17 Moisture, Clouds, and Precipitation

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

17.1 List and describe the processes that cause water to change from one state of matter to another. Define *latent heat* and explain why it is important.

17.2 Distinguish between relative humidity and dew point. Write a generalization relating how temperature changes affect relative humidity.

17.3 Explain how adiabatic cooling results in cloud formation.

17.4 List and describe the four mechanisms that cause air to rise.

17.5 Describe how atmospheric stability is determined and compare conditional instability with absolute instability.

17.6 List the necessary conditions for condensation and briefly describe the two criteria used for cloud classification.

17.7 Define *fog* and explain how the various types of fog form.

17.8 Describe the two mechanisms that produce precipitation.

17.9 List the different types of precipitation and explain how each type forms.

17.10 Explain how precipitation is measured.

Cumulonimbus clouds are often associated with thunderstorms and severe weather. (Photo by Cusp/SuperStock)

Water vapor is an odorless, colorless gas that mixes freely with the other gases of the atmosphere. Unlike oxygen and nitrogen—the two most abundant components of the atmosphere—water can change from one state of matter to another (solid, liquid, or gas) at the temperatures and pressures experienced on Earth. Because of this unique property, water freely leaves the oceans as a gas and returns again as a liquid or solid.

As you observe day-to-day weather changes, you might ask: Why is it generally more humid in the summer than in the winter? Why do clouds form on some occasions but not on others? Why do some clouds look thin and harmless, whereas others form gray and ominous towers? Answers to these questions involve the role of water vapor in the atmosphere, the central theme of this chapter.

17.1 WATER'S CHANGES OF STATE

List and describe the processes that cause water to change from one state of matter to another. Define *latent heat* and explain why it is important.

Water is the only substance that exists in the atmosphere as a solid, liquid, and gas (**FIGURE 17.1**). It is made of hydrogen and oxygen atoms that are bonded together to form water molecules (H_2O). In all three states of matter (even ice), these molecules are in constant motion; the higher the temperature, the more vigorous the movement. The chief difference among liquid water, ice, and water vapor is the arrangement of the water molecules.

Ice, Liquid Water, and Water Vapor

Ice is composed of water molecules that are held together by mutual molecular attractions. The molecules form a tight, orderly network, as shown in **FIGURE 17.2**. As a consequence, the water molecules in ice are not free to move relative to each other but rather vibrate about fixed sites. When ice is heated, the molecules oscillate more rapidly. When the rate of molecular movement increases sufficiently, the bonds between some of the water molecules are broken, resulting in melting.

URE 17.1 Caught in a **vnpour** (Photo by AP Photo/ tone, Marcel Bier)

In the liquid state, water molecules are still tightly packed but are moving fast enough that they are able to slide past one another. As a result, liquid water is fluid and will take the shape of its container.

As liquid water gains heat from its environment, some of the molecules will acquire enough energy to break the remaining molecular attractions and escape from the surface, becoming water vapor. Water-vapor molecules are widely spaced compared to liquid water and exhibit very energetic random motion. What distinguishes a gas from a liquid is its compressibility (and expandability). For example, you can easily put more and more air into a tire and increase its volume only slightly. However, you can't put 10 gallons of gasoline into a 5-gallon can.

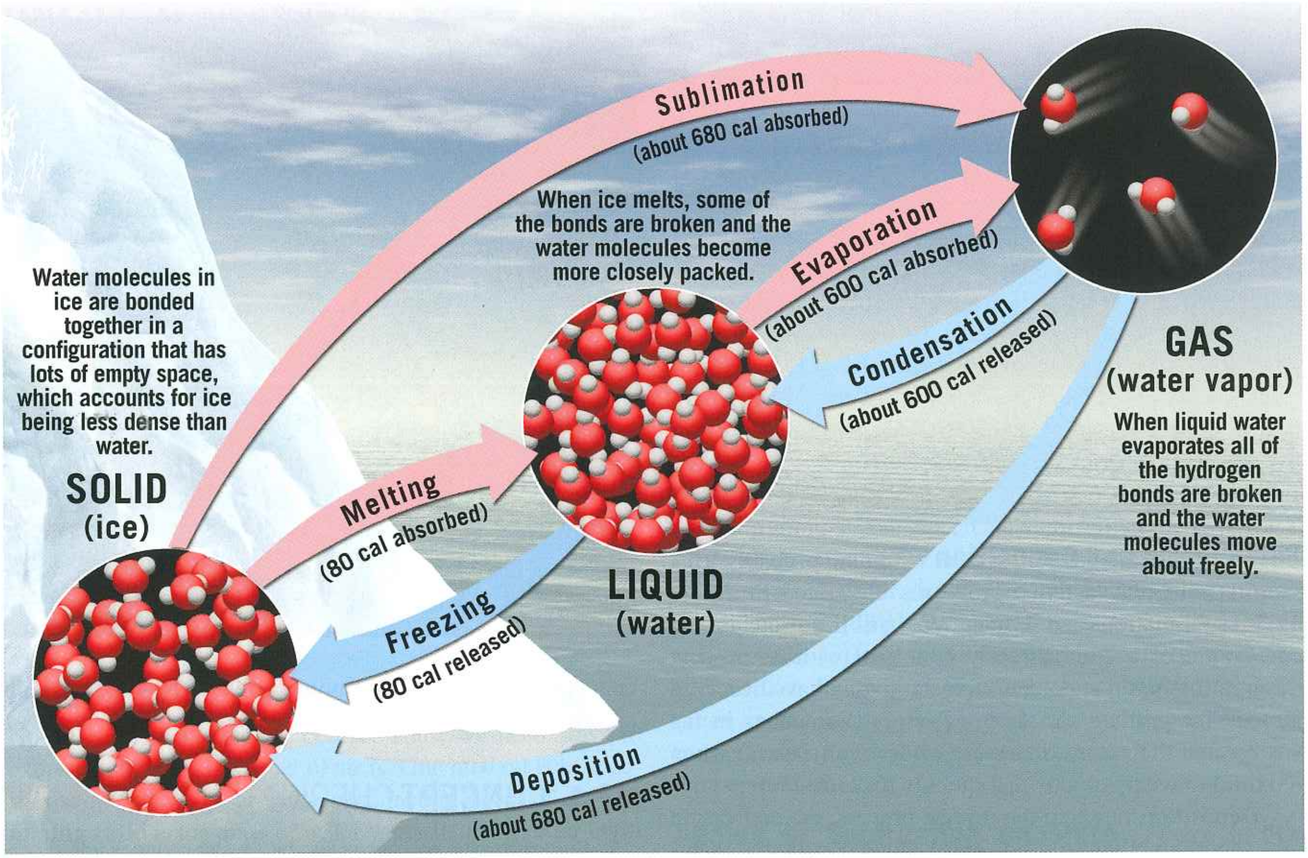
To summarize, when water changes state, it does not turn into a different substance; only the distances and interactions among the water molecules change.

Latent Heat

Whenever water changes state, heat is exchanged between water and its surroundings. When water evaporates, heat is absorbed (see Figure 17.2). Meteorologists often measure heat energy in calories. One **calorie** is the amount of heat required to raise the temperature of 1 gram of water 1°C (1.8°F). Thus, when 10 calories of heat are absorbed by 1 gram of water, the molecules vibrate faster, and a 10°C (18°F) temperature rise occurs.

Under certain conditions, heat may be added to a substance without an accompanying rise in temperature. For example, when a glass of ice water is warmed, the temperature of the ice–water mixture remains a constant 0°C (32°F) until all the ice has melted. If adding heat does not raise the temperature, where does this energy go? In this case, the added energy goes into breaking the molecular attractions between the water molecules in the ice cubes.

Because the heat used to melt ice does not produce a temperature change, it is referred to as **latent heat**. (*Latent* means "hidden," like the latent fingerprints hidden at a crime



SmartFigure 17.2 Changes of State Involve an Exchange of Heat The numbers represent the approximate number of calories either absorbed or released when 1 gram of water changes from one state of matter to another.

scene.) This energy can be thought of as being stored in liquid water, and it is not released to its surroundings as heat until the liquid returns to the solid state.

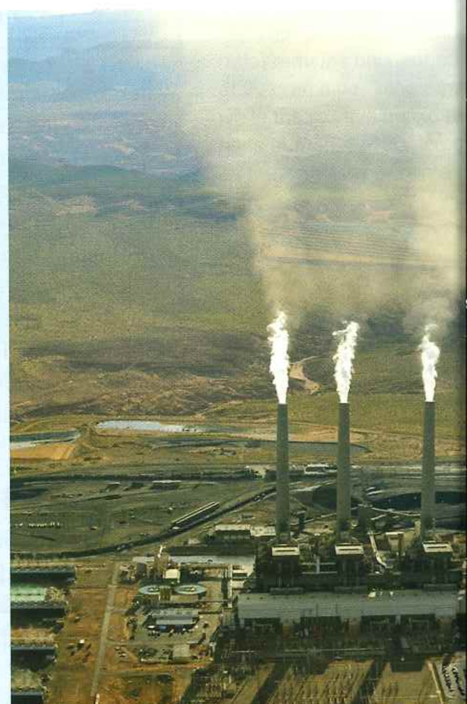
Melting 1 gram of ice requires 80 calories, an amount referred to as *latent heat of melting*. *Freezing*, the reverse process, releases these 80 calories per gram to the environment as *latent heat of fusion*.

Evaporation and Condensation We saw that heat is absorbed when ice is converted to liquid water. Heat is also absorbed during **evaporation**, the process of converting a liquid to a gas (vapor). The energy absorbed by water molecules during evaporation is used to give them the motion needed to escape the surface of the liquid and become a gas. This energy is referred to as the *latent heat of vaporization*. During the process of evaporation, it is the higher-temperature (faster-moving) molecules that escape the surface. As a result, the average molecular motion (temperature) of the remaining water is reduced—hence the common expression "evaporation is a cooling process." You have undoubtedly experienced this cooling effect when stepping dripping wet from a swimming pool or bathtub. In this situation, the energy used to evaporate water comes from your skin—hence, you feel cool.

The reverse process, **condensation**, occurs when water vapor changes to the liquid state. During condensation, water-vapor molecules release energy (*latent heat of condensation*) in an amount equivalent to what was absorbed during evaporation. When condensation occurs in the atmosphere, it results in the formation of such phenomena as fog and clouds.

As you will see, latent heat plays an important role in many atmospheric processes. In particular, when water vapor condenses to form cloud droplets, latent heat of condensation is released, warming the surrounding air and giving it buoyancy. When the moisture content of air is high, this process can spur the growth of towering storm clouds.

EYE ON EARTH



The Navajo Generating Station, located on the Navajo Indian Reservation near Page, Arizona, has three 236-meter (560-feet) stacks. (Photo by Michael Collier)

QUESTION 1 *What fuel is this plant burning to generate electricity? (Hint: Look directly behind the facility.)*

QUESTION 2 *Why do power-generating facilities such as this one have tall stacks?*

QUESTION 3 *Explain why the "smoke" changes color from bright white to pale yellow when it reaches a height of about 200 feet above the stacks.*

FIGURE 17.3 Examples of Condensation and Deposition (Top photo by NaturePL/SuperStock; bottom photo by elen_studio/Fotolia)

Condensation of water vapor generates phenomena such as dew, clouds, and fog.

Frost on a windowpane, an example of deposition.

Sublimation and Deposition You are probably least familiar with the last two processes illustrated in Figure 17.2—sublimation and deposition. **Sublimation** is the conversion of a solid directly to a gas, without passing through the liquid state. Examples you may have observed include the gradual shrinking of unused ice cubes in the freezer and the rapid conversion of dry ice (frozen carbon dioxide) to wispy clouds that quickly disappear.

Deposition refers to the reverse process, the conversion of a vapor directly to a solid. This change occurs, for example, when water vapor is deposited as ice on solid objects such as grass or windows (**FIGURE 17.3**). These deposits are called *white frost* or *hoar frost* and are frequently referred to simply as *frost*. A household example of the process of deposition is the "frost" that accumulates in a freezer. As shown in Figure 17.2, deposition releases an amount of energy equal to the total amount released by condensation and freezing.

17.1 CONCEPT CHECKS

1. Summarize the processes by which water changes from one state of matter to another. Indicate whether energy is absorbed or released.
2. What is *latent heat*?
3. What is a common example of sublimation?
4. How does frost form?

17.2 HUMIDITY: WATER VAPOR IN THE AIR

Distinguish between relative humidity and dew point. Write a generalization relating how temperature changes affect relative humidity.

Water vapor constitutes only a small fraction of the atmosphere, varying from as little as one-tenth of 1 percent up to about 4 percent by volume. But the importance of water in the air is far greater than these small percentages would indicate. Indeed, scientists agree that *water vapor* is the most important gas in the atmosphere when it comes to understanding atmospheric processes.

Humidity is the general term for the amount of water vapor in air. Meteorologists employ several methods to express the water-vapor content of the air; we examine three: mixing ratio, relative humidity, and dew-point temperature.

Saturation

Before we consider these humidity measures further, it is important to understand the concept of **saturation**. Imagine a closed jar that contains water overlain by dry air, both at the same temperature. 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. In the open atmosphere, this pressure is termed **vapor pressure** and is defined as the part of the total atmospheric pressure that can be attributed to the water-vapor content.

In the closed container, as more and more molecules escape from the water surface, the steadily increasing vapor pressure in the air above forces more and more of these molecules to return to the liquid. Eventually the number of vapor molecules returning to the surface will balance the number leaving. At that point, the air is *saturated*. If we add heat to the container, thereby increasing the temperature of the water and air, more water will evaporate before a balance is reached. Consequently, at higher temperatures, more moisture is required for saturation. The amount of water vapor required for saturation at various temperatures is shown in **TABLE 17.1**.

TABLE 17.1 Amount of Water Vapor Needed to Saturate 1 Kilogram of Air at Various Temperatures

Temperature °C (°F)	Water-Vapor Content at Saturation (grams)
–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

Mixing Ratio

Not all air is saturated, of course. Thus, we need ways to express how humid a parcel of air is. One method is to specify the amount of water vapor contained in a unit of air. The **mixing ratio** is the mass of water vapor in a unit of air compared to the remaining mass of dry air:

$$\text{mixing ratio} = \frac{\text{mass of water vapor (grams)}}{\text{mass of dry air (kilograms)}}$$

Table 17.1 shows the mixing ratios of saturated air at various temperatures. For example, at 25°C (77°F), a saturated parcel of air (1 kilogram) would contain 20 grams of water vapor.

Because the mixing ratio is expressed in units of mass (usually in grams per kilogram), it is not affected by changes in pressure or temperature. However, measuring the mixing ratio by direct sampling is time-consuming. Thus, other methods are employed to express the moisture content of the air. These include relative humidity and dew-point temperature.

