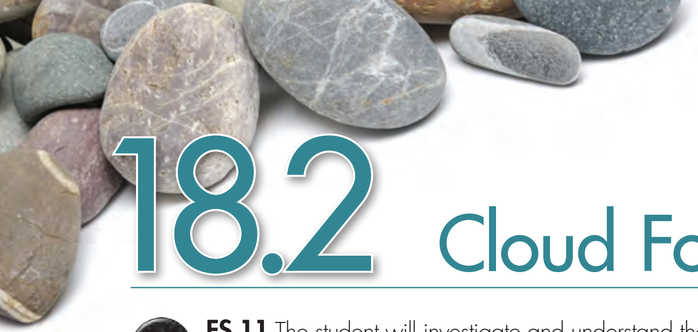
1. What is the most important gas for understanding atmospheric processes?
2. What happens to heat during a change of state?
3. How does the temperature of air influence its ability to hold water?
4. What does relative humidity describe about air?
5. List two ways that relative humidity can be changed.
6. What does a low dew point indicate about the moisture content of air?

Think Critically

7. **Interpret Visuals** Study Figure 2. For 1 gram of water, how do the energy requirements for melting and evaporation compare?

MATH PRACTICE

8. **Calculate** The air over Fort Myers, Florida, has a dew point of 25°C. Fort Myers has twice the water vapor content of the air over St. Louis, Missouri, and four times the water vapor content as air over Tucson, Arizona. Determine the dew points for St. Louis and Tucson.



18.2 Cloud Formation

ES.11 The student will investigate and understand the origin and evolution of the atmosphere and the interrelationship of geologic processes, biologic processes, and human activities on its composition and dynamics. Key concepts include **c.** atmospheric regulation mechanisms including the effects of density differences and energy transfer.

Key Questions

What happens to air when it is compressed or allowed to expand?

List four mechanisms that can cause air to rise.

Contrast movements of stable and unstable air.

What conditions in air favor condensation of water?

Vocabulary

- dry adiabatic rate
- wet adiabatic rate
- orographic lifting
- front
- temperature inversion
- condensation nuclei

Reading Strategy

Identify Main Ideas Copy the table. As you read, write the main idea for each topic.

Topic	Main Idea
Adiabatic temperature changes	a. ___?___
Stability measurements	b. ___?___
Degrees of stability	c. ___?___

RECALL THAT CONDENSATION occurs when water vapor changes to a liquid. Condensation may form dew, fog, or clouds. Although these three forms are different, all require saturated air to develop. Saturation occurs either when enough water vapor is added to air or, more commonly, when air is cooled to its dew point.

Near Earth's surface, heat is quickly exchanged between the ground and the air above. During evening hours, the surface radiates heat away, causing the surface and adjacent air to cool rapidly. This radiational cooling causes the formation of dew and some types of fog. In contrast, clouds, such as those shown in **Figure 6,** often form during the warmest part of the day. Clearly, some other process must cool air enough to generate clouds.

Air Compression and Expansion

If you have pumped up a bicycle tire, you might have noticed that the pump barrel became warm. The increase in temperature you felt resulted from the work you did on the air to compress it. When air is compressed, the motion of gas molecules increases and the air temperature rises. The opposite happens when air is allowed to escape from a bicycle tire. The air expands and cools. The expanding air pushes on the surrounding air and cools by an amount equal to the energy expended while pushing on the surrounding air.

FIGURE 6 Clouds Clouds form when air is cooled to its dew point.

Adiabatic Temperature Changes Temperature changes that happen even though heat isn't added or subtracted are called *adiabatic temperature changes.* They result when air is compressed or allowed to expand. **When air is allowed to expand, it cools, and when it is compressed, it warms.**

Expansion and Cooling As you travel from Earth's surface upward through the atmosphere, the atmospheric pressure decreases. This happens because there are fewer and fewer gas molecules. Any time a volume of air moves upward, it passes through regions of successively lower pressure. As a result, the ascending air expands and cools. Unsaturated air cools at the constant rate of 10°C for every 1000 meters of ascent. In contrast, descending air encounters higher pressures, compresses, and is heated 10°C for every 1000 meters it moves downward. This rate of cooling or heating applies only to unsaturated air and is called the **dry adiabatic rate.**

If a parcel of air rises high enough, it will eventually cool to its dew point. Here the process of condensation begins. From this point on as the air rises, latent heat of condensation stored in the water vapor will be released. Although the air will continue to cool after condensation begins, the released latent heat works against the adiabatic cooling process. This slower rate of cooling caused by the addition of latent heat is called the **wet adiabatic rate.** Because the amount of latent heat released depends on the quantity of moisture present in the air, the wet adiabatic rate varies from 5–9°C per 1000 meters.

Figure 7 shows the role of adiabatic cooling in the formation of clouds. Note that from the surface up to the condensation level the air cools at the dry adiabatic rate. The wet adiabatic rate begins at the condensation level.

Reading Checkpoint *What happens to heat stored in water vapor when it is cooled to its dew point?*

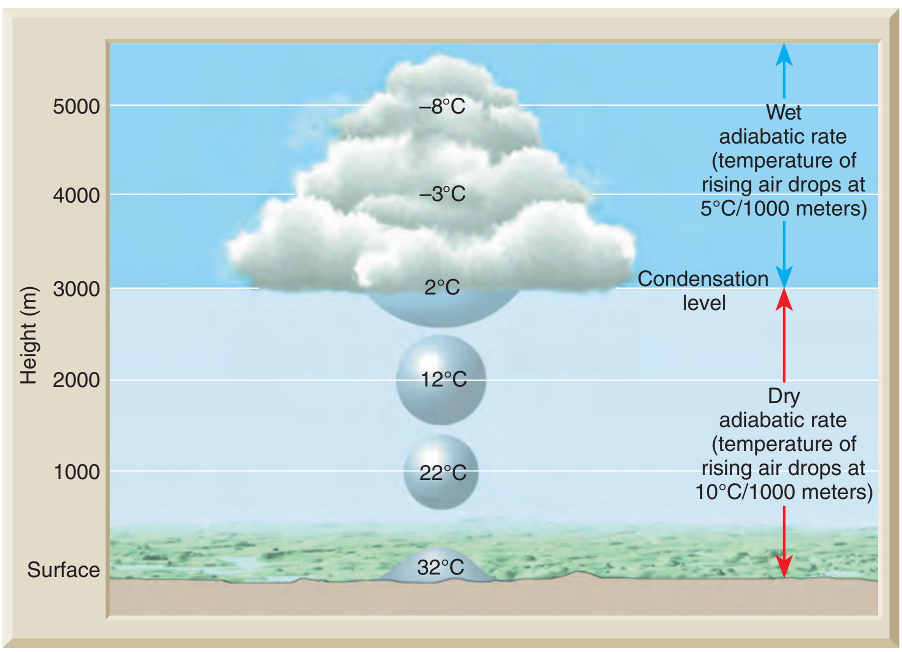


FIGURE 7 Cloud Formation by Adiabatic Cooling Rising air cools at the dry adiabatic rate of 10°C per 1000 meters, until the air reaches the dew point and condensation (cloud formation) begins. As air continues to rise, the latent heat released by condensation reduces the rate of cooling.
Interpret Visuals ***Use this diagram to determine the approximate air temperature at 3500 m.***

Processes That Lift Air

In general, air resists vertical movement. Air located near the surface tends to stay near the surface. Air far above the surface tends to remain far above the surface. Some exceptions to this happen when conditions in the atmosphere make air buoyant enough to rise without the aid of outside forces. In other situations, clouds form because there is some mechanical process that forces air to rise. **Four mechanisms that can cause air to rise are orographic lifting, frontal wedging, convergence, and localized convective lifting.**

PLANET DIARY

For an activity on **Orographic lifting and rainfall,** visit PlanetDiary.com/HSES.