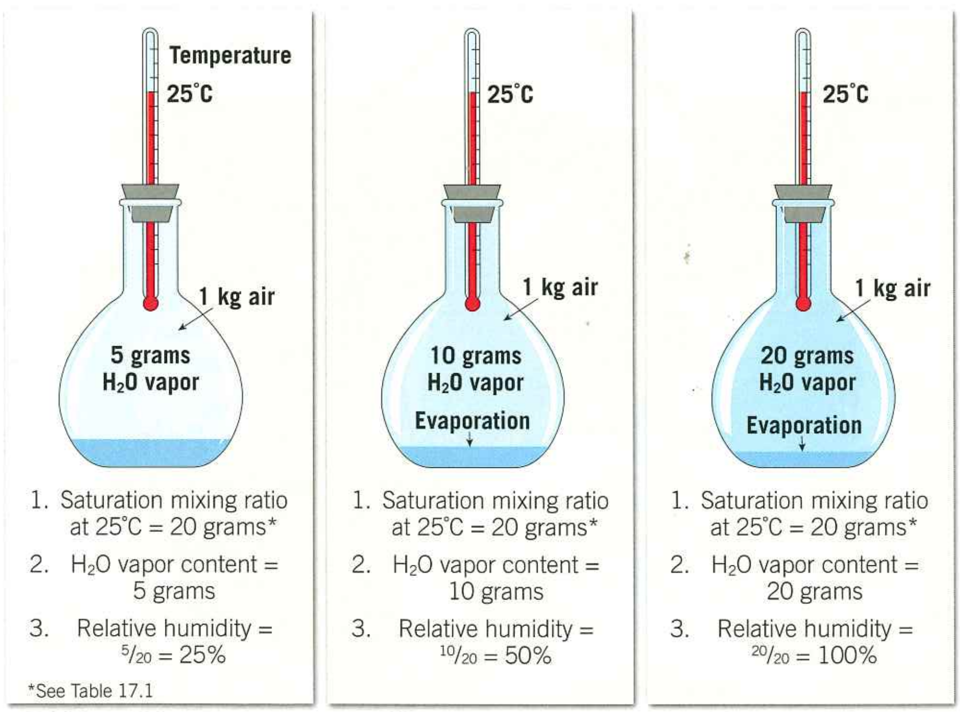
Relative Humidity

The most familiar and, unfortunately, the 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 required for saturation at that temperature (and pressure).* Thus, relative humidity indicates how near the air is to saturation rather than the actual quantity of water vapor in the air.

To illustrate, we see from Table 17.1 that at 25°C (77°F), air is saturated when it contains 20 grams of water vapor per kilogram of air. Thus, if the air contains 10 grams per kilogram on a 25°C day, the relative humidity is expressed as 10/20, or 50 percent. If air with a temperature of 25°C had a water-vapor content of 20 grams per kilogram, the relative humidity would be expressed as 20/20, or 100 percent. When the relative humidity reaches 100 percent, the air is saturated.

Because relative humidity is based on the air's water-vapor content, as well as the amount of moisture required for saturation, it can be changed in either of two ways. First, relative humidity can be changed by the addition or removal of water vapor. Second, because the amount of moisture required for saturation is a function of air temperature, relative humidity varies with temperature. (Recall that the amount of water vapor required for saturation is temperature dependent, and at higher temperatures, it takes more water vapor to saturate air than at lower temperatures.)

Adding or Subtracting Moisture Notice in **FIGURE 17.4** that when water vapor is added to a parcel of air, its relative humidity increases until saturation occurs (100 percent relative humidity). What if even more moisture is added to this parcel of saturated air? Does the relative humidity exceed 100 percent? Normally, this situation does not occur. Instead, the excess water vapor condenses to form liquid water.



A. Initial condition: 5 grams of water vapor

B. Addition of 5 grams of water vapor = 10 grams

C. Addition of 10 grams of water vapor = 20 grams

FIGURE 17.4 The Relationship Between Relative Humidity and Water Vapor Content At a constant temperature, the capacity (saturation mixing ratio) remains unchanged at 20 grams per kilogram, while the relative humidity rises from 25 to 100 percent as the water-vapor content increases.

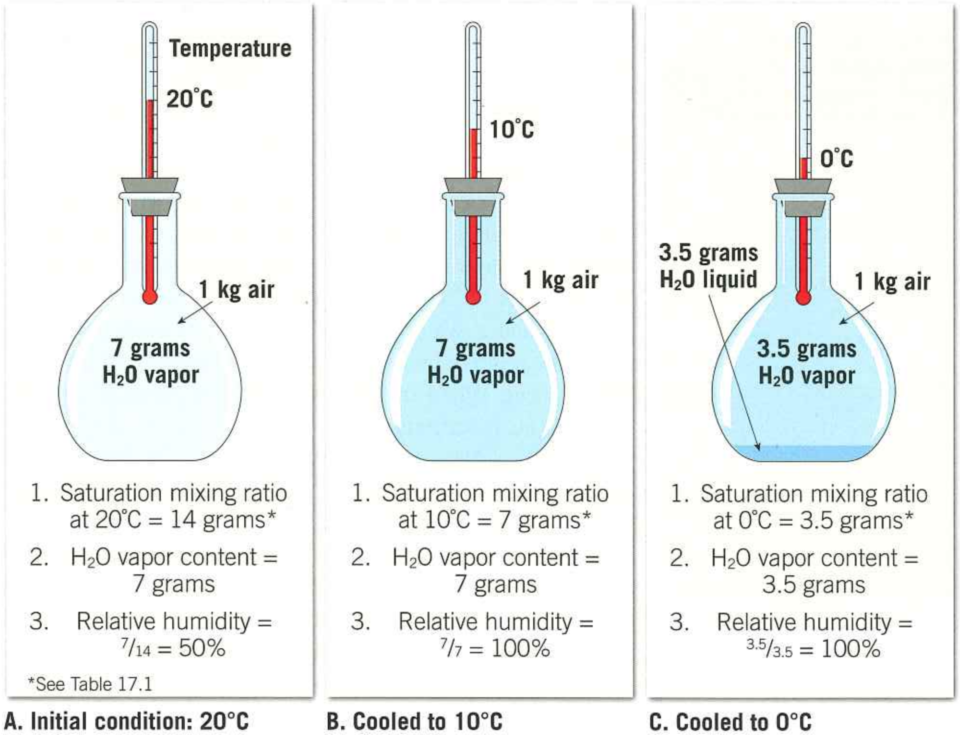


FIGURE 17.5 How Relative Humidity Varies with Temperature When the water-vapor content (mixing ratio) is constant, a decrease in air temperature causes an increase in relative humidity. In this example, when the temperature of the air in the flask was lowered from 20° to 10°C, the relative humidity increased from 50 to 100 percent. Further cooling (from 10° to 0°C) causes one-half of the water vapor to condense. In nature, cooling of air below its saturation mixing ratio generally causes condensation in the form of clouds, dew, or fog.

In nature, moisture is added to the air mainly via evaporation from the oceans. However, plants, soil, and smaller bodies of water also make substantial contributions.

Changes with Temperature The second condition that affects relative humidity is air temperature. Examine **FIGURE 17.5** carefully. Note in Figure 17.5A that when air at 20°C contains 7 grams of water vapor per kilogram it has a relative humidity of 50 percent. This can be verified by referring to Table 17.1. Here we can see that at 20°C, air is saturated when it contains 14 grams of water vapor per kilogram of air. Because the air in Figure 17.5A contains 7 grams of water vapor, its relative humidity is 7/14, or 50 percent.

When the flask is cooled from 20° to 10°C, as shown in Figure 17.5B, the relative humidity increases from 50 to 100 percent. We can conclude that when the water-vapor content remains constant, *a decrease in temperature results in an increase in relative humidity.*

What happens when the air is cooled below the temperature at which saturation occurs? Figure 17.5C illustrates this situation. Notice from Table 17.1 that when the flask is cooled to 0°C, the air is saturated at 3.5 grams of water vapor per kilogram of air. Because this flask originally contained 7 grams of water vapor, 3.5 grams of water vapor will condense to form liquid droplets that collect on the walls of the container. The relative humidity of the air inside remains at 100 percent. This brings up an important concept. When air aloft is cooled below its saturation level, some of the water vapor condenses to form clouds. As clouds are made of liquid droplets (or ice crystals), they are no longer part of the *water-vapor* content of the air. (Clouds are not water vapor; they are composed of liquid water droplets or ice crystals too tiny to fall to Earth.)

We can summarize the effects of temperature on relative humidity as follows: When the water-vapor content of air remains at a constant level, a decrease in air temperature results in an increase in relative humidity, and an increase in temperature causes a decrease in relative humidity. In **FIGURE 17.6** the variations in temperature and relative humidity during a typical day demonstrate the relationship just described.

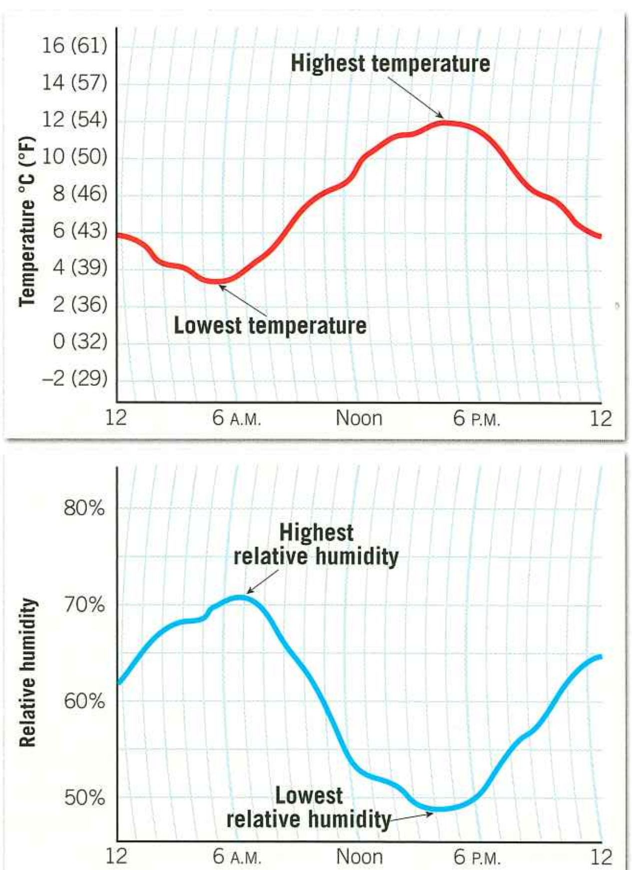


FIGURE 17.6 Typical Daily Variations in Temperature and Relative Humidity This graph shows the daily variations in temperature and relative humidity during a spring day at Washington, DC. When temperature increases, relative humidity drops (see midafternoon) and vice versa.

Dew-Point Temperature

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. For example, in Figure 17.5, the unsaturated air in the flask had to be cooled to 10°C before saturation occurred. Therefore, 10°C is the dew-point temperature for this air. In nature, cooling below the dew point causes water vapor to condense, typically as dew, fog, or clouds. The term *dew point*

FIGURE 17.7 Condensation, or "Dew," on a Cold Drinking Glass The cold glass chills the surrounding layer of air below its dew-point temperature, causing condensation. (amana images inc./Alamy)

stems from the fact that during nighttime hours, objects near the ground often cool below the dew-point temperature and become coated with dew. A similar phenomenon is the condensation of water that occurs when the air adjacent to a cold drink reaches its dew point (**FIGURE 17.7**).

Unlike relative humidity, which is a measure of how near the air is to being saturated, dew-point temperature is a measure of its *actual moisture* content. Because the dew-point temperature is directly related to the amount of water vapor in the air, and because it is easy to determine, it is one of the most useful measures of humidity.

The amount of water vapor needed for saturation is temperature dependent: For every 10°C (18°F) increase in temperature, the amount of water vapor needed for saturation doubles (see Table 17.1). Therefore, relatively cold *saturated air* (0°C [32°F]) contains about half the water vapor of *saturated air* having a temperature of 10°C (50°F) and roughly one-fourth that of warm *saturated air* with a temperature of 20°C (68°F). Because the dew point is the temperature at which saturation occurs, we can conclude that high dew-point temperatures indicate moist air, and low dew-point temperatures indicate dry air. More precisely, we know that air over Fort Myers, Florida, with a dew point of 25°C (77°F), contains about twice the water vapor of air situated over St. Louis, Missouri, with a dew point of 15°C (59°F), and four times that of Tucson, Arizona, with a dew point of 5°C (41°F).

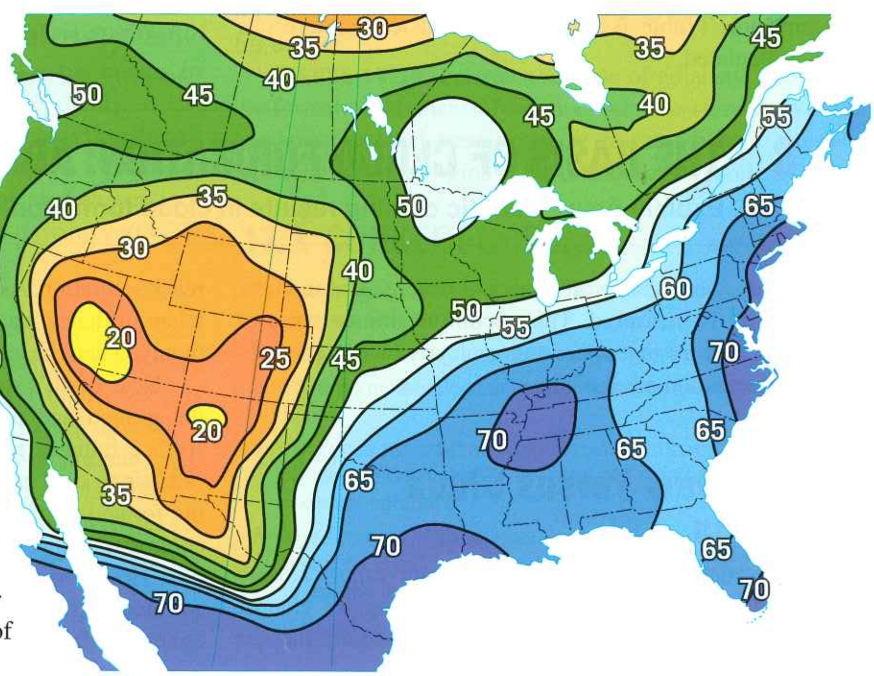
Because the dew-point temperature is a good measure of the amount of water vapor in the air, it is the measure of atmospheric moisture that appears on a variety of weather maps. Notice on the map in **FIGURE 17.8** that most of the places located near the warm Gulf of Mexico have dew-point temperatures that exceed 70°F (21°C). When the dew point exceeds 65°F (18°C), most people consider the air to be humid, and air with a dew point of 75°F (24°C) or higher is oppressive. Also notice in Figure 17.8 that although the Southeast is dominated by humid conditions (dew points above 65°F), most of the remainder of the country is experiencing drier air.