Orographic Lifting When elevated terrains, such as mountains, act as barriers to air flow and force air to ascend, this is called **orographic lifting**. Look at **Figure 8A.** As air goes up a mountain slope, adiabatic cooling often generates clouds and precipitation. Many of the rainiest places on Earth are located on these windward mountain slopes.

By the time air reaches the leeward side of a mountain, which is away from the wind, much of the air's moisture has been lost. If the air descends, it warms adiabatically. This makes condensation and precipitation even less likely. A *rain shadow desert* can occur on the leeward side of the mountain. For example, the Great Basin Desert of the western United States lies only a few hundred kilometers from the Pacific Ocean, cut off rom the ocean's moisture by the Sierra Nevada Mountains.

Frontal Wedging If orographic lifting were the only mechanism that lifted air, the relatively flat central portion of North America would be an expansive desert instead of the nation's breadbasket. Fortunately, this is not the case.

In central North America, masses of warm air and cold air collide, producing a **front.** Here the cooler, denser air acts as a barrier over which the warmer, less dense air rises. This process, called *frontal wedging,* is shown in **Figure 8B.** Weather-producing fronts are associated with specific storm systems called middle-latitude cyclones. You will study these in the Weather Patterns and Severe Storms chapter.

VISUAL SUMMARY

PROCESSES THAT LIFT AIR

FIGURE 8 There are four different mechanisms that can cause air to rise—orographic lifting, frontal wedging, convergence, and localized convective lifting.
Relate Cause and Effect ***Why does the warm air mass move upward over the cold air mass?***

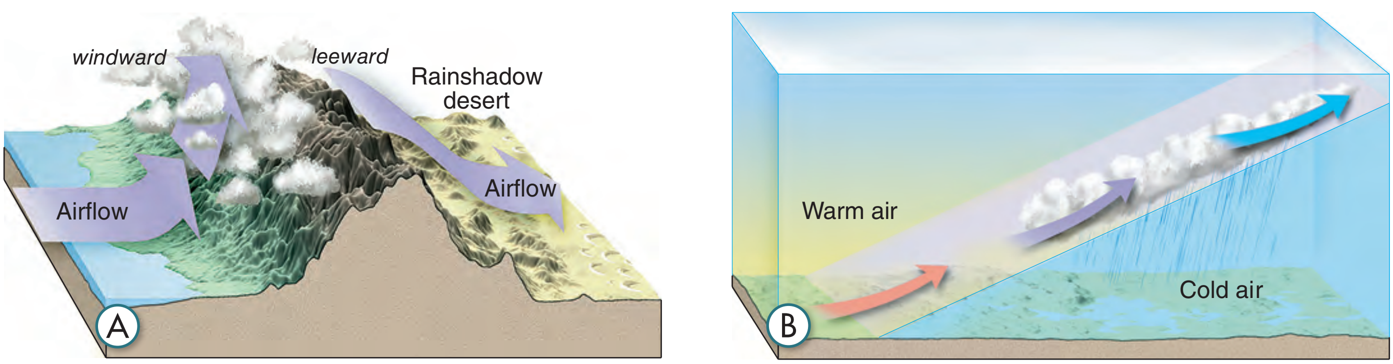


FIGURE 8
A Orographic Lifting Mountains are a barrier to air flow and force air to ascend.

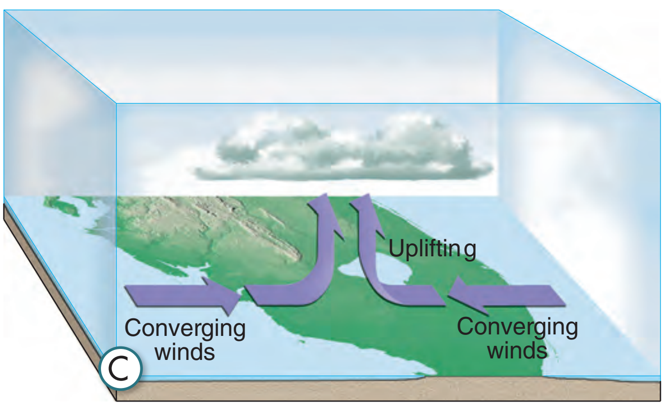
B Frontal Wedging Warm, less dense air rises above cooler, denser air.

Convergence Recall that the collision of contrasting air masses forces air to rise. In a more general sense, whenever air in the lower atmosphere flows together, lifting results. This is called *convergence.* When air flows in from more than one direction, it must go somewhere. Because it cannot go down, it goes up, as shown in **Figure 8C.** This leads to adiabatic cooling and possibly cloud formation.

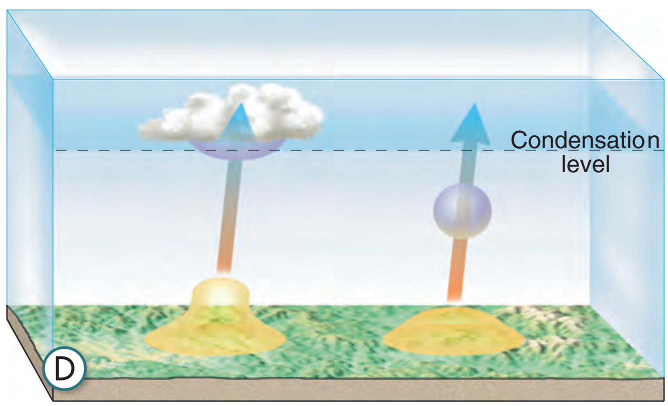
The Florida peninsula provides an example of how convergence can cause cloud development and precipitation. On warm days, the airflow is from the ocean to the land along both coasts of Florida. This leads to a pileup of air along the coasts and general convergence over the peninsula. This pattern of air movement and the uplift hat results is helped along by intense solar heating of the land. The result is that the peninsula of Florida experiences the greatest number of mid-afternoon thunderstorms in the United States.

Localized Convective Lifting On warm summer days, unequal heating of Earth's surface may cause pockets of air to be warmed more than the surrounding air. For example, air above a paved parking lot will be warmed more than the air above an adjacent wooded park. Consequently, the parcel of air above the parking lot, which is warmer and less dense than the surrounding air, will move upward, as shown in **Figure 8D.** These rising parcels of warmer air are called *thermals.* The process that produces rising thermals is *localized convective lifting.* Birds such as hawks and eagles use these thermals to carry them to great heights where they can gaze down on unsuspecting prey. People have learned to use these warm parcels effectively for hang gliding. When warm parcels of air rise above the condensation level, clouds form. These clouds may produce mid-afternoon rain showers.

Reading Checkpoint *What are thermals?*



C Convergence Air is forced to rise when two air masses collide.



D Localized Convective Lifting Unequal heating of Earth's surface causes parcels of air to rise.

Stability

If a volume of air was forced to rise, its temperature would drop because of expansion. If this volume of air was cooler than the surrounding environment, it would be denser, and if allowed to do so, it would sink to its original position. Air of this type, called *stable air,* resists vertical movement.