Measuring Humidity

Relative humidity is commonly measured using a **hygrometer** (*hygro* = moisture, *metron* = measuring instrument). One type of hygrometer, called a **psychrometer**, consists of two identical thermometers mounted side by side (**FIGURE 17.9**). One thermometer, the *dry-bulb* thermometer, gives the current air temperature. The other, called the *wet-bulb* thermometer, has a thin muslin wick tied around the end (see the ends of the thermometers in Figure 17.9).

To use the psychrometer, the cloth sleeve is saturated with water, and a continuous current of air is passed over the wick (see Figure 17.9). This is done either by swinging the instrument freely in the air or by fanning air past it. As a consequence, 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.

The amount of cooling that takes place is directly proportional to the dryness of the air. The drier the air, the



SmartFigure 17.8 Map Showing Dew-Point Temperatures on a Typical September Day Dew-point temperatures above 60°F dominate the southeastern United States, indicating that this region is blanketed with humid air, while much drier conditions prevail over the American Southwest.

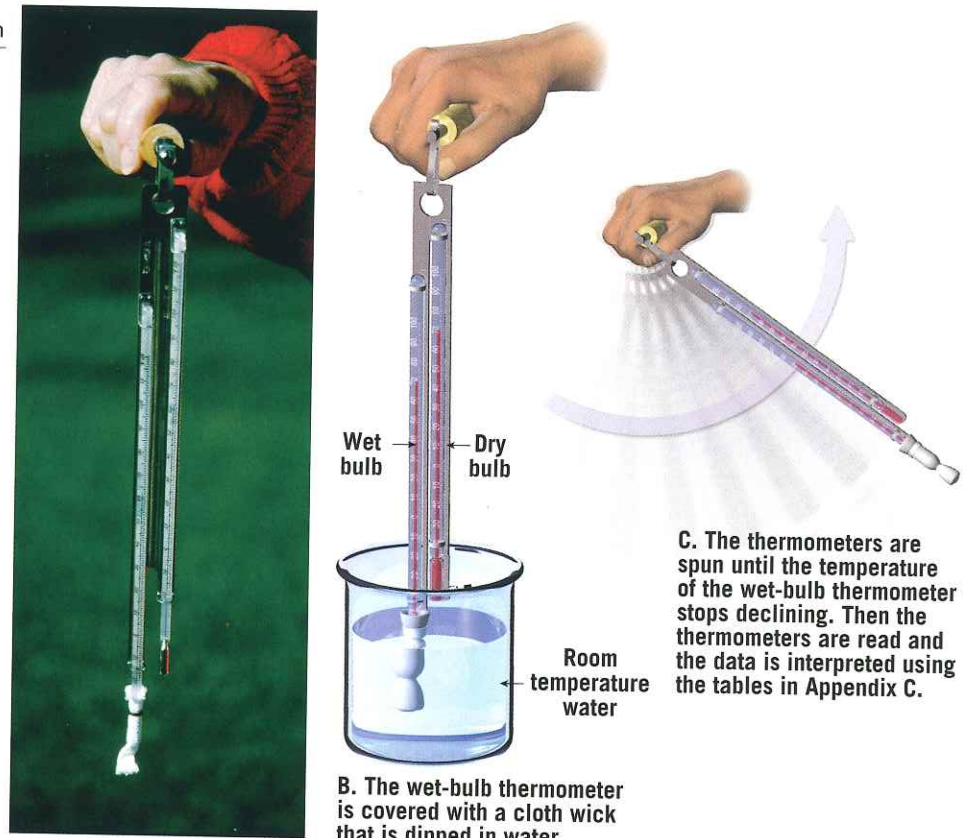


FIGURE 17.9 Sling Psychrometer Used to Determine Both Relative Humidity and Dew Point (Photo by E. J. Tarbuck)

A. The dry-bulb thermometer gives the current air temperature.

B. The wet-bulb thermometer is covered with a cloth wick that is dipped in water.

C. The thermometers are spun until the temperature of the wet-bulb thermometer stops declining. Then the thermometers are read and the data is interpreted using the tables in Appendix C.

greater the amount of moisture that evaporates. The more heat the evaporating water absorbs, the greater the cooling. Therefore, the larger the difference that is observed between the thermometer readings, the lower the relative humidity; the smaller the difference, the higher 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 from the thermometer readings, a standard table is used (refer to Appendix B, Table B.1). With the same information but using a different table (Table B.2), the dew-point temperature can also be calculated.

17.2 CONCEPT CHECKS

1 Describe how the water vapor content of air at saturation is related to air temperature.

2 List three measures that are used to express humidity.

3 How do relative humidity and mixing ratio differ?

4 If the amount of water vapor in the air remains unchanged, how does a decrease in temperature affect relative humidity?

5 On a warm summer day when the relative humidity is high, it may seem even warmer than the thermometer indicates. Why do we feel so uncomfortable on these muggy days?

17.3 THE BASIS OF CLOUD FORMATION: ADIABATIC COOLING

Explain how adiabatic cooling results in cloud formation.

We have considered basic properties of water vapor and how its variability is measured. This section examines some of the important roles that water vapor plays in weather, especially the formation of clouds.

Fog and Dew Versus Cloud Formation

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 that air reach saturation. As indicated earlier, saturation occurs either when sufficient water vapor is added to the air or, more commonly, when the air is cooled to its dew point.

Near Earth's surface, heat is readily 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 radiation cooling accounts for the formation of dew and some types of fog. Thus, surface cooling that occurs after sunset accounts for some condensation. However, cloud formation often takes place during the warmest part of the day. Clearly some other mechanism must operate aloft that cools air sufficiently to generate clouds.

Adiabatic Temperature Changes

The process that is responsible for most cloud formation is easily demonstrated if you have ever pumped up a bicycle tire and noticed that the pump barrel became quite warm. The heat you felt was a result of the work you did on the air to compress it. When energy is used to compress air, the motion of the gas molecules increases, and therefore the temperature of the air rises. Conversely, air that is allowed to escape from a bicycle tire *expands and cools*. This results because the expanding air pushes (does work on) the surrounding air and must cool by an amount equivalent to the energy expended.

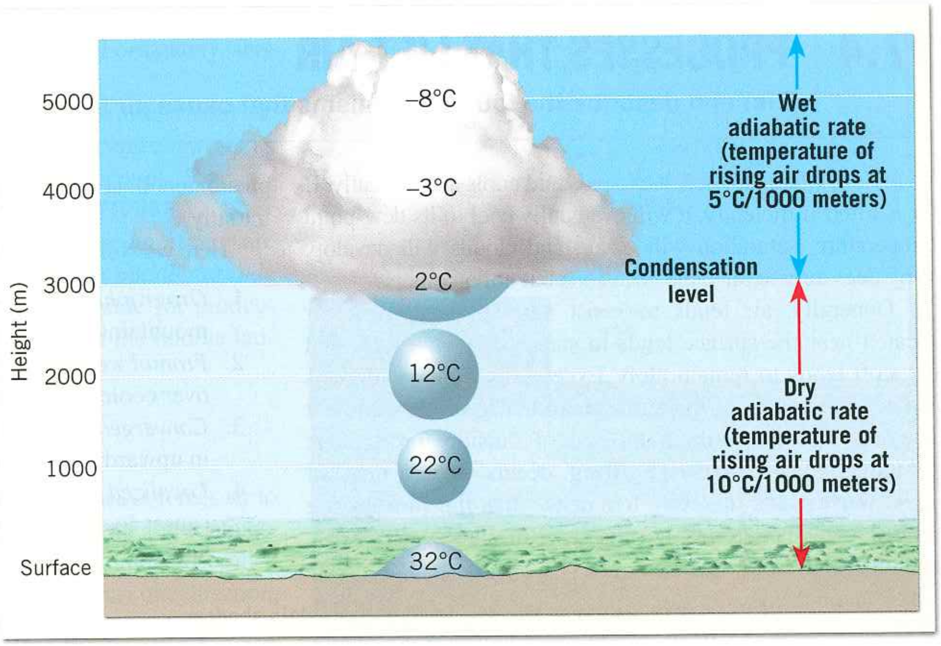


FIGURE 17.10 Dry Versus Wet Adiabatic Rates of Cooling Rising air cools at the dry adiabatic rate of 10° per 1000 meters, until the air reaches the dew point and condensation (cloud formation) begins. As air continues to rise, the latent heat released by condensation reduces the rate of cooling. The wet adiabatic rate is therefore always less than the dry adiabatic rate.

You have probably felt the cooling effect of the propellant gas expanding as you have applied hairspray or spray deodorant. As the compressed gas in an aerosol spray can is released, it quickly expands and cools. This drop in temperature occurs *even though heat is neither added nor subtracted.* Such variations are known as **adiabatic temperature changes** and result when air is compressed or allowed to expand. In summary, *when air is allowed to expand, it cools, and when it is compressed, it warms.*

Adiabatic Cooling and Condensation

To simplify the following discussion, it helps to imagine a volume of air enclosed in a thin elastic cover. Meteorologists call this imaginary volume of air a **parcel**. Typically, we consider a parcel to be a few hundred cubic meters in volume, and we assume that it acts independently of the surrounding air. It is also assumed that no heat is transferred into or out of the parcel. Although this image is highly idealized, over short time spans, a parcel of air behaves in a manner much like an actual volume of air moving vertically in the atmosphere.

Dry Adiabatic Rate As you travel from Earth's surface upward through the atmosphere, the atmospheric pressure rapidly diminishes because there are fewer and fewer gas molecules. Thus, any time a parcel of air moves upward, it passes through regions of successively lower pressure, and the ascending air expands. As it expands, it cools adiabatically. Unsaturated air cools at a constant rate of 10°C for every 1000 meters of ascent (5.5°F per 1000 feet).

Conversely, descending air comes under increasingly higher pressures, compresses, and is heated 10°C for every 1000 meters of descent. This rate of cooling or heating applies only to *unsaturated air* and is known as the **dry adiabatic rate**.

Wet Adiabatic Rate If a parcel of air rises high enough, it will eventually cool to its dew point, where the process of condensation begins. From this point on along its ascent, *latent heat of condensation* stored in the water vapor will be liberated. Although the air will continue to cool after condensation begins, the released latent heat works against the adiabatic process, thereby reducing the rate at which the air cools. This slower rate of cooling caused by the addition of latent heat is called the **wet adiabatic rate** of cooling. Because the amount of latent heat released depends on the quantity of moisture present in the air, the wet adiabatic rate varies from 5°C per 1000 meters for air with a high moisture content to 9°C per 1000 meters for dry air.

FIGURE 17.10 illustrates 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.

17.3 CONCEPT CHECKS

1. How is the formation of dew different from cloud formation? How are they similar?
2. Why does air cool when it rises through the atmosphere?
3. What do meteorologists mean when they use the word *parcel*?
4. Why does the adiabatic rate of cooling change when condensation begins? Why is the wet adiabatic rate not a constant number?
5. The contents of an aerosol spray can are under very high pressure. Explain why the spray feels cold when it is allowed to escape the container.

17.4 PROCESSES THAT LIFT AIR

List and describe the four mechanisms that cause air to rise.

To review, when air rises, it expands and cools adiabatically. If air is lifted sufficiently, it will eventually cool to its dew-point temperature, saturation will occur, and clouds will develop. Why does air rise on some occasions but not on others?

Generally, air tends to resist vertical movement; air located near the surface tends to stay near the surface, and air aloft tends to remain aloft. Exceptions to these patterns include conditions in the atmosphere that give air sufficient buoyancy to rise without the aid of outside forces. One example, called **convective lifting**, occurs when a mass of air is warmer and therefore less dense than the surrounding air. In most situations, however, when you see clouds forming, there is some mechanical phenomenon at work that forces the air to rise (at least initially).

Here we will look at four mechanisms that cause air to rise:

1. *Orographic lifting*—Air is forced to rise over a mountainous barrier.
2. *Frontal wedging*—Warmer, less dense air is forced over cooler, denser air.
3. *Convergence*—A pileup of horizontal airflow results in upward movement.
4. *Localized convective lifting*—Unequal surface heating causes localized pockets of air to rise because of their buoyancy.

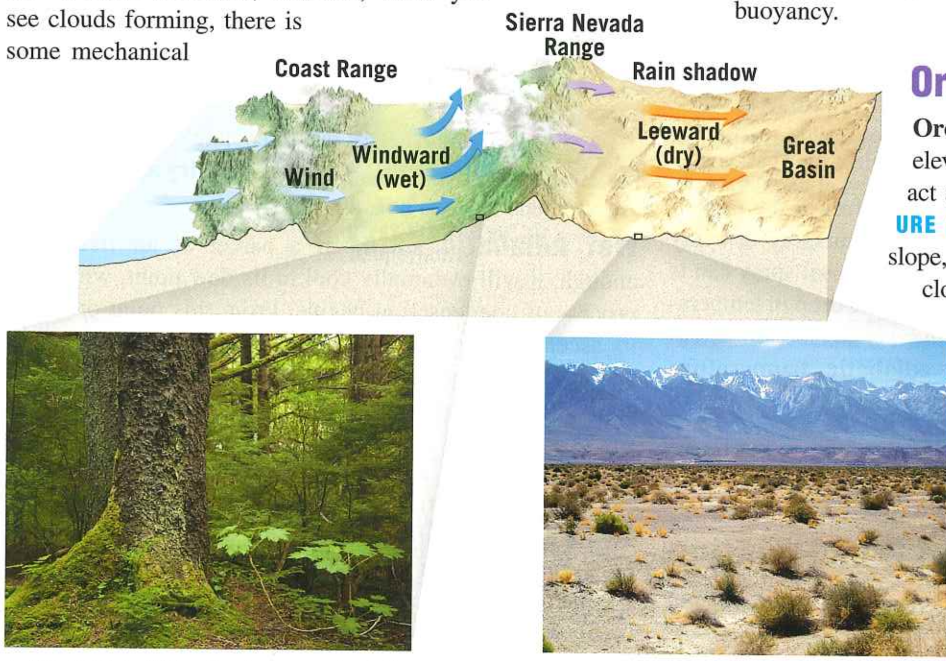


FIGURE 17.11 Orographic Lifting and Rain Shadow Deserts (Photo A by Shutterstock/Dean Pennala; photo B by Dennis Tasa)

A. Orographic lifting leads to precipitation on windward slopes.

B. By the time air reaches the leeward side of the mountains, much of the moisture has been lost, resulting in a *rain shadow desert*.

Orographic Lifting

Orographic lifting occurs when elevated terrains, such as mountains, act as barriers to the flow of air (**FIGURE 17.11**). As air ascends a mountain slope, adiabatic cooling often generates clouds and copious precipitation. In fact, many of the rainiest places in the world are located on windward mountain slopes.