Density Differences If this imaginary volume of rising air was warmer and therefore less dense than the surrounding air, it would continue to rise until it reached an altitude where its temperature equaled that of its surroundings. This is exactly how a hot-air balloon works. The balloon rises as long as it is warmer and less dense than the surrounding air, as shown in **Figure 9.** This type of air is classified as *unstable air.* **Stable air tends to remain in its original position, while unstable air tends to rise.**

Stability Measurements Air stability is determined by measuring the temperature of the atmosphere at various heights. The rate of change of air temperature with height is called the *environmental lapse rate.* This rate is determined from observations made by aircraft nd by radiosondes. A *radiosonde* is an instrument designed to collect weather data high in the atmosphere. Radiosondes are often carried into the air by balloons.

Degrees of Stability Air is stable when the temperature decreases gradually with increasing altitude. The most stable conditions happen when air temperature actually increases with height, called a **temperature inversion.** Temperature inversions frequently happen on clear nights as a result of radiation cooling off arth's surface.

FIGURE 9 Unstable Air Hot-air balloons will rise as long as the air inside them is warmer than the air in the atmosphere surrounding them.

FIGURE 10 Clouds from Unstable Air These clouds provide evidence of unstable conditions in the atmosphere.

The inversion is created because the ground and the air immediately above the ground will cool more rapidly than air higher above the ground. Under these conditions, there is very little vertical air movement. In contrast, air is considered unstable when the air close to the surface of Earth is significantly warmer than the air higher above the surface, indicating a large environmental lapse rate. Under these conditions, the air actually turns over, as the warm air below rises and is displaced by the colder air higher above the ground.

Stability and Daily Weather Recall that stable air resists vertical movement and that unstable air rises freely. But how do these facts apply to the daily weather?

Because stable air resists upward movement, you might conclude that clouds won't form when stable conditions are present in the atmosphere. Although this seems reasonable, remember that there are processes that force air above Earth's surface. These include orographic lifting, frontal wedging, and convergence. When stable air is forced above Earth's surface, the clouds that form are widespread and have little vertical thickness when compared to their horizontal dimension. Precipitation, if any, is light to moderate.

In contrast, clouds associated with the lifting of unstable air are towering and often generate thunderstorms and occasionally even a tornado. For this reason, on a dreary, overcast day with light drizzle, stable air has been forced above Earth's surface. During a day when cauliflower-shaped clouds appear to be growing as if bubbles of hot air are surging upward, the air moving up is unstable. **Figure 10** shows cauliflower-shaped clouds caused by the rising of unstable air.

Reading Checkpoint *What types of weather can result when stable air rises?*

Condensation

Recall that condensation happens when water vapor in the air changes to a liquid. This may be in the form of dew, fog, or clouds. **For any of these forms of condensation to occur, the air must be saturated.** Saturation occurs most commonly when air is cooled to its dew point, or less often when water vapor is added to the air.

Types of Surfaces Generally, there must be a surface for water vapor to condense on. When dew forms, objects at or near the ground, such as grass and car windows, serve this purpose. But when condensation occurs in the air above the ground, tiny bits of particulate matter, called **condensation nuclei,** serve as surfaces for water-vapor condensation. These nuclei are important because if they are absent, a relative humidity much above 100 percent is needed to produce clouds.

Particles in the Lower Atmosphere Condensation nuclei such as microscopic dust, smoke, and salt particles from the ocean are abundant in the lower atmosphere. Because of these plentiful particles, relative humidity rarely exceeds 100 percent. Some particles, such as ocean salt, are especially good nuclei because they absorb water. When condensation takes place, the initial growth rate of cloud droplets is rapid. It diminishes quickly because the excess water vapor is quickly absorbed by the numerous competing particles. This results in the formation of a cloud consisting of millions upon millions of tiny water droplets. These droplets are all so fi e that they remain suspended in air. In the next lesson, you will examine types of clouds and the precipitation that forms from them.

18.2 Assessment

Review Key Concepts

1. Describe what happens to air temperature when work is done on the air to compress it.
2. What does *stability* mean in terms of air movement?
3. List four mechanisms that cause air to rise.
4. Describe conditions that cause condensation of liquid water in air.
5. What is a temperature inversion?
6. Which types of condensation nuclei are especially good for condensation to form?

Think Criticallly

7. **Form a Hypothesis** Study a world map. Hypothesize about other regions on Earth, other than the Florida peninsula, where convergence might cause cloud development and precipitation.

CONNECTING CONCEPTS

8. **Explain** Review the atmospheric temperature changes that occur due to altitude. Then write a paragraph explaining how these differ from adiabatic temperature changes in parcels of air.

BIGIDEA WEATHER AND CLIMATE

9. **Relate Cause and Effect** Describe how the process of frontal wedging is involved in cloud formation.

18.3 Cloud Types and Precipitation

ES.12 The student will investigate and understand that energy transfer between the sun and Earth and its atmosphere drives weather and climate on Earth. Key concepts include **b.** prediction of weather patterns.

CLOUDS ARE AMONG the most striking and noticeable effects of the atmosphere and its weather. Clouds are a result of condensation best described as visible mixtures of tiny droplets of liquid water or tiny crystals of ice. Clouds are of interest to meteorologists because clouds show what is going on in the atmosphere. If you try to recognize different types of clouds, you might fi d it hard to do. But, if you learn the basic classification scheme for clouds, recognizing cloud types will be easy.

Types of Clouds

Cloud Forms

Clouds are classified on the basis of their form and height. The three basic forms are: cirrus, cumulus, and stratus. All other clouds reflect one of these three basic forms or are combinations or modifications of them.

▶ ***Cirrus Clouds*** **Cirrus** (*cirrus* = a curl of hair) clouds are white, thin, and found high in the atmosphere. They can occur as patches or as delicate veil-like sheets or extended wispy fibers that often have a feathery appearance. An example of cirrus clouds is shown in **Figure 11.**

▶ ***Cumulus Clouds*** **Cumulus** (*cumulus* = a pile) clouds consist of rounded individual cloud masses. The clouds in Figure 10 in the previous lesson are cumulus clouds. Normally, they have a flat base and the appearance of rising domes or towers. These clouds are frequently described as having a structure resembling a cotton ball.

FIGURE 11 Cirrus Clouds These thin, white clouds that are high in the atmosphere are cirrus clouds.

Key Questions

How are clouds classified?

How are clouds and fogs similar and different?

What must happen in order for precipitation to form?

What controls the type of precipitation that reaches Earth's surface?

Vocabulary

- cirrus • cumulus • stratus
- Bergeron process
- supercooled water
- supersaturated air
- collision-coalescence process

Reading Strategy

Build Vocabulary Copy the table. As you read, add definitions.

Vocabulary Term	Definition
Cirrus	a. ___?___
Cumulus	b. ___?___
Stratus	c. ___?___
Coalescence	d. ___?___

▶ ***Stratus Clouds*** **Stratus** (*stratum* = a layer) clouds are best described as sheets or layers that cover much or all of the sky. While there may be minor breaks, there are no distinct individual cloud units.

Levels of Cloud Heights There are three levels of cloud heights: high, middle, and low, as shown in **Figure 12.** High clouds normally have bases above 6000 meters. Middle clouds generally occupy heights from 2000 to 6000 meters. Low clouds form below 2000 meters. The altitudes listed for each height category are not hard and fast. There is some seasonal and latitudinal variation. For example, at high latitudes or during cold winter months in the mid-latitudes, high clouds often are found at lower altitudes.

▶ ***High Clouds*** Three cloud types make up the family of high clouds: cirrus, cirrostratus, and cirrocumulus. As shown in **Figure 12,** cirrocumulus clouds consist of fluffy masses, while cirrostratus clouds are flat layers. All high clouds are thin and white and are often made up of ice crystals. This is because of the low temperatures and small quantities of water vapor present at high altitudes. These clouds are not considered precipitation makers. However, when cirrus clouds are followed by cirrocumulus or cirrostratus clouds and increased sky coverage, they may warn of approaching stormy weather.

▶ ***Middle Clouds*** Clouds found in the middle range, from about 2000 to 6000 meters, have the prefix *alto-* as part of their name.

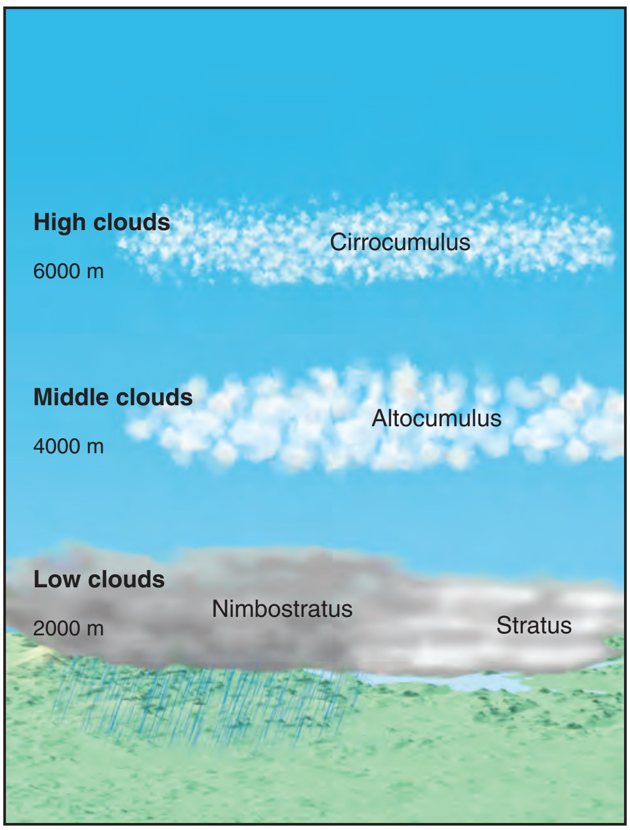


FIGURE 12 Cloud Classification Clouds are classified according to form and height.
Interpret Visuals ***Which cloud types are the chief precipitation makers?***

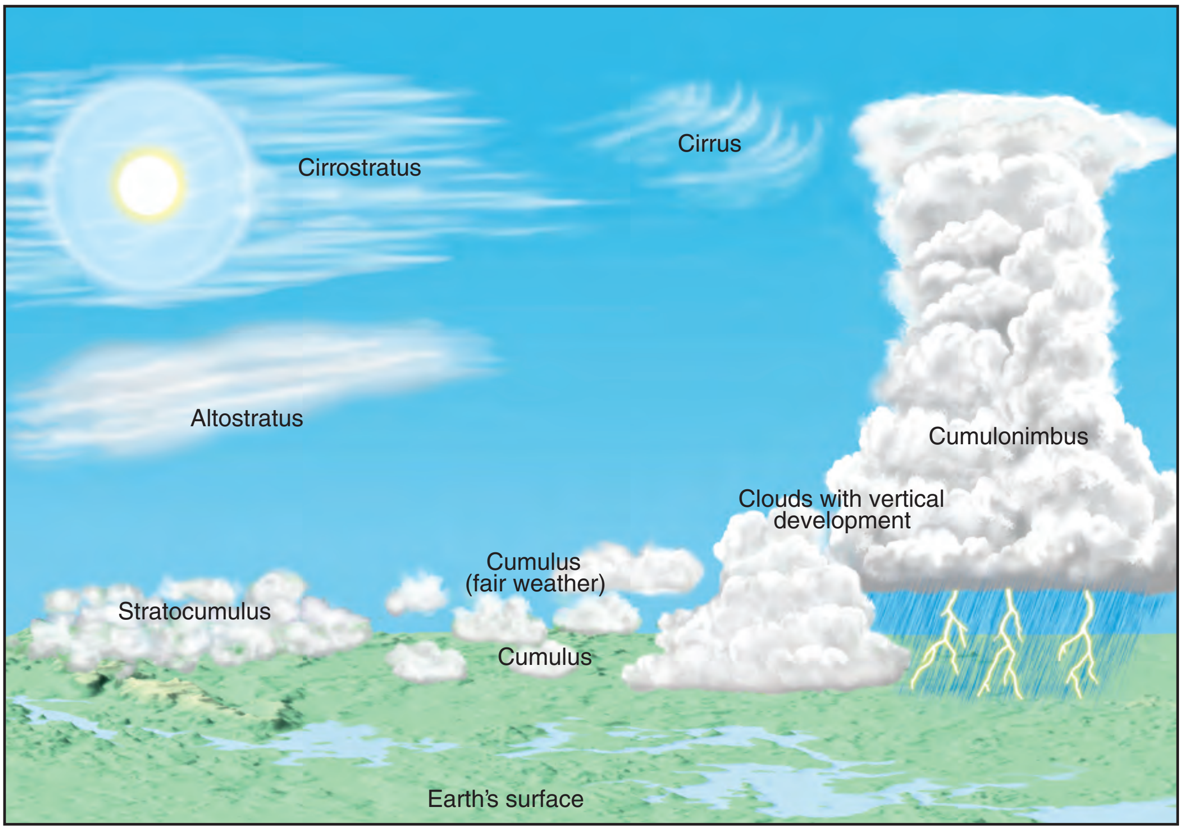
Altocumulus clouds are composed of rounded masses that differ from cirrocumulus clouds in that altocumulus clouds are larger and denser, as shown in **Figure 12.**

Altostratus clouds create a uniform white to grayish sheet covering the sky with the sun or moon visible as a bright spot. Infrequent light snow or drizzle may accompany these clouds.

▶ ***Low Clouds*** There are three members in the family of low clouds: stratus, stratocumulus, and nimbostratus. As illustrated in **Figure 12,** stratus clouds are a uniform, foglike layer of clouds that frequently covers much of the sky. Occasionally, these clouds may produce light precipitation. When stratus clouds develop a scalloped bottom that appears as long parallel rolls or broken rounded patches, they are called stratocumulus clouds.

Nimbostratus clouds derive their name from the Latin word *nimbus,* which means "rainy cloud," and *stratus,* which means "to cover with a layer." As the name suggests, nimbostratus clouds are one of the main precipitation makers. Nimbostratus clouds form during stable conditions. You might not expect clouds to develop in stable air. But cloud growth of this type is common when air is forced upward, as occurs along a mountain range, a front, or where converging winds cause air to rise. Such a forced upward movement of stable air can result in a cloud layer that is largely horizontal compared to its depth.

Reading Checkpoint *What does the Latin word* stratus *mean?*



Clouds of Vertical Development Some clouds do not fit into any of the three height categories mentioned. Such clouds have their bases in the low height range but often extend upward into the middle or high altitudes. They all are related to one another and are associated with unstable air. Although cumulus clouds are often connected with fair weather, they may grow dramatically under the proper circumstances. Once upward movement is triggered, acceleration is powerful, and clouds with great vertical range form. The end result often is a cumulonimbus cloud that may produce rain showers or a thunderstorm.