By the time air reaches the leeward side of a mountain, much of its moisture has been lost. If the air descends, it warms adiabatically, making condensation and precipitation even less likely. As shown in Figure 17.11, the result can be a **rain shadow desert**. The Great Basin Desert of the western United States lies only a few hundred kilometers from the Pacific Ocean, but it is effectively cut off from the ocean's moisture by the imposing Sierra Nevada. The Gobi Desert of Mongolia, the Takla Makan of China, and the Patagonia Desert of Argentina are other examples of deserts that exist because they are on the leeward sides of mountains. (For a map showing deserts, see Figure 6.30, page 193.)

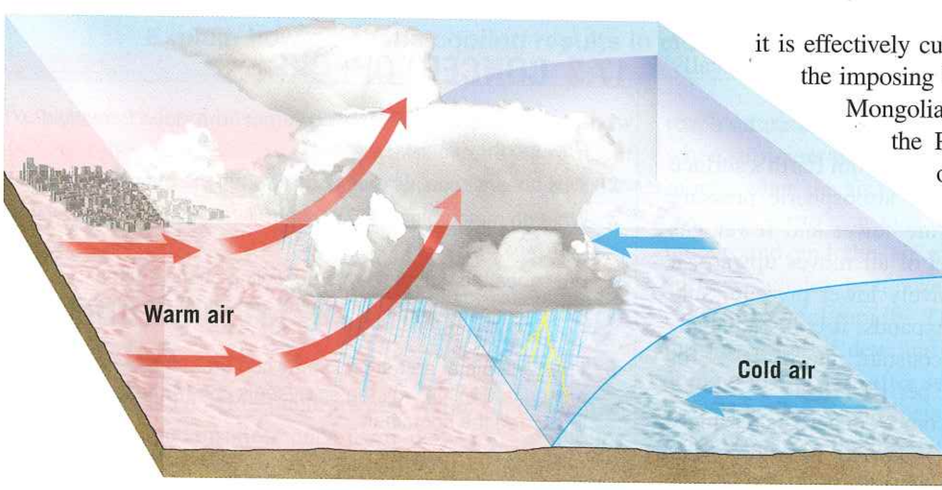


FIGURE 17.12 Frontal Wedging Colder, denser air acts as a barrier over which warmer, less dense air rises.

Frontal Wedging

If orographic lifting were the only mechanism that forced air aloft, 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 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 illustrated in **FIGURE 17.12**.

It should be noted that weather-producing fronts are associated with storm systems called *middle-latitude cyclones*. Because these storms are responsible for producing a high percentage of the precipitation in the middle latitudes, we examine them closely in Chapter 19.

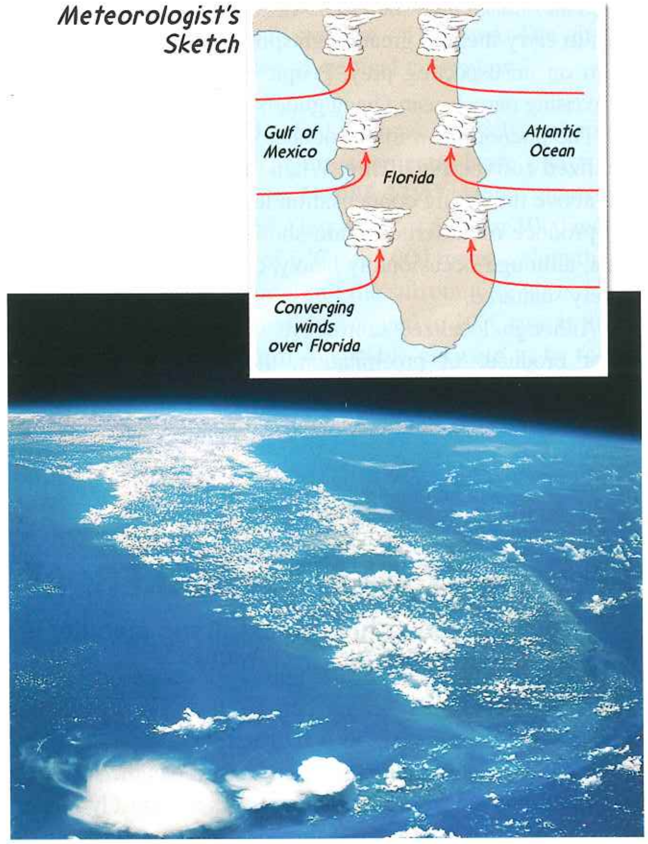
Convergence

We saw 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 phenomenon is called **convergence**. When air flows in from more than one direction, it must go somewhere. Because it cannot go down, it goes up. This leads to adiabatic cooling and possible cloud formation.

Convergence can also occur whenever an obstacle slows or restricts horizontal airflow (wind). When air moves from a relatively smooth surface, such as the ocean, onto an irregular landscape, its speed is reduced. The result is a pileup of air (convergence). This is similar to what happens when people leave a well-attended sporting event and a pileup results at the exits. When air converges, the air molecules do not simply squeeze closer together (like people); rather, there is a net upward flow.

The Florida peninsula provides an excellent example of the role that convergence can play in initiating cloud development and precipitation (**FIGURE 17.13**). 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 that results is aided by intense solar heating of the land. This is why the peninsula of Florida experiences the greatest frequency of midafternoon thunderstorms in the United States.

Convergence as a mechanism of forceful lifting is a major contributor to the weather associated with middle-latitude cyclones and hurricanes. The low-level horizontal airflow associated with these systems is inward and upward around their centers. These important weather producers are covered in more detail later, but for now remember that convergence near the surface results in a general upward flow.



SmartFigure 17.13 Surface Convergence Enhances Cloud Development When surface air converges, the column of air increases in height because the air is crammed into a smaller and smaller space. The result is forced lifting and adiabatic cooling that generates clouds. This photo shows southern Florida, viewed from the Space Shuttle. On warm days, airflow from the Atlantic Ocean and Gulf of Mexico onto the Florida peninsula generates many midafternoon thunderstorms. (Photo by NASA)

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 instance, 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 (less dense) than the surrounding air, will be buoyed upward (**FIGURE 17.14**). These rising parcels of warmer air are

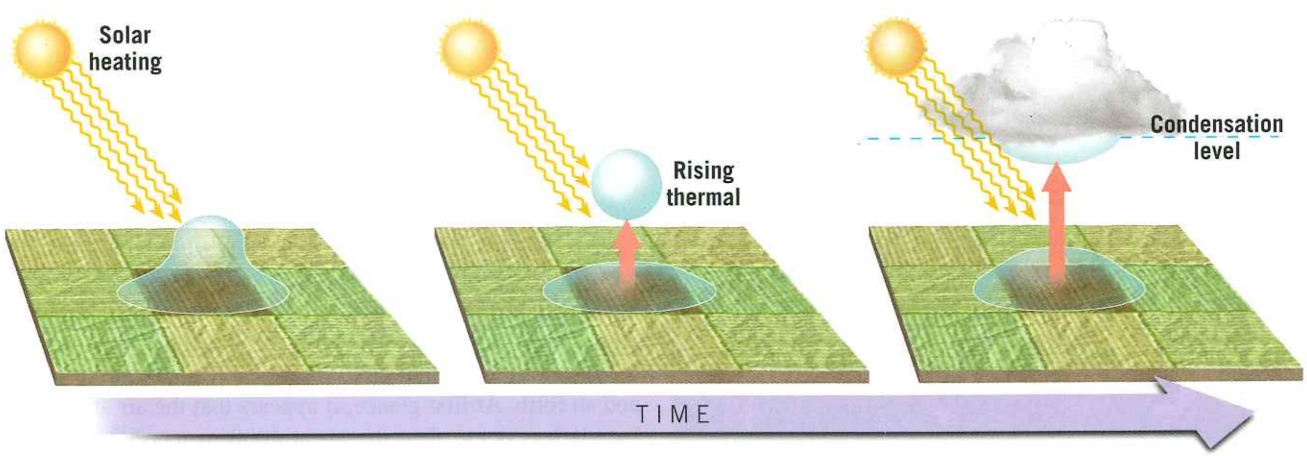


FIGURE 17.14 Localized Convective Lifting Unequal heating of Earth's surface causes pockets of air to be warmed more than the surrounding air. These buoyant parcels of hot air (thermals) rise, and if they reach the condensation level clouds form.

called *thermals*. Birds such as hawks and eagles use these thermals to carry them to great heights, from which they can gaze down on unsuspecting prey. People have learned to employ these rising parcels using hang gliders as a way to "fly."

The phenomenon that produces rising thermals is called **localized convective lifting**. When these warm parcels of air rise above the lifting condensation level, clouds form, which can produce midafternoon rain showers. The accompanying rains, although occasionally heavy, are of short duration and widely scattered.

Although localized convective lifting by itself is not a major producer of precipitation, the added buoyancy that results from surface heating contributes significantly to the lifting initiated by the other mechanisms. In addition, even though the other mechanisms force air to rise, convective lifting occurs because the air is warmer (less dense) than the surrounding air and rises for the same reasons as does a hot-air balloon.

17.4 CONCEPT CHECKS

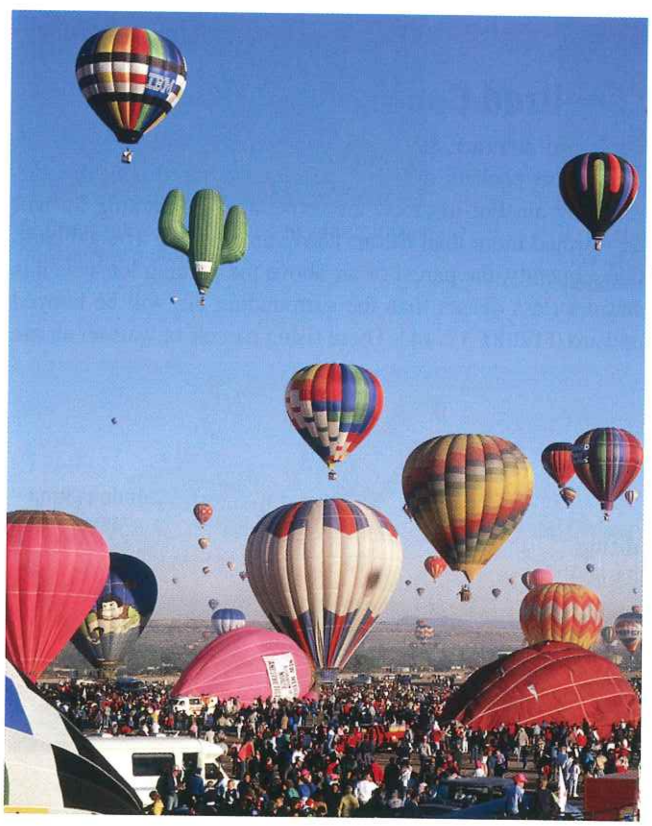
1 List four mechanisms that cause air to rise.
2 How do orographic lifting and frontal wedging force air to rise?
3 Explain why the Great Basin area of the western United States is dry. What term is applied to this situation?
4 What causes the Florida peninsula to experience the greatest frequency of midafternoon thunderstorms in the United States?

17.5 THE WEATHERMAKER: ATMOSPHERIC STABILITY

Describe how atmospheric stability is determined and compare conditional instability with absolute instability.

When air rises, it cools and usually produces clouds. Why do clouds vary so much in size, and why does the resulting precipitation vary so much? The answers are closely related to the *stability* of the air.

Recall that a parcel of air can be thought of as having a thin, flexible cover that allows it to expand but prevents it from mixing with the surrounding air (picture a hot-air balloon). If this parcel were forced to rise, *its temperature would decrease because of expansion*. By comparing the parcel's temperature to that of the surrounding air, we can determine the stability of the bubble. If the parcel's temperature is lower than that of the surrounding environment, it will be denser; if it is allowed to move freely, it will sink to its original position. Air of this type, called **stable air**, resists vertical movement.



IGURE 17.15 Hot Air ises Hot-air balloons rise rough the atmosphere ecause the heated air inside e balloons is warmer (less ense) than the surrounding . (Photo by Steve Vidler/ perStock)

If, however, our imaginary rising parcel is *warmer* and hence less dense than the surrounding air, it will continue to rise until it reaches an altitude where its temperature equals that of its surroundings. This is exactly how a hot-air balloon works, rising as long as it is warmer and less dense than the surrounding air (**FIGURE 17.15**). This type of air is classified as **unstable air**. In summary, stability is a property of air that describes its tendency to remain in its original position (stable) or to rise (unstable).

Types of Stability

The stability of air is determined by measuring the temperature of the atmosphere at various heights. Recall from Chapter 16 that this measure is called the *environmental lapse rate*. The environmental lapse rate is the temperature of the atmosphere, as determined from observations made by radiosondes and aircraft. It is important not to confuse this with *adiabatic temperature changes*, which are changes in temperature caused by expansion or compression as a parcel of air rises or descends.