Fog

Physically, there is no difference between a fog and a cloud. Their appearance and structure are the same. The difference is the method and place of formation. Clouds result when air rises and cools adiabatically. Most fogs are the result of radiational cooling or the movement of air over a cold surface. Fogs also can form when enough water vapor is added to the air to bring about saturation. **Fog is defi ed as a cloud with its base at or very near the ground.** When fog is dense, visibility may be only a few dozen meters or less, making travel not only difficult but often dangerous.

FIGURE 13 Fog When water vapor rising from the warm lake water meets cold air, the water vapor condenses to form fog.

Fogs Caused by Cooling A blanket of fog is produced in some West Coast locations when warm, moist air from the Pacific Ocean moves over the cold California Current and then is carried onshore by prevailing winds. Fogs also can form on cool, clear, calm nights when Earth's surface cools rapidly by radiation. As the night progresses, a thin layer of air in contact with the ground is cooled below its dew point. As the air cools, it becomes denser and drains into low areas such as river valleys, where thick fog accumulations may occur.

Fogs Caused by Evaporation When cool air moves over warm water, enough moisture may evaporate from the water surface to produce saturation. As the rising water vapor meets the cold air, it immediately condenses and rises with the air that is being warmed from below. This type of fog over water has a steaming appearance, as shown in **Figure 13.** It is fairly common over lakes and rivers in the fall and early winter, when the water may still be relatively warm and the air is rather crisp.

How Precipitation Forms

Cloud droplets are very tiny, averaging less than 20 micrometers in diameter. Because of their small size, the rate at which cloud droplets fall is incredibly slow. Most cloud droplets would evaporate before falling a few meters into unsaturated air below. **For precipitation to form, cloud droplets must grow in volume by roughly one million times.**

Cold Cloud Precipitation The process that generates much of the precipitation in the middle latitudes occurs in cold clouds and is called the **Bergeron process.** The Bergeron process, shown in **Figure 14,** relies on two physical processes: supercooling and supersaturation. Cloud droplets do not freeze at 0°C as expected. In fact, pure water suspended in air does not freeze until it reaches a temperature of nearly −40°C. Water in the liquid state below 0°C is said to be **supercooled water.** Supercooled water will readily freeze if it touches a solid object. Freezing nuclei are materials that have a crystal form that closely matches that of ice. Freezing nuclei can cause supercooled water to freeze.

When air is saturated (100 percent relative humidity) with respect to water, it is **supersaturated air** (greater than 100 percent humidity) with respect to ice. Ice crystals cannot coexist with water droplets in the air because the air "appears" supersaturated to the ice crystals. Any excess water vapor becomes ice that lowers the relative humidity near the surrounding droplets. Water droplets then evaporate to provide a continual source of water vapor for the growth of ice crystals.

Because the level of supersaturation with respect to ice can be quite high, the growth of ice crystals is rapid enough to produce crystals that are large enough to fall. As they fall, the ice crystals contact cloud drops causing them to freeze. A chain reaction can occur and large crystals, called *snowflakes,* form. When the surface temperature is above 4°C, snowflakes usually melt before they reach the ground.

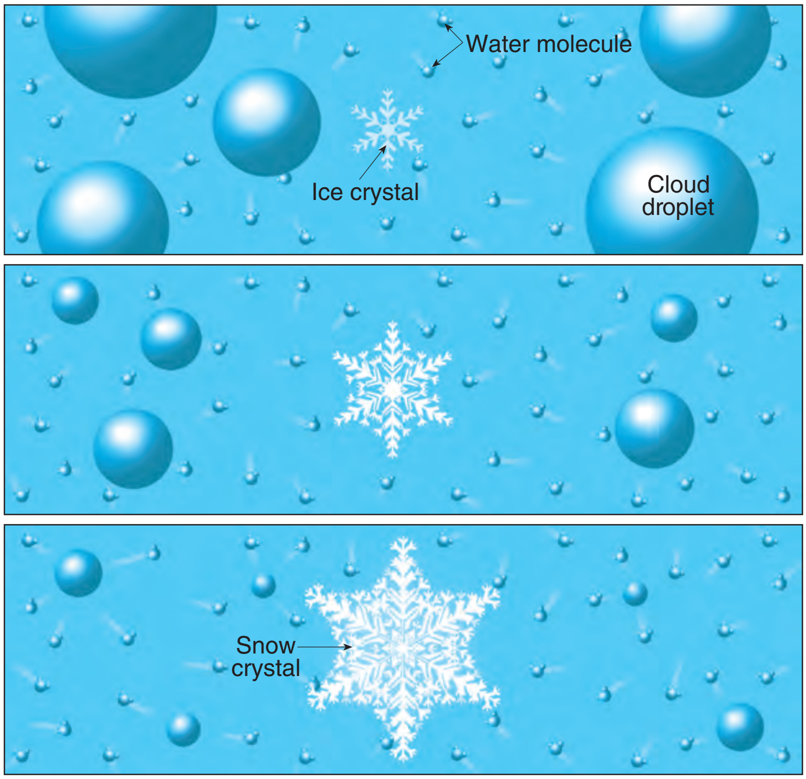


FIGURE 14 The Bergeron Process
Ice crystals grow at the expense of cloud droplets until they are large enough to fall. The size of these particles has been greatly exaggerated.

Warm Cloud Precipitation Much rainfall can be associated with clouds located well below the freezing level, especially in the tropics. In warm clouds, the mechanism that forms raindrops is the **collision-coalescence process.** Some water-absorbing particles, such as salt, can remove water vapor from the air at relative humidities less than 100 percent, forming drops that are quite large. As these large droplets move through the cloud, they collide and coalesce (join together) with smaller, slower droplets.

Forms of Precipitation

The type of precipitation that reaches Earth's surface depends on the temperature profi e in the lowest few kilometers of the atmosphere. A *temperature profile* is the way the air temperature changes with altitude. Even on a hot summer day, a heavy downpour may have begun as a snowstorm high in the clouds overhead.

Rain and Snow In meteorology, the term *rain* means drops of water that fall from a cloud and have a diameter of at least 0.5 mm. Smaller drops are called *drizzle.* Recall that when the surface temperature is above 4°C, snowflakes usually melt and continue their descent as rain before they reach the ground. At very low temperatures (when the moisture content of air is low) light, fluffy snow made up of individual six-sided ice crystals forms. At temperatures warmer than −5°C, ice crystals join into larger clumps.

FIGURE 15 Hail This largest recorded hailstone fell over Kansas in 1970 and weighed 766 grams.

Sleet, Glaze, and Hail *Sleet* is the fall of small particles of clear-to-translucent ice. For sleet to form, a layer of air with temperatures above freezing must overlie a subfreezing layer near the ground. *Glaze,* also known as freezing rain, results when raindrops become supercooled (below 0°C) as they fall through subfreezing air near the ground and turn to ice when they impact objects.

Hail is produced in cumulonimbus clouds. Hailstones begin as small ice pellets that grow by collecting supercooled water droplets as they fall through a cloud. If the ice pellets encounter a strong updraft, they may be carried upward and begin the downward journey once more. Each trip through the supercooled portion of the cloud may be represented by another layer of ice. One hailstone, shown in **Figure 15,** actually grew to weigh 766 grams.

18.3 Assessment

Review Key Concepts

1. How are clouds classified?

2. Compare and contrast clouds and fogs.

3. What must happen in order for precipitation to form?

4. Describe how the temperature profile of air near Earth's surface controls the type of precipitation that falls to the ground.

Think Critically

5. Predict What type of precipitation would fall to Earth's surface if a thick layer of air near the ground was −8°C?

6. Classify Identify the following cloud types as producers of heavy, light, or generally no precipitation.
- **a.** cirrocumulus
- **b.** cumulonimbus
- **c.** stratus
- **d.** nimbostratus

BIGIDEA WEATHER AND CLIMATE

7. Compare and Contrast Write a paragraph comparing the Bergeron and collision-coalescence processes. Relate each to the type(s) of precipitation that can result.

Atmospheric Stability and Air Pollution

Local air quality is closely linked to the atmosphere's ability to scatter pollutants. If the air into which pollution is released is not dispersed, the air will become more toxic. Two of the most important atmospheric conditions affecting the distribution of pollutants are wind speed and atmospheric stability.

High wind speeds mix polluted air into a larger volume of surrounding air, causing the pollution to be more diluted. When winds are slower, there is less turbulence and mixing, so the concentration of pollutants is higher.

Atmospheric stability is a measure of air's ability to flow vertically. When the atmosphere is unstable, air can flow vertically, dispersing pollutants away from their source on Earth's surface. During a temperature inversion, the atmosphere is very stable and it does not move much vertically. Warm air overlying cooler air acts as a lid and prevents upward air flow, which traps pollutants below, as shown in **Figure 16.**

While all temperature inversions form close to Earth's surface, some form closer than others. A surface inversion develops close to the ground on clear and relatively calm nights because the ground is a better radiator of heat than the air above it. Radiation from the ground to the clear night sky causes more rapid cooling at the surface than higher in the atmosphere. The result is that the air close to the ground is cooled more than the air above, yielding a temperature profile similar to the one shown in **Figure 17.** After sunrise, the ground is heated and the inversion disappears.

Although surface inversions usually are shallow, they may be thick in regions where the land surface is uneven. Because cold air is denser than warm air, the chilled air near the surface gradually drains from slopes into adjacent lowlands and valleys. As might be expected, these thicker surface inversions will not spread out as quickly after sunrise.

FIGURE 16
Air Pollution in Downtown Los Angeles Temperature inversions act as lids to trap pollutants below.

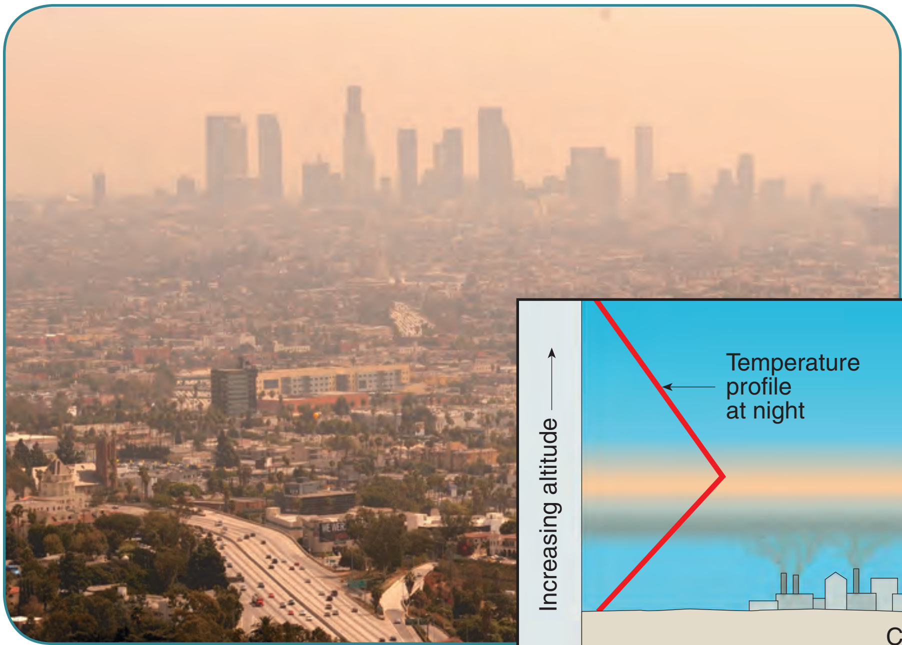
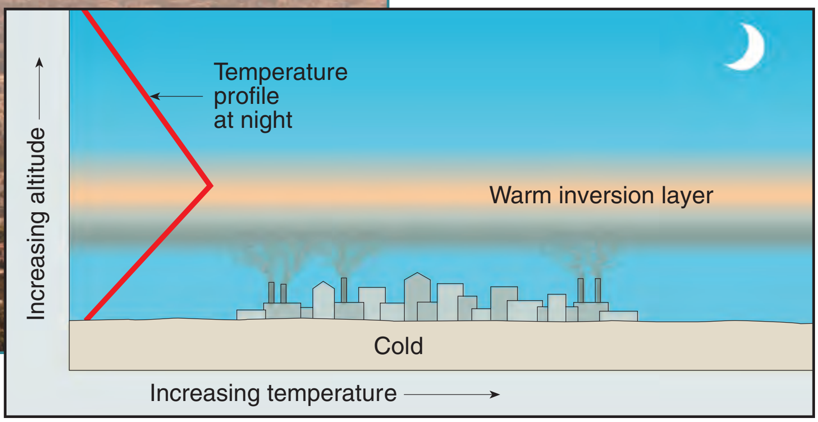


FIGURE 17
General Temperature Profile for a Surface Inversion Cool air and pollutants are trapped below the layer of warm air.



INQUIRY
EXPLORATION LAB

Measuring Humidity

Problem How can relative humidity be determined?

Materials calculator, water at room temperature, psychrometer
Alternative materials for psychrometer: 2 thermometers, cotton gauze, paper fan, string

Skills Observe, Measure, Analyze Data, Calculate

Connect to the Big idea Relative humidity is a measurement used to describe water vapor in the air. In general, it expresses how close the air is to saturation. In this lab, you will use a psychrometer and a data table to determine the relative humidity of air.

Procedure

Part A: Calculating Relative Humidity From Water Vapor Content

1. On a sheet of paper, make a copy of **Data Table 1.**
2. Relative humidity is the ratio of the air's water vapor content to its water vapor capacity at a given temperature. Relative humidity is expressed as a percent.

   Relative humidity (%) =

   $$\frac{\text{Water vapor content}}{\text{Water vapor capacity}} \times 100$$
3. At 25°C, the water vapor capacity is 20 grams of water per kilogram of air. Use this information to complete **Data Table 1.**

Part B: Determining Relative Humidity Using a Psychrometer

4. A psychrometer consists of two thermometers. The wet-bulb thermometer has a cloth wick that is wet with water and spun for about 1 minute. Relative humidity is determined from the difference in temperature reading between the dry-bulb temperature and the wet-bulb temperature, by using **Data Table 2.** For example, suppose a dry-bulb temperature is measured as 20°C, and a wet-bulb temperature is 14°C. Read the relative humidity from **Data Table 2.**
5. If a psychrometer is not available, construct a wet-bulb thermometer by tying a piece of cotton gauze around the end of a thermometer. Wet it with room-temperature water, and fan it until the temperature stops changing.
6. Make wet-bulb and dry-bulb temperature measurements for air in your classroom and air outside the school building. On a separate sheet of paper, make a copy of **Data Table 3.** Record your measurements. Use your measurements and **Data Table 2** to determine the relative humidity inside and outside.