To illustrate, we examine a situation in which the environmental lapse rate is 5°C per 1000 meters (**FIGURE 17.16**). Under this condition, when air at the surface has a temperature of 25°C, the air at 1000 meters will be 5° cooler, or 20°C, the air at 2000 meters will have a temperature of 15°C, and so forth. At first glance, it appears that the air at the surface is less dense than the air at 1000 meters because it is

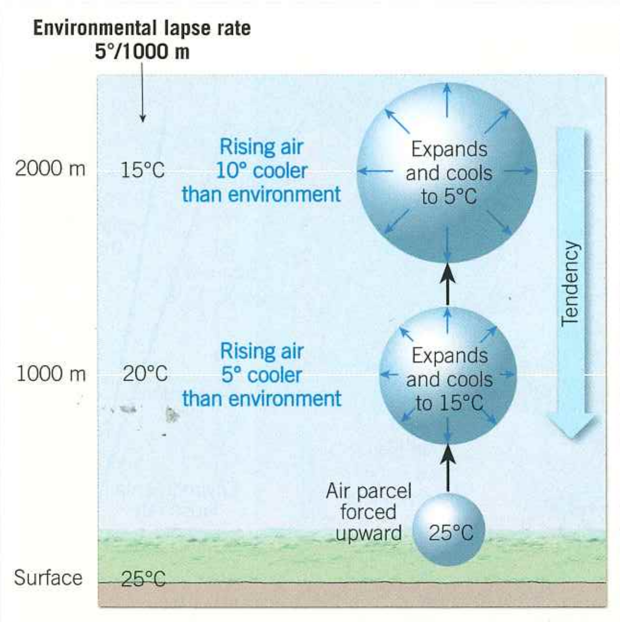


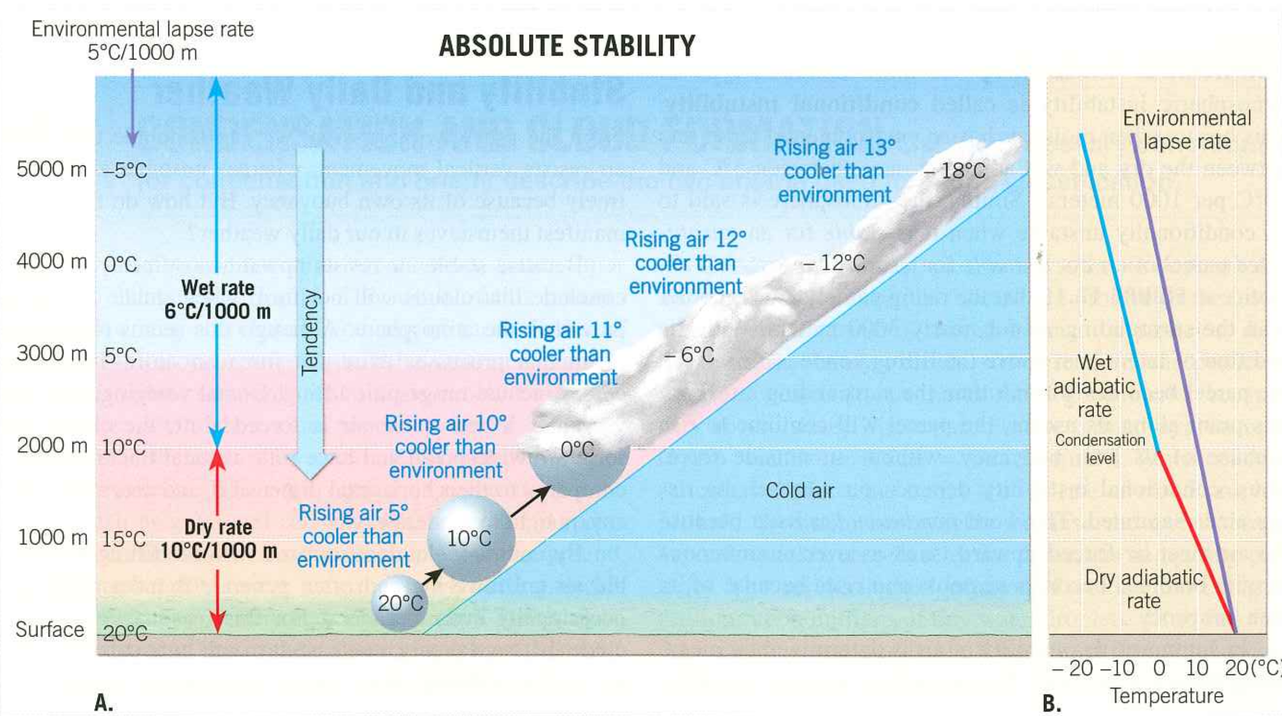
FIGURE 17.16 When an Unsaturated Parcel of Air Is Lifted, It Expands and Cools at the Dry Adiabatic Rate (10°C per 1000 meters) Because the temperature of the rising parcel of air is lower than the surrounding environment, it will be heavier, and sink to its original position if it is allowed to do so. Air of this type is referred to as *stable*.

5° warmer. However, if the air near the surface were unsaturated and were to rise to 1000 meters, it would expand and cool at the dry adiabatic rate of 10°C per 1000 meters. Therefore, upon reaching 1000 meters, its temperature would have dropped 10°C. Being 5° cooler than its environment, it would be denser and tend to sink to its original position. Hence, we say that the air near the surface is potentially cooler than the air aloft and therefore will not rise on its own. The air just described is *stable* and resists vertical movement.

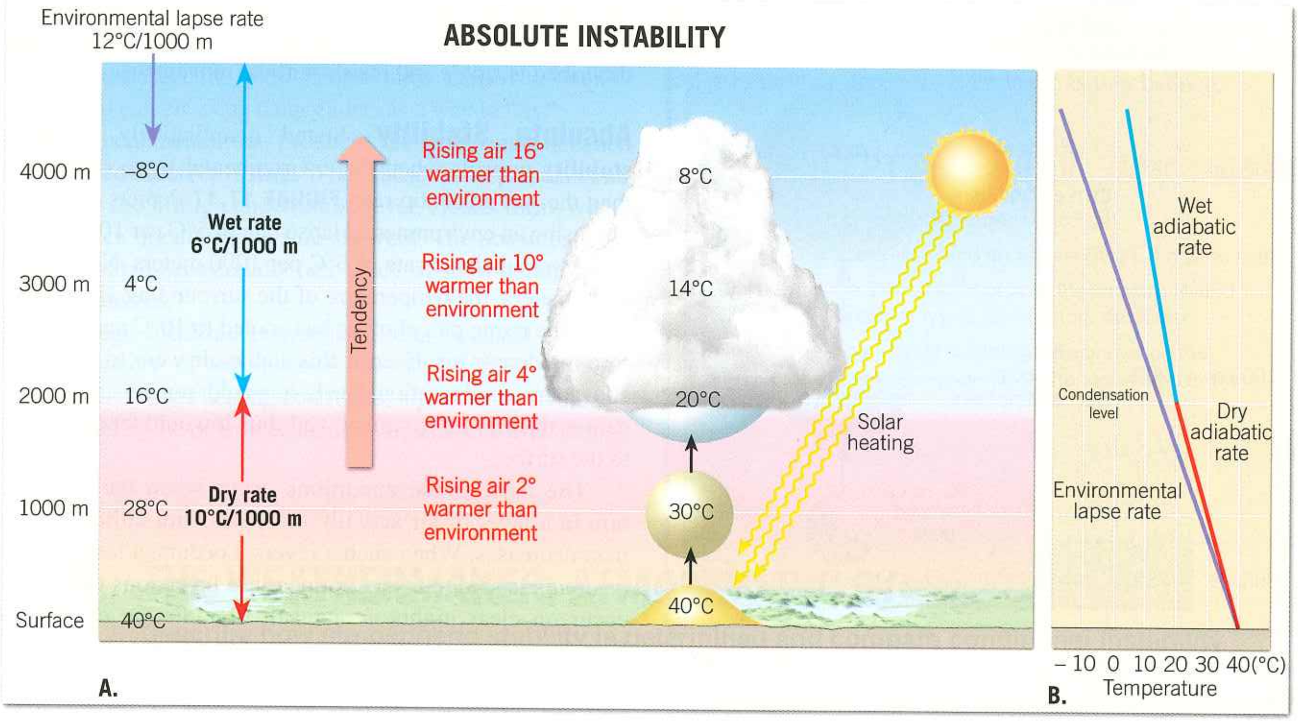
Absolute Stability Stated quantitatively, **absolute stability** prevails when the environmental lapse rate is less than the wet adiabatic rate. **FIGURE 17.17** depicts this situation using an environmental lapse rate of 5°C per 1000 meters and a wet adiabatic rate of 6°C per 1000 meters. Note that at 1000 meters, the temperature of the surrounding air is 15°C, while the rising parcel of air has cooled to 10°C and is therefore the denser air. Even if this stable air were to be forced above the condensation level, it would remain cooler and denser than its environment, and thus it would tend to return to the surface.

The most stable conditions occur when the temperature in a layer of air actually increases with altitude rather than decreases. When such a reversal occurs, a *temperature inversion* is said to exist. Temperature inversions frequently occur on clear nights as a result of radiation cooling of Earth's surface. Under these conditions, an inversion is created because the ground and the air immediately above will cool more rapidly than the air aloft. When warm air overlies cooler air, it acts as a lid and prevents appreciable vertical mixing. Because of this, temperature inversions are responsible for trapping pollutants in a narrow zone near Earth's surface.

Absolute Instability At the other extreme from absolute stability, air is said to exhibit **absolute instability** when the environmental lapse rate is greater than the dry adiabatic rate. As shown in **FIGURE 17.18**, the ascending parcel of air is always warmer than its environment and



SmartFigure 17.17 Atmospheric Conditions That Result in Absolute Stability **A.** The rising parcel of air is always cooler and heavier than the surrounding air and is therefore stable. **B.** Graphic representation of the conditions shown in part A.



IGURE 17.18 tmosphere Conditions hat Result in Absolute nstability **A.** Absolute stability develops when olar heating causes the wermost layer of the mosphere to be warmed a higher temperature an the air aloft. The result a steep environmental pse rate that renders the mosphere unstable. **B.** raphic representation of the nditions shown in part A.

will continue to rise because of its own buoyancy. However, absolute instability is generally found near Earth's surface. On hot, sunny days the air above some surfaces, such as shopping center parking lots, is heated more than the air over adjacent surfaces. These invisible pockets of more intensely heated air, being less dense than the air aloft, will rise like a hot-air balloon. This phenomenon produces the small, fluffy clouds we associate with fair weather. Occasionally, when the surface air is considerably warmer than the air aloft, clouds with considerable vertical development can form.

Conditional Instability A more common type of atmospheric instability is called **conditional instability**. This occurs when moist air has an environmental lapse rate between the dry and wet adiabatic rates (between 5°C and 10°C per 1000 meters). Simply, the atmosphere is said to be conditionally unstable when it is *stable* for an *unsaturated* parcel of air but *unstable* for a *saturated* parcel of air. Notice in **FIGURE 17.19** that the rising parcel of air is cooler than the surrounding air for nearly 3000 meters. With the addition of latent heat above the lifting condensation level, the parcel becomes warmer than the surrounding air. From this point along its ascent, the parcel will continue to rise because of its own buoyancy, without an outside force. Thus, conditional instability depends on whether the rising air is saturated. The word *conditional* is used because the air must be forced upward, such as over mountainous terrain, before it becomes unstable and rises because of its own buoyancy.

In summary, the stability of air is determined by measuring the temperature of the atmosphere at various heights. In simple terms, a column of air is deemed unstable when the air near the bottom of this layer is significantly warmer (less dense) than the air aloft, indicating a steep environmental lapse rate. Under these conditions, the air actually turns over, as the warm air below rises and displaces the colder air aloft. Conversely, the air is considered to be stable when the temperature drops gradually with increasing altitude. The most stable conditions occur during a temperature inversion, when the temperature actually increases with height. Under these conditions, there is very little vertical air movement.

Stability and Daily Weather

From the previous discussion, we can conclude that stable air resists vertical movement, whereas unstable air ascends freely because of its own buoyancy. But how do these facts manifest themselves in our daily weather?

Because stable air resists upward movement, we might conclude that clouds will not form when stable conditions prevail in the atmosphere. Although this seems reasonable, recall that processes exist that *force* air aloft. These processes include orographic lifting, frontal wedging, and convergence. When stable air is forced aloft, the clouds that form are widespread and have little vertical thickness when compared to their horizontal dimension, and precipitation, if any, is light to moderate.

By contrast, clouds associated with the lifting of unstable air are towering and often generate thunderstorms and occasionally even tornadoes. For this reason, we can conclude that on a dreary, overcast day with light drizzle, stable air has been forced aloft. On the other hand, during a day

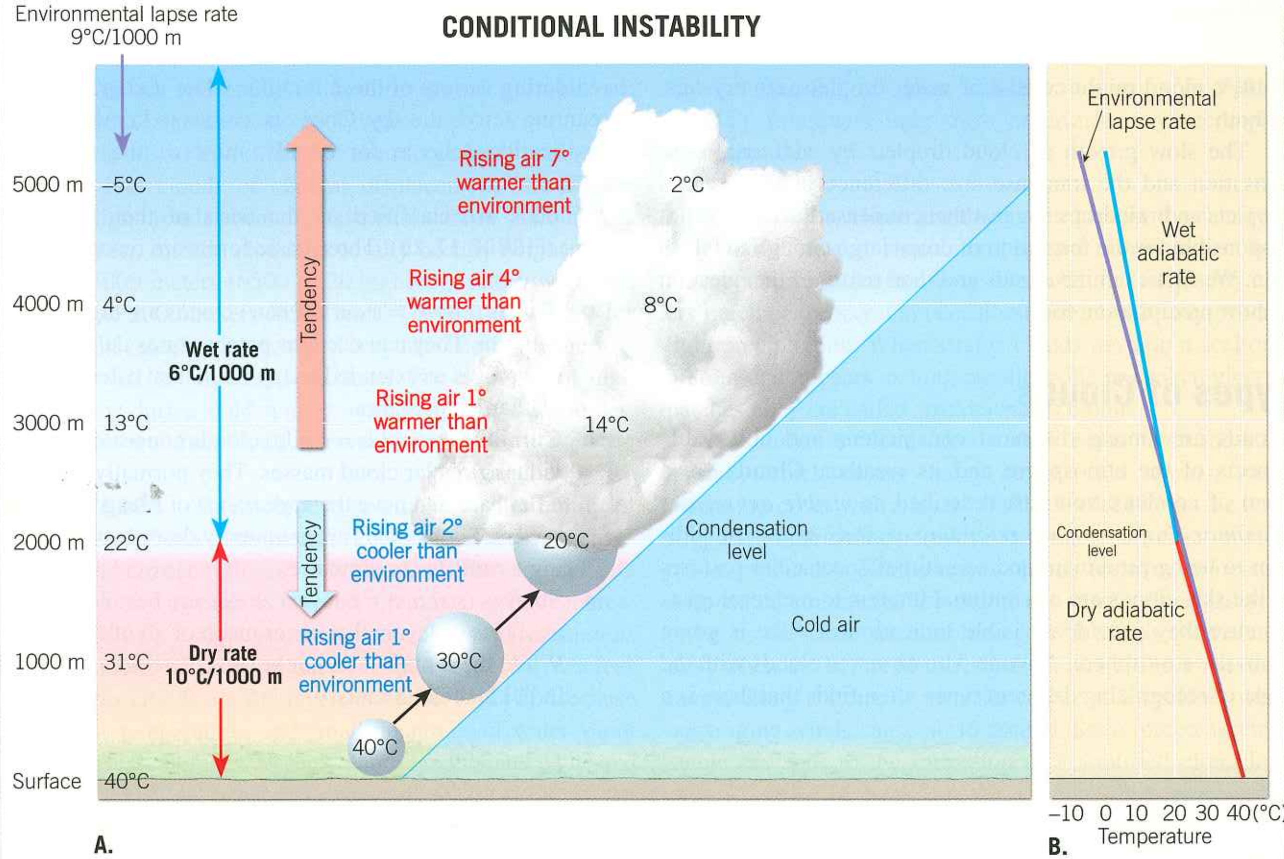


FIGURE 17.19 Conditional Instability May Result When Warm Air Is Forced to Rise Along a Frontal Boundary **A.** Note that the environmental lapse rate of 9°C per 1000 meters lies between the dry and wet adiabatic rates. The parcel of air is cooler than the surrounding air up to nearly 3000 meters, where its tendency is to sink toward the surface (stable). Above this level, however, the parcel is warmer than its environment and will rise because of its own buoyancy (unstable). Thus, when conditionally unstable air is forced to rise, the result can be towering cumulus clouds. **B.** Graphic representation of the conditions shown in part A.

when cauliflower-shaped clouds appear to be growing as if bubbles of hot air are surging upward, we can be fairly certain that the ascending air is unstable.