Analyze and Conclude

1. **Compare and Contrast** How do the relative humidity measurements for inside and outside compare? Why are your determinations similar or different?
2. **Apply Concepts** Explain the principle behind using a psychrometer to determine relative humidity.
3. **Apply Concepts** Suppose you hear on the radio that the relative humidity is 90 percent on a winter day. Can you conclude that this air contains more moisture than air on a summer day with a 40 percent relative humidity? Explain why or why not.
4. **Apply Concepts** Why is a cool basement often damp in the summer?

Data Table 1 Relative Humidity Determination Based on Water Vapor Content

Air Temperature (C)	Water Vapor Content (g/kg)	Water Vapor Capacity (g/kg)	Relative Humidity (%)
25	5	20	25
25	12		
25	18		

Data Table 2 Relative Humidity (percent)

Dry-bulb Temperature (°C)	*Depression of Wet-bulb Temperature* (Dry-bulb Temperature − Wet-bulb Temperature = Depression of the Wet Bulb)																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
−20	28																					
−18	40																					
−16	48	0																				
−14	55	11																				
−12	61	23																				
−10	66	33	0																			
−8	71	41	13																			
−6	73	48	20	0																		
−4	77	54	43	11																		
−2	79	58	37	20	1																	
0	81	63	45	28	11																	
2	83	67	51	36	20	6																
4	85	70	56	42	27	14																
6	86	72	59	46	35	22	10	0														
8	87	74	62	51	39	28	17	6														
10	88	76	65	54	43	33	24	13	4													
12	88	78	67	57	48	38	28	19	10	2												
14	89	79	69	60	50	41	33	25	16	8	1											
16	90	80	71	62	54	45	37	29	21	14	7	1										
18	91	81	72	64	56	48	40	33	26	19	12	6	0									
20	91	82	74	66	58	51	44	36	30	23	17	11	5	0								
22	92	83	75	68	60	53	46	40	33	27	21	15	10	4	0							
24	92	84	76	69	62	55	49	42	36	30	25	20	14	9	4	0						
26	92	85	77	70	64	57	51	45	39	34	28	23	18	13	9	5						
28	93	86	78	71	65	59	53	47	42	36	31	26	21	17	12	8	2					
30	93	86	79	72	66	61	55	49	44	39	34	29	25	20	16	12	8	4				
32	93	86	80	73	68	62	56	51	46	41	36	32	27	22	19	14	11	8	4			
34	93	86	81	74	69	63	58	52	48	43	38	34	30	26	22	18	14	11	8	5		
36	94	87	81	75	69	64	59	54	50	44	40	36	32	28	24	21	17	13	10	7	4	
38	94	87	82	76	70	66	60	55	51	46	42	38	34	30	26	23	20	16	13	10	7	5
40	94	89	82	76	71	67	61	57	52	48	44	40	36	33	29	25	22	19	16	13	10	7

Relative Humidity Values

Data Table 3 Relative Humidity Determinations Using Dry- and Wet-Bulb Thermometers

	Inside	Outside
Dry-bulb temperature (°C)		
Wet-bulb temperature (°C)		
Difference between dry-bulb and wet-bulb temperatures (°C)		
Relative humidity (%)		

ES.1 The student will plan and conduct investigations in which **a.** volume, area, mass, elapsed time, direction, temperature, pressure, distance, density, and changes in elevation/depth are calculated utilizing the most appropriate tools; and **c.** scales, diagrams, charts, graphs, tables, imagery, models, and profiles are constructed and interpreted. **ES.12** The student will investigate and understand that energy transfer between the sun and Earth and its atmosphere drives weather and climate on Earth. Key concepts include **a.** observation and collection of weather data.

18 Study Guide

Big idea Weather and Climate

18.1 Water in the Atmosphere

Water vapor is the most important gas in the atmosphere for understanding atmospheric processes.

The process of changing state requires that energy is transferred in the form of heat.

When saturated, warm air contains more water vapor than saturated cold air.

Relative humidity is a ratio of the air's actual water-vapor content compared with the amount of water vapor needed for saturation at that temperature and pressure.

When the water-vapor content of air remains constant, lowering air temperature causes an increase in relative humidity, and raising air temperature causes a decrease in relative humidity.

precipitation (504)
latent heat (505)
evaporation (505)
condensation (506)
sublimation (506)
deposition (506)
humidity (506)
saturated (506)
relative humidity (506)
dew point (508)
hygrometer (508)

18.2 Cloud Formation

When air is allowed to expand, it cools, and when it is compressed, it warms.

Four mechanisms that can cause air to rise are orographic lifting, frontal wedging, convergence, and localized convective lifting.

Stable air tends to remain in its original position, while unstable air tends to rise.

For condensation of water to occur, the air must be saturated.

dry adiabatic rate (511)
wet adiabatic rate (511)
orographic lifting (512)
front (512)
temperature inversion (514)
condensation nuclei (516)

18.3 Cloud Types and Precipitation

Clouds are classified on the basis of their form and height.

Fog is a cloud with its base at or very near the ground.

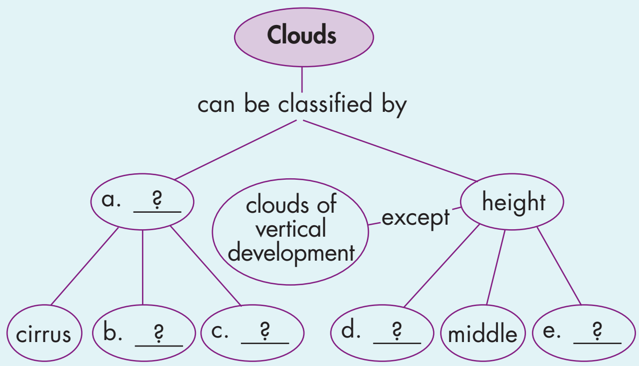
In order for precipitation to form, cloud droplets must grow in volume by roughly one million times.

The type of precipitation that reaches Earth's surface depends on the temperature profile in the lowest few kilometers of the atmosphere.

cirrus (517)
cumulus (517)
stratus (518)
Bergeron process (521)
supercooled water (521)
supersaturated air (521)
collision-coalescence process (521)

Think Visually

Copy the concept map below onto a sheet of paper. Use information from the chapter to complete the concept map.



18 Assessment

Review Content

Choose the letter that best answers the question or completes the statement.

1. What is the general term for water vapor in air?
   a. capacity
   b. condensation
   c. humidity
   d. saturation

2. During which process does water vapor change to the liquid state?
   a. condensation
   b. deposition
   c. melting
   d. sublimation

3. The ratio of air's actual water-vapor content to the amount of water needed for saturation is the
   a. adiabatic rate.
   b. dew point.
   c. relative humidity.
   d. water capacity.

4. What are visible mixtures of tiny water droplets or ice crystals suspended in air?
   a. clouds
   b. dew
   c. hail
   d. sleet

5. Air that has a 100 percent relative humidity is said to be
   a. dry.
   b. saturated.
   c. stable.
   d. unstable.

6. Compared to clouds, fogs are
   a. a different composition.
   b. at lower altitudes.
   c. colder.
   d. thicker.

7. Which of the following clouds are high, white, and thin?
   a. cirrus
   b. cumulus
   c. nimbostratus
   d. stratus

8. Which of the following words means "rainy cloud"?
   a. cirrus
   b. cumulus
   c. nimbus
   d. stratus

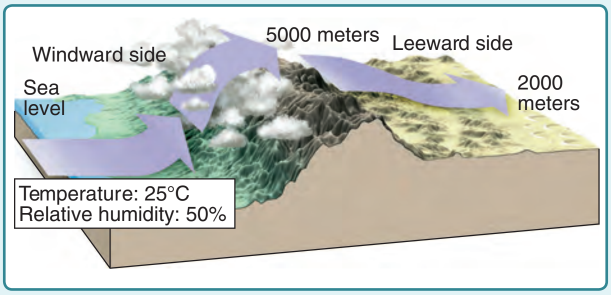
9. Which of the following substances changes from one state of matter to another at temperatures and pressures experienced at Earth's surface?
   a. carbon dioxide
   b. nitrogen
   c. oxygen
   d. water

10. Which of the following forms when supercooled raindrops freeze on contact with solid objects near Earth's surface?
   a. freezing rain
   b. hail
   c. sleet
   d. snow

Understand Concepts

11. What happens when unstable air is forced to rise?
12. Describe the conditions that might cause convergence.
13. As you drink an ice-cold beverage on a hot day, the outside of the glass becomes wet. Explain why this happens.
14. What is the difference between condensation and precipitation?
15. Why does air cool when it rises through the atmosphere? What is this type of cooling known as?
16. Write a general statement relating air temperature and the amount of water vapor needed to saturate the air.
17. Describe the difference between clouds and water vapor.
18. List two changes of state for water that cause latent heat to be released.

Use the figure below to answer Questions 19 and 20.



19. Which air-lifting mechanism is shown?
20. Use the dry adiabatic rate of 10°C per kilometer to determine the air temperature on the windward side of the mountains at an altitude of 500 meters.

Think Critically

21. **Apply Concepts** What is the physical property of thermals that helps birds of prey? Describe how this physical property helps these birds.

22. **Apply Concepts** Explain how urban areas contribute to localized convective lifting.

23. **Identify Cause and Effect** Describe how atmospheric stability affects daily weather. Include specific examples.

24. **Apply Concepts** In general, when traveling in foggy conditions, what types of topography should you be most cautious of?

Math Skills

Use the table below to answer Questions 25–27.

Water Vapor Needed for Saturation

Temperature		Mass of water vapor per kg of air (g/kg)
°C	°F	
−40	(−40)	0.1
−30	(−22)	0.3
−20	(−4)	0.75
−10	(14)	2
0	(32)	3.5
5	(41)	5
10	(50)	7
15	(59)	10
20	(68)	14
25	(77)	20
30	(86)	26.5
35	(95)	35
40	(104)	47

25. **Analyze Data** According to the table, how much water vapor is required to saturate a kilogram of air at each of the following temperatures?

a. 40°C
b. 0°C
c. −10°C

26. **Calculate** How does the amount of water vapor required to saturate 1 kilogram of air change when it is cooled from 10°C to 0°C?

27. **Calculate** Use the table to determine the relative humidity of air at 15°C when its water vapor content is 7 g/kg.

Concepts in Action

28. **Infer** Mount Waialeale, Hawaii, is located on a windward mountain slope. A weather station there records the highest average annual rainfall at 1234 cm. Explain what processes could contribute to this extreme rainfall.

29. **Interpret Visuals** After studying Figure 2, summarize the processes by which water changes from one state of matter to another. For each case, point out whether heat energy is absorbed or released.

30. **Writing in Science** The amount of precipitation that falls at any particular place and time is controlled by the quantity of moisture in the air and many other factors, which may include (1) an increase in the elevation of the land, (2) a decrease in the area covered by forests and other types of vegetation, and (3) an increase in the percentage of time that the winds blow from an adjacent body of water. Write a paragraph explaining how each of these factors might change the precipitation at a particular location.

Performance-Based Assessment

Design an Experiment Design and conduct an experiment that explores daily variations in temperature and relative humidity. As a first step, write a clear hypothesis statement. Then plan and design the experiment. Include sample data tables in your plan. Have your teacher approve your plan before you begin.

Virginia SOL Test Prep

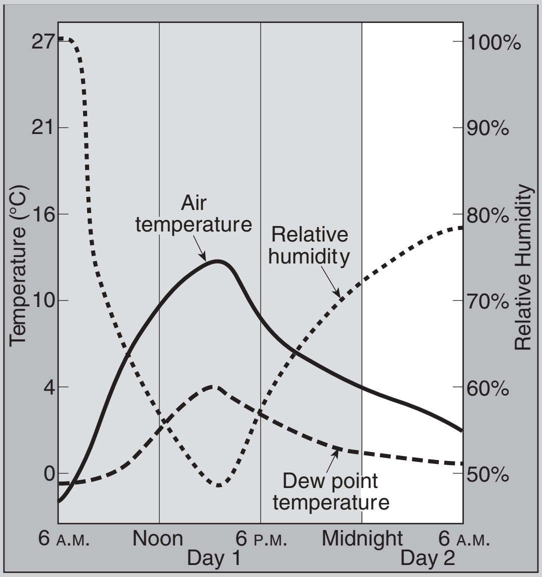
Tips for Success

When answering a question with a graph, keep these tips in mind:

- Study the graph's labels, title, and scale. This may help you identify what information is available from the graph.
- Recall equations, definitions, and relationships that may help you interpret the graph.

Check your answer against the graph.

Graph 1 Temperature and Relative Humidity



The graph above depicts variations in temperature and relative humidity on a spring day. Which of the following statements is true?

A When temperature increases, relative humidity increases.
B When temperature decreases, relative humidity decreases.
C When temperature increases, relative humidity decreases.
D Temperature and relative humidity are not related.

(Answer: C)

Choose the letter that best answers the question.

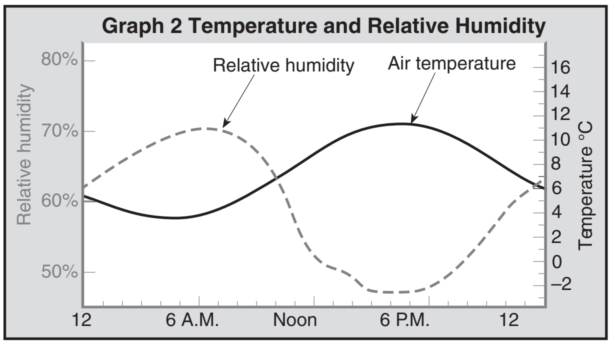
1 The dew point is the temperature at which—
A cumulus clouds change to cirrus clouds
B hailstones are formed
C liquid water changes to vapor
D air becomes saturated with water vapor
ES.12.a

2 Which process is most important for cloud formation?
F cooling by compression of air
G cooling by contact with a cold surface
H cooling by expansion of air
J cooling by radiation from Earth's surface
ES.11.c

3 The process by which water vapor changes directly to a solid is—
A condensation
B deposition
C evaporation
D sublimation
ES.11.c

Use the graph below to answer Question 4.

Graph 2 Temperature and Relative Humidity



4 According to this graph, when is relative humidity at its maximum?
F midnight
G 6 A.M.
H noon
J 6 P.M.
ES.12.a

If You Have Trouble With . . .

Question	1	2	3	4
See Lesson	18.1	18.2	18.1	18.2