In summary, stability plays an important role in determining our daily weather. To a large degree, stability determines the type of clouds that develop and whether precipitation will come as a gentle shower or a heavy downpour.

17.5 CONCEPT CHECKS

1. Explain the difference between the environmental lapse rate and adiabatic cooling.
2. Describe absolute stability in your own words.
3. Compare absolute instability and conditional instability.
4. What types of clouds and precipitation, if any, form when stable air is forced aloft?
5. Describe the weather associated with unstable air.

17.6 CONDENSATION AND CLOUD FORMATION

List the necessary conditions for condensation and briefly describe the two criteria used for cloud classification.

To review briefly, condensation occurs when water vapor in the air changes to a liquid. The result of this process may be 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.

Generally, there must be a surface on which the water vapor can condense. When dew occurs, 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, known as **condensation nuclei**, serve as surfaces for water-vapor condensation. These nuclei are very important, for in their absence, a relative humidity well in excess of 100 percent is needed to produce clouds.

Condensation nuclei such as microscopic dust, smoke, and salt particles (from the ocean) are profuse in the lower atmosphere. Because of this abundance of particles, relative humidity rarely exceeds 101 percent. Some particles, such as ocean salt, are particularly good nuclei because they absorb water. These particles are termed **hygroscopic** (*hygro* = moisture, *scopic* = to seek) **nuclei**. 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, all so fine that they remain suspended in air. When cloud formation occurs at below-freezing temperatures, tiny ice crystals form.

Thus, a cloud might consist of water droplets, ice crystals, or both.

The slow growth of cloud droplets by additional condensation and the immense size difference between cloud droplets and raindrops suggest that condensation alone is not responsible for the formation of drops large enough to fall as rain. We first examine clouds and then return to the question of how precipitation forms.

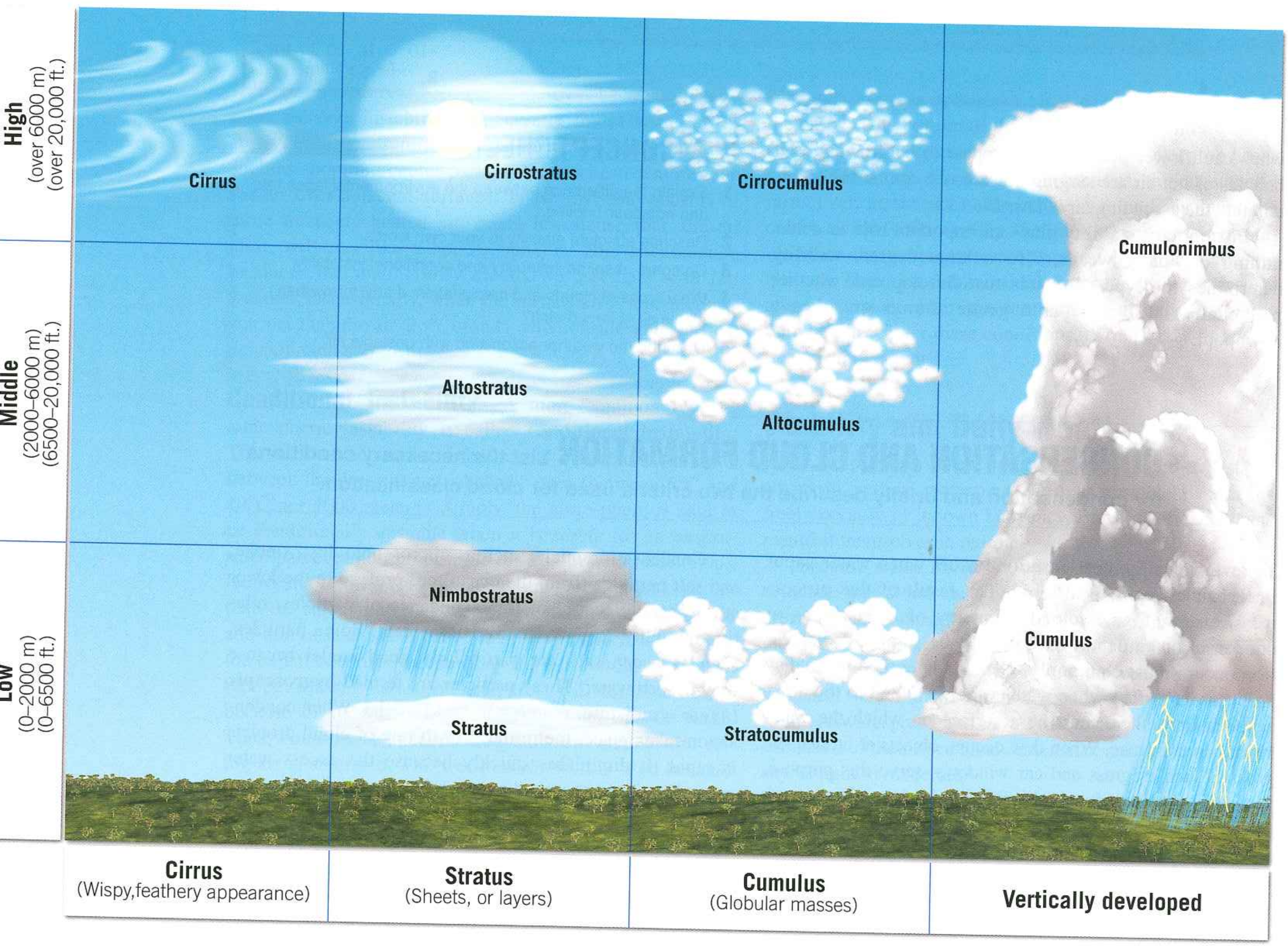
Types of Clouds

SmartFigure 17.20 Classification of Clouds, Based on Height and Form

Clouds are among the most conspicuous and observable aspects of the atmosphere and its weather. **Clouds** are a form of condensation best described as *visible aggregates of minute droplets of water or tiny crystals of ice.* In addition to being prominent and sometimes spectacular features in the sky, clouds are of continual interest to meteorologists because they provide a visible indication of what is going on in the atmosphere. Anyone who observes clouds with the hope of recognizing different types often finds that there is a bewildering variety of these familiar white and gray masses streaming across the sky. Once one comes to know the basic classification scheme for clouds, most of the confusion vanishes.

Clouds are classified on the basis of their *form* and *height* (**FIGURE 17.20**). Three basic forms are recognized:

- **Cirrus** (*cirrus* = a curl of hair) clouds are high, white, and thin. They can occur as patches or as delicate veil-like sheets or extended wispy fibers that often have a feathery appearance.
- **Cumulus** (*cumulus* = a pile) clouds consist of individual globular cloud masses. They normally exhibit a flat base and have the appearance of rising domes or towers. Such clouds are frequently described as having a cauliflower structure.
- **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.



All other clouds reflect one of these three basic forms or are combinations or modifications of them.

Four levels of cloud heights are recognized: high, middle, low, and clouds of vertical displacement (see Figure 17.20). **High clouds** normally have bases above 6000 meters (20,000 feet), **middle clouds** generally occupy heights from 2000 to 6000 meters (6500 to 20,000 feet), and **low clouds** form below 2000 meters (6500 feet). The altitudes listed for each height category are not hard and fast. There is some seasonal as well as latitudinal variation. For example, at high latitudes or during cold winter months in the midlatitudes, high clouds are often found at lower altitudes.

High Clouds Three cloud types make up the family of high clouds (above 6000 meters [20,000 feet]): cirrus, cirrostratus, and cirrocumulus. *Cirrus* clouds are thin and delicate and sometimes appear as hooked filaments called "mares' tails" (**FIGURE 17.21A**). As the names suggest, *cirrocumulus* clouds consist of fluffy masses (**FIGURE 17.21B**), whereas *cirrostratus* clouds are flat layers (**FIGURE 17.21C**). Because of the low temperatures and small quantities of water vapor present at high altitudes, all high clouds are thin and white and are made up of ice crystals. Furthermore, these clouds are not considered precipitation makers. However, when cirrus clouds are followed by cirrocumulus clouds and increased sky coverage, they may warn of impending stormy weather.

Middle Clouds Clouds that appear in the middle range (2000–6000 meters [6500–20,000 feet]) have the prefix *alto* as part of their name. *Altocumulus* clouds are composed of globular masses that differ from cirrocumulus clouds in that they are larger and denser (**FIGURE 17.21D**). *Altostratus* clouds create a uniform white to grayish sheet covering the sky, with the Sun or Moon visible as a bright spot (**FIGURE 17.21E**). 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. *Stratus* are a uniform foglike layer of clouds that frequently covers much of the sky. On occasion these clouds may produce light precipitation. When stratus clouds develop a scalloped bottom that appears as long parallel rolls or broken globular patches, they are called *stratocumulus* clouds.

Nimbostratus clouds derive their name from the Latin *nimbus*, which means "rainy cloud," and *stratus*, which means "to cover with a layer" (**FIGURE 17.21F**). As the name suggests, nimbostratus clouds are some of the chief precipitation producers. Nimbostratus clouds form in association with stable conditions. We might not expect clouds to grow or persist in stable air, but cloud growth of this type is common when air is forced to rise, as occurs along a mountain range, along a front, or near the center of a cyclone, where converging winds cause air to ascend. Such forced ascent of stable air leads to the formation of a stratified cloud layer that is large horizontally compared to its depth.

Clouds of Vertical Development Some clouds do not fit into any one of the three height categories just mentioned. Such clouds have their bases in the low height range but often extend upward into the middle or high altitudes. Consequently, clouds in this category are called **clouds of vertical development**. They are all related to one another and are associated with unstable air. Although *cumulus* clouds are often connected with fair weather (**FIGURE 17.21G**), they may grow dramatically under the proper circumstances. Once

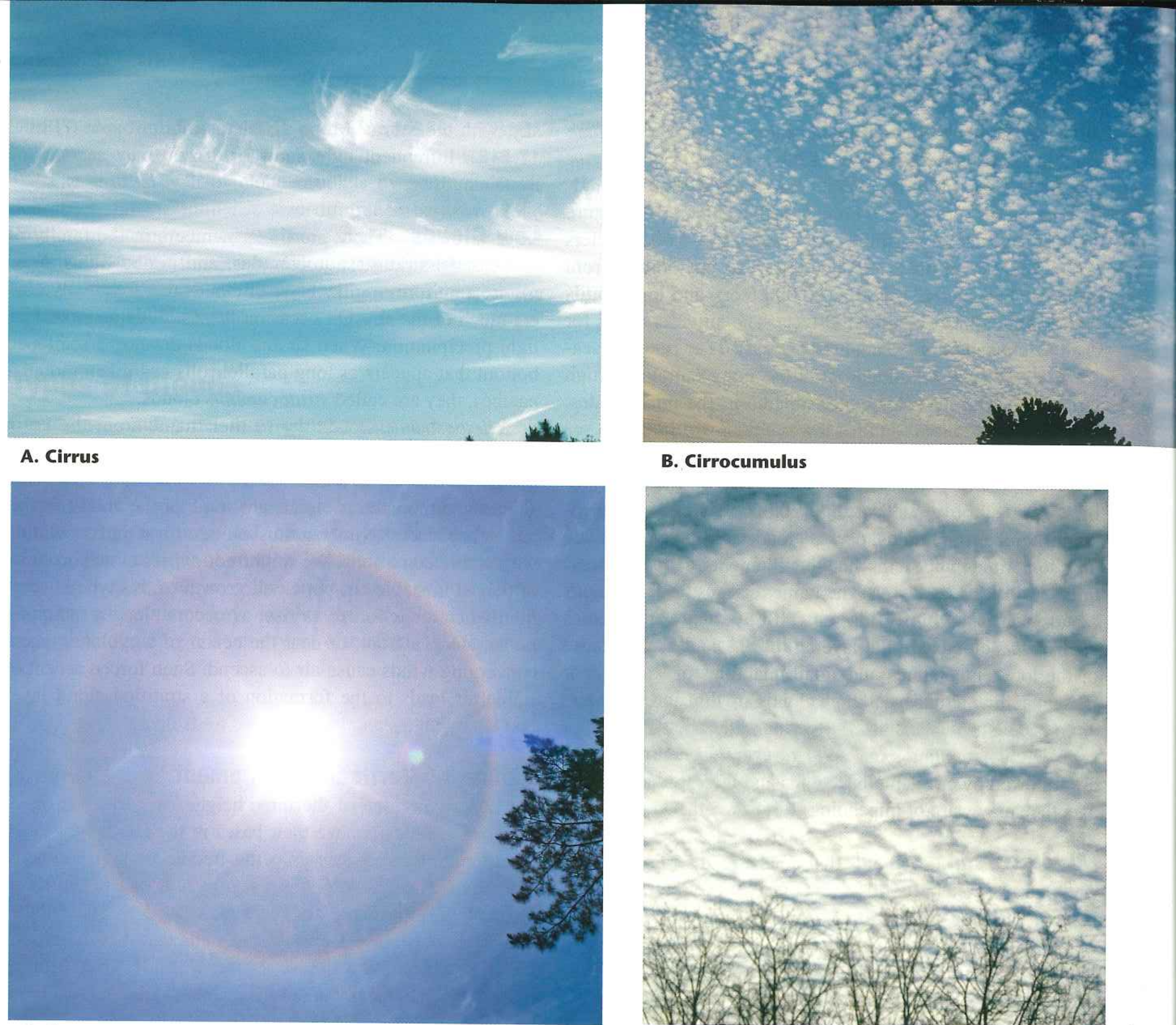
EYE ON EARTH

The cloud perched on the top of this volcano is called a *cap cloud*, and it may remain in place for hours. Cap clouds belong to a group of clouds called *orographic clouds*. (Photo by amana images inc./Alamy)

QUESTION 1 *Describe how cap clouds form, based on the fact that they are referred to as orographic clouds.*

QUESTION 2 *Explain why this group of clouds have relatively flat bases.*

QUESTION 3 *Cap clouds are related to another cloud type that has a very similar shape and form in mountainous regions. Do an internet search to find the name of the related cloud type.*



A. Cirrus

B. Cirrocumulus

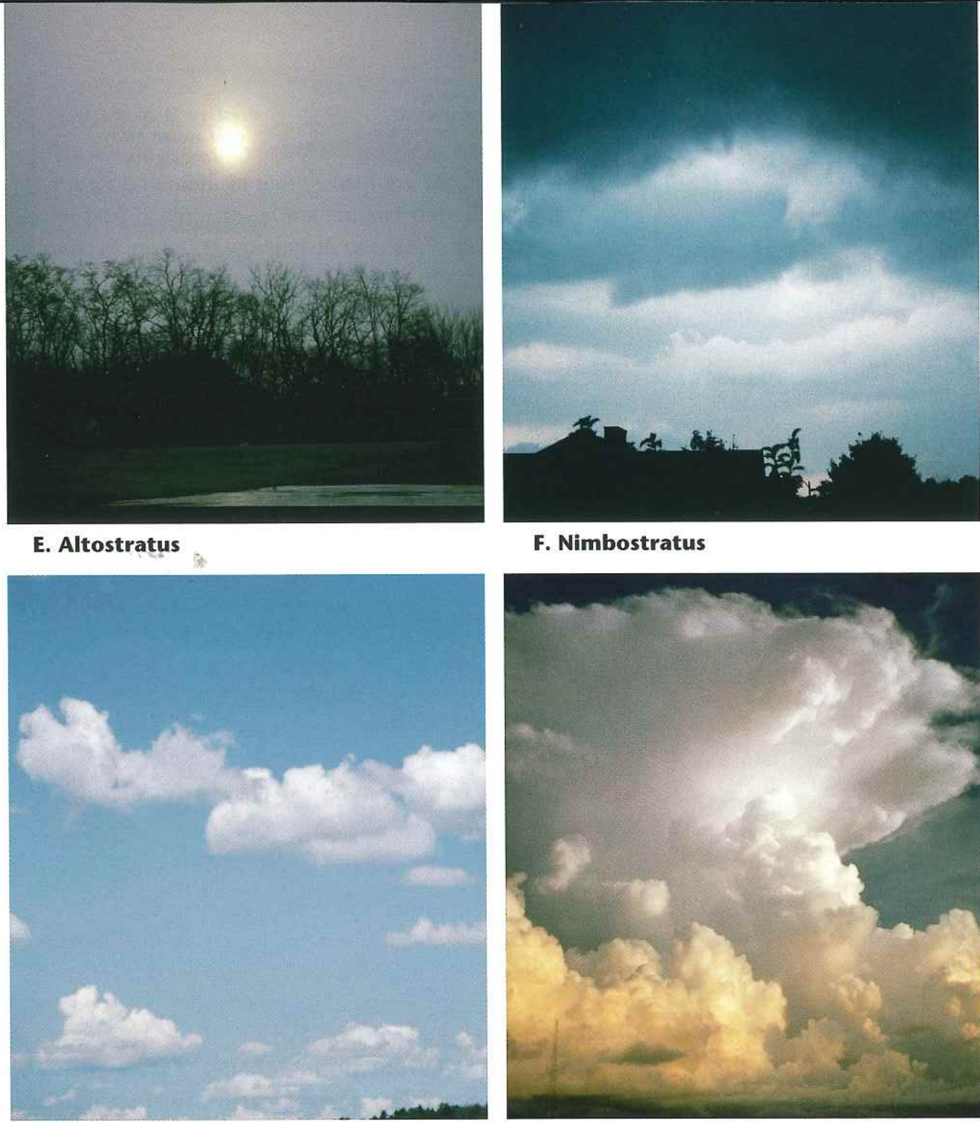
C. Cirrostratus

D. Altocumulus

FIGURE 17.21 Common Forms of Several Different Cloud Types (Photos A, B, D, E, F, and G by E. J. Tarbuck; photo C by Jung-Pang Wu/Getty Images Inc; photo H by Doug Millar/Science Source)

TABLE 17.2 Cloud Types and Characteristics

Cloud Family and Height	Cloud Type	Characteristics
High clouds: above 6000 meters (20,000 feet)	Cirrus	Thin, delicate, fibrous, ice-crystal clouds. Sometimes appear as hooked filaments called "mares' tails" (see Figure 17.21A).
	Cirrocumulus	Thin, white, ice-crystal clouds in the form of ripples, waves, or globular masses, all in a row. May produce a "mackerel sky." Least common of the high clouds (see Figure 17.21B).
	Cirrostratus	Thin sheet of white, ice-crystal clouds that may give the sky a milky look. Sometimes produce halos around the Sun or Moon (see Figure 17.21C).
Middle clouds: 2000–6000 meters (6500–20,000 feet)	Altocumulus	White to gray clouds often composed of separate globules; "sheep-back" clouds (see Figure 17.21D).
	Altostratus	Stratified veil of clouds that are generally thin and may produce very light precipitation. When thin, the Sun or Moon may be visible as a bright spot, but no halos are produced (see Figure 17.21E).
Low clouds: below 2000 meters (6500 feet)	Stratocumulus	Soft gray clouds in globular patches or rolls. Rolls may join together to make a continuous cloud.
	Stratus	Low uniform layer resembling fog but not resting on the ground. May produce drizzle.
	Nimbostratus	Amorphous layer of dark gray clouds. Some of the chief precipitation-producing clouds (see Figure 17.21F).
Clouds of vertical development: 500–18,000 meters (1600–60,000 feet)	Cumulus	Dense, billowy clouds, often characterized by flat bases. May occur as isolated clouds or closely packed (see Figure 17.21G).
	Cumulonimbus	Towering cloud sometimes spreading out on top to form an "anvil head." Associated with heavy rainfall, thunder, lightning, hail, and tornadoes (see Figure 17.21H).



E. Altostratus

F. Nimbostratus

G. Cumulus

H. Cumulonimbus

FIGURE 17.21 Common Forms of Several Different Cloud Types (continued)

upward movement is triggered, acceleration is powerful, and clouds with great vertical extent form. The end result is often a towering cloud, called a *cumulonimbus*, that usually produces rain showers or a thunderstorm (**FIGURE 17.21H**).

Definite weather patterns can often be associated with particular clouds or certain combinations of cloud types, so it is important to become familiar with cloud descriptions and characteristics. **TABLE 17.2** lists the 10 basic cloud types that are recognized internationally and gives some characteristics of each.

17.6 CONCEPT CHECKS

1. As you drink an ice-cold beverage on a warm, humid day, the outside of the glass or bottle becomes wet. Explain.
2. What is the function of condensation nuclei in cloud formation?
3. What is the basis for the classification of clouds?
4. Why are high clouds always thin?
5. Which cloud types are associated with the following characteristics: thunder, halos, precipitation, hail, lightning, mares' tails?

17.7 FOG

Define *fog* and explain how the various types of fog form.

Fog is generally considered to be an atmospheric hazard. When it is light, visibility is reduced to 2 or 3 kilometers (1 or 2 miles). However, when it is dense, visibility may be cut to a few dozen meters or less, making travel by any mode not only difficult but often dangerous. Officially, visibility must be reduced to 1 kilometer (0.6 mile) or less before fog is reported. While this figure is arbitrary, it does provide an objective criterion for comparing fog frequencies at different locations.

Fog is defined as *a cloud with its base at or very near the ground.* There is no basic physical difference between fog and a cloud; their appearance and structure are the same. The essential difference has to do with the method and place of formation. Whereas clouds result when air rises and cools adiabatically, most fogs result from radiation cooling or the movement of air over a cold surface. (The exception is upslope fog.) In other circumstances, fogs form when enough water vapor is added to the air to bring about saturation (evaporation fogs). We examine both of these types.

FIGURE 17.22 Advection Fog Rolling into San Francisco Bay Advection fog in coastal areas often occurs when warm, moist air flows over the cold waters of an ocean current and is cooled below its dew-point temperature. (Photo by Ed Pritchard/Getty Images)

A.

B.

FIGURE 17.23 Radiation Fog **A.** Satellite image of dense fog in California's San Joaquin Valley on November 20, 2002. This early morning fog was caused by radiation cooling that occurred on a clear, cool evening. It was responsible for several accidents in the region, including a 14-car pileup. The white areas to the east of the fog are the snowcapped Sierra Nevada. (Photo by NASA) **B.** Radiation fog can make the morning commute hazardous. (Photo by Tim Gainey/Alamy)

Fogs Caused by Cooling

Three common fogs form when air at Earth's surface is chilled below its dew point. Often a fog is a combination of these types.

Advection Fog When warm, moist air moves over a cool surface, the result might be a blanket of fog called **advection fog** (**FIGURE 17.22**). Examples of such fogs are very common. The foggiest location in the United States, and perhaps in the world, is Cape Disappointment, Washington. The name is indeed appropriate because this station averages 2552 hours of fog each year (there are about 8760 hours in a year). The fog experienced at Cape Disappointment, and at other West Coast locations, is produced when warm, moist air from the Pacific Ocean moves over the cold California Current and is then carried onshore by the prevailing winds. Advection fogs are also relatively common in the winter season, when warm air from the Gulf of Mexico moves across cold, often snow-covered surfaces of the Midwest and East.

Radiation Fog **Radiation fog** forms 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 and becomes denser, it drains into low areas, resulting in "pockets" of fog. The largest pockets are often river valleys, where thick accumulations may occur (**FIGURE 17.23**).

Radiation fog may also form when the skies clear after a rainfall. In these situations, the air near the surface is close to saturation, and only a small amount of radiation cooling is needed to promote condensation. Radiation fog of this type often occurs around sunset, and it can make driving hazardous.

Upslope Fog As its name implies, **upslope fog** is created when relatively humid air moves up a gradually sloping plain or up the steep slopes of a mountain. As a result of this upward movement, air expands and cools adiabatically. If the dew point is reached, an extensive layer of fog may form. In the United States, the Great Plains offers an excellent example. When humid easterly or southeasterly winds blow westward from the Mississippi River upslope toward the Rocky Mountains, the air gradually rises, resulting in an adiabatic temperature decrease of about 13°C. When the difference between the air temperature and dew point of westward-moving air is less than 13°C, an extensive fog can result in the western plains.

FIGURE 17.24 Steam Fog Rising from Sierra Lake, Blanca, Arizona (Photo by Michael Collier)

Evaporation Fogs

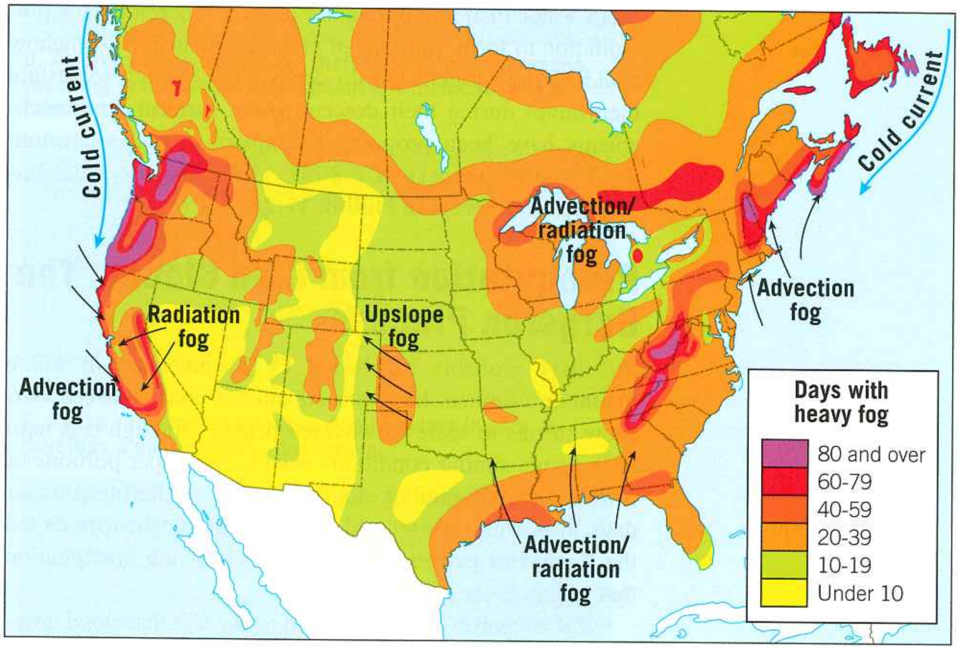
When the saturation of air occurs primarily because of the addition of water vapor, the resulting fogs are called *evaporation fogs*. Two types of evaporation fogs are recognized: steam fog and frontal, or precipitation, fog.

Steam Fog 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 re-condenses and rises with the air that is being warmed from below. Because the water has a steaming appearance, the phenomenon is called **steam fog**. Steam fog 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 (**FIGURE 17.24**). Steam fog is often shallow because as the steam rises, it evaporates in the unsaturated air above.

Frontal Fog When frontal wedging occurs, warm air is lifted over colder air. If the resulting clouds yield rain, and the cold air below is near the dew point, enough rain will evaporate to produce fog. A fog formed in this manner is called **frontal fog**, or **precipitation fog**. The result is a more-or-less continuous zone of condensed water droplets reaching from the ground up through the clouds.

Both steam fog and frontal fog result from the addition of moisture to a layer of air. The air is usually cool or cold and already near saturation. Because air's capacity for water vapor at low temperatures is small, only a relatively modest amount of evaporation is necessary to produce saturated conditions and fog.

The frequency of dense fog varies considerably from place to place (**FIGURE 17.25**). As might be expected, fog incidence is highest in coastal areas, especially where cold currents prevail, as along the Pacific and New England coasts. Relatively high frequencies are also found in the Great Lakes region and in the humid Appalachian Mountains of the East. By contrast, fogs are rare in the interior of the continent, especially in the arid and semiarid areas of the West.



SmartFigure 17.25 Map Showing the Average Number of Days per Year with Heavy Fog Notice that the frequency of dense fog varies considerably from place to place. Coastal areas, particularly the Pacific Northwest and New England, where cold currents prevail, have high occurrences of dense fog.

17.7 CONCEPT CHECKS

1 Define *fog*.
2 List five main types of fog and describe how each type forms.

17.8 HOW PRECIPITATION FORMS

Describe the two mechanisms that produce precipitation.

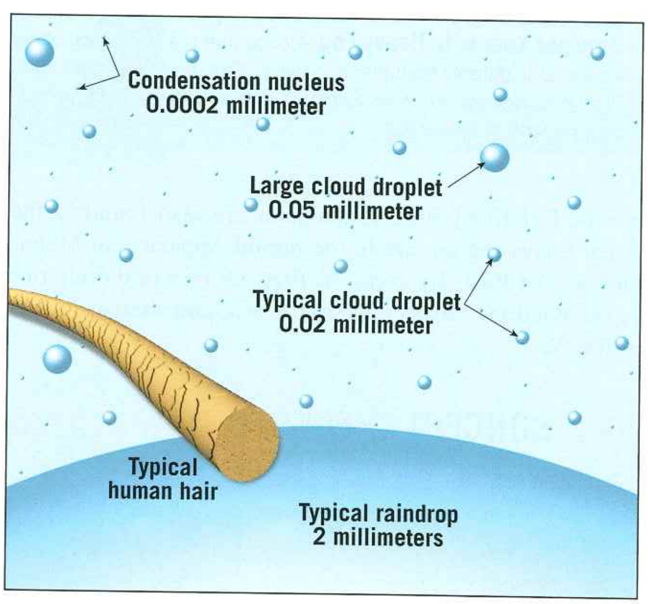
All clouds contain water. But why do some clouds produce precipitation while others drift placidly overhead? This simple question perplexed meteorologists for many years. First, cloud droplets are very small, averaging less than 10 micrometers in diameter; for comparison, a human hair is about 75 micrometers in diameter (**FIGURE 17.26**). Because of their small size, cloud droplets fall incredibly slowly. In addition, clouds are made up of many billions of these droplets, all competing for the available water vapor; thus, their continued growth via condensation is extremely slow. So, what causes precipitation?

A raindrop large enough to reach the ground without completely evaporating contains roughly 1 million times more water than a single cloud droplet. Therefore, for precipitation to form, millions of cloud droplets must somehow coalesce (join together) into drops large enough to sustain themselves during their descent to the surface. Two mechanisms have been proposed to explain this phenomenon: the *Bergeron process* in **FIGURE 17.27** and the *collision-coalescence process* in **FIGURE 17.28**.

Precipitation from Cold Clouds: The Bergeron Process

You have probably watched a TV documentary in which mountain climbers have braved intense cold and ferocious snow storms to scale ice-covered peaks. Although it is hard to imagine, similar conditions exist in the upper portions of towering cumulonimbus clouds, even on sweltering summer days. It is within these cold clouds that a mechanism called the **Bergeron process** generates much of the precipitation that occurs in the middle latitudes.

The Bergeron process is based on the fact that cloud droplets remain liquid at temperatures as low as –40°C (–40°F).



IGURE 17.26 omparative Diameters f Particles Involved Condensation and recipitation Processes

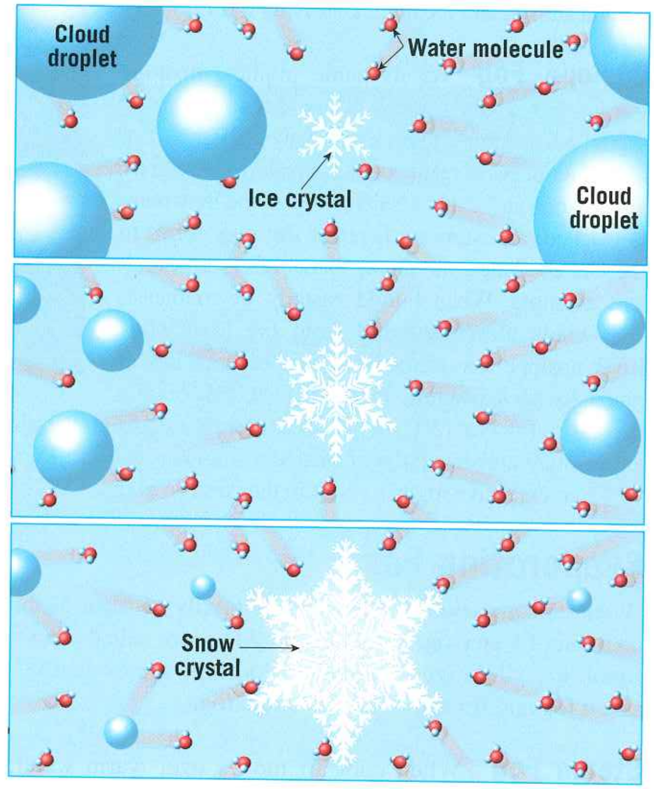


FIGURE 17.27 The Bergeron Process Ice crystals grow at the expense of cloud droplets until they are large enough to fall. The size of these particles has been greatly exaggerated.

Liquid water at temperatures below freezing is referred to as **supercooled**, and it becomes solid, or freezes, upon impact with objects. This explains why airplanes collect ice when they pass through a cloud composed of subzero droplets, a condition called *icing*. Supercooled water droplets also freeze upon contact with particles in the atmosphere known as **freezing nuclei**. Because freezing nuclei are relatively sparse, cold clouds primarily consist of supercooled droplets intermixed with a lesser amount of ice crystals.

When ice crystals and supercooled water droplets coexist in a cloud, the conditions are ideal for generating precipitation. Because ice crystals have a greater affinity for water vapor than does liquid water, they collect the available water vapor at a much faster rate. In turn, the water droplets evaporate to replenish the diminishing water vapor, thereby providing a continual source of moisture for the growth of ice crystals. As shown in Figure 17.27, the result is that ice crystals grow larger, at the expense of the water droplets, which shrink in size.

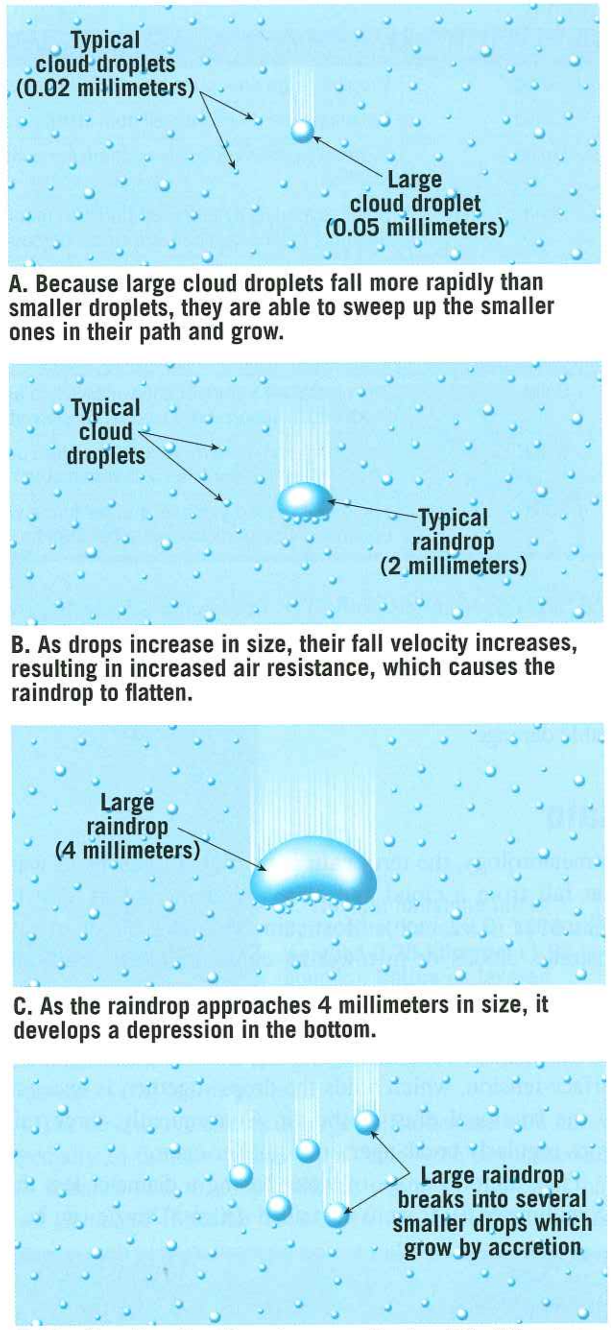
Eventually, this process generates ice crystals large enough to fall as snowflakes. During their descent, these ice crystals become larger as they intercept supercooled cloud droplets that freeze on them. When the surface temperature is about 4°C (39°F) or higher, snowflakes usually melt before they reach the ground and continue their descent as rain.

Precipitation from Warm Clouds: The Collision–Coalescence Process

A few decades ago, meteorologists believed that the Bergeron process was responsible for the formation of most precipitation. However, it was discovered that copious rainfall may be produced within clouds located well below the freezing level (*warm clouds*), particularly in the tropics. This led to the proposal of a second mechanism thought to produce precipitation—the **collision–coalescence process**.

Research has shown that clouds composed entirely of liquid droplets must contain some droplets larger than 20 micrometers (0.02 millimeters) for precipitation to form. These large droplets usually form when *hygroscopic particles* (particles that attract water), such as sea salt, are abundant in the atmosphere. Hygroscopic particles begin to remove water vapor from the air when the relative humidity is under 100 percent, and the cloud droplets that form on them can grow quite large. Because the rate at which drops fall is size dependent, these "giant" droplets fall most rapidly. As they plummet, they collide with smaller, slower droplets (see Figure 17.28). After many such collisions, these droplets may grow large enough to fall to the surface without evaporating. Updrafts also aid this process because they cause the droplets to traverse the cloud repeatedly.

Raindrops can grow to a maximum size of 5 millimeters, at which point they fall at a rate of 33 kilometers (20 miles) per hour. At this size and speed, the water's surface tension, which holds the drop together, is overcome by the drag imposed by the air, causing the drops to break apart. The resulting breakup of a large raindrop produces numerous smaller drops that begin anew the task of sweeping up cloud droplets. Drops that are less than 0.5 millimeter (0.02 inch) upon reaching the ground are termed *drizzle* and require about 10 minutes to fall from a cloud 1000 meters (3300 feet) overhead.



A. Because large cloud droplets fall more rapidly than smaller droplets, they are able to sweep up the smaller ones in their path and grow.

B. As drops increase in size, their fall velocity increases, resulting in increased air resistance, which causes the raindrop to flatten.

C. As the raindrop approaches 4 millimeters in size, it develops a depression in the bottom.

D. Finally, when the diameter exceeds about 5 millimeters, the depression grows upward almost explosively, forming a donut-like ring of water that immediately breaks into smaller drops.

FIGURE 17.28 The Collision–Coalescence Process Most cloud droplets are so small that the motion of the air keeps them suspended. The drops are not drawn to scale; a typical raindrop has a volume equal to roughly 1 million cloud droplets.

17.8 CONCEPT CHECKS

1. What is the difference between precipitation and condensation?
2. Describe the Bergeron process in your own words.
3. What conditions favor the collision–coalescence process?

17.9 FORMS OF PRECIPITATION

List the different types of precipitation and explain how each type forms.

Much of the world's precipitation begins as snow crystals or other solid forms, such as hail or graupel (**TABLE 17.3**). Entering the warmer air below the cloud, these ice particles often melt and reach the ground as raindrops. In some parts of the world, particularly the subtropics, precipitation often forms in clouds that are warmer than 0°C (32°F). These rains frequently occur over the ocean, where cloud condensation nuclei are not plentiful and those that exist vary in size. Under such conditions, cloud droplets can grow rapidly by the collision–coalescence process to produce copious amounts of rain.

Because atmospheric conditions vary greatly from place to place as well as seasonally, several different forms of precipitation are possible. Rain and snow are the most common and familiar, but the other forms of precipitation listed in Table

TABLE 17.3 **Forms of Precipitation**

Type	Appropriate Size	State of Matter	Description
Mist	0.005–0.05 mm	Liquid	Droplets large enough to be felt on the face when air is moving 1 meter/second. Associated with stratus clouds.
Drizzle	0.05–0.5 mm	Liquid	Small uniform drops that fall from stratus clouds, generally for several hours.
Rain	0.5–5 mm	Liquid	Generally produced by nimbostratus or cumulonimbus clouds. When heavy, it can show high variability from one place to another.
Sleet	0.5–5 mm	Solid	Small, spherical to lumpy ice particles that form when raindrops freeze while falling through a layer of subfreezing air. Because the ice particles are small, damage, if any, is generally minor. Sleet can make travel hazardous.
Glaze	Layers 1 mm–2 cm thick	Solid	Produced when supercooled raindrops freeze on contact with solid objects. Glaze can form a thick coating of ice having sufficient weight to seriously damage trees and power lines.
Rime	Variable accumulations	Solid	Deposits usually consisting of ice feathers that point into the wind. These delicate, frostlike accumulations form as supercooled cloud or fog droplets encounter objects and freeze on contact.
Snow	1 mm–2 cm	Solid	The crystalline nature of snow allows it to assume many shapes, including six-sided crystals, plates, and needles. Produced in supercooled clouds, where water vapor is deposited as ice crystals that remain frozen during their descent.
Hail	5 mm–10 cm or larger	Solid	Precipitation in the form of hard, rounded pellets or irregular lumps of ice. Produced in large cumulonimbus clouds, where frozen ice particles and supercooled water coexist.
Graupel	2–5 mm	Solid	Sometimes called soft hail, graupel forms when rime collects on snow crystals to produce irregular masses of "soft" ice. Because these particles are softer than hailstones, they normally flatten out upon impact.

17.3 are important as well. The occurrence of sleet, glaze, or hail is often associated with important weather events. Although limited in occurrence and sporadic in both time and space, these forms, especially glaze and hail, can cause considerable damage.

Rain

In meteorology, the term **rain** is restricted to drops of water that fall from a cloud and have a diameter of at least 0.5 millimeter (0.02 inch). Most rain originates either in nimbostratus clouds or in towering cumulonimbus clouds that are capable of producing unusually heavy rainfalls known as *cloudbursts*. Raindrops rarely exceed about 5 millimeters (0.2 inch) in diameter. Larger drops do not survive because surface tension, which holds the drops together, is exceeded by the frictional drag of the air. Consequently, large raindrops regularly break apart into smaller ones.

Fine, uniform drops of water having a diameter less than 0.5 millimeter (0.02 inch) are called *drizzle*. Drizzle can be so fine that the tiny drops appear to float, and their impact is almost imperceptible. Drizzle and small raindrops generally are produced in stratus or nimbostratus clouds, where precipitation can be continuous for several hours or, on rare occasions, for days.

GURE 17.29 Glaze rms When Supercooled aindrops Freeze on ontact with Objects In nuary 1998, an ice storm historic proportions caused ormous damage in New gland and southeastern nada. Nearly 5 days of ezing rain (glaze) left lions without electricity—me for as long as a month. oto by Dick Blume/Syracuse wspapers/The Image Works)

Snow

Snow is precipitation in the form of ice crystals (snowflakes) or, more often, aggregates of crystals. The size, shape, and concentration of snowflakes depend to a great extent on the temperature at which they form.

Recall that at very low temperatures, the moisture content of air is small. The result is the formation of very light, fluffy snow made up of individual six-sided ice crystals. This is the "powder" that downhill skiers talk so much about. By contrast, at temperatures warmer than about −5°C (23°F), the ice crystals join together into larger clumps consisting of tangled aggregates of crystals. Snowfalls composed of these composite snowflakes are generally heavy and have a high moisture content, which makes them ideal for making snowballs.

Sleet and Glaze

Sleet is a wintertime phenomenon and refers to the fall of small particles of ice that are clear to translucent. For sleet to be produced, a layer of air with temperatures above freezing must overlie a subfreezing layer near the ground. When raindrops, which are often melted snow, leave the warmer air and encounter the colder air below, they freeze and reach the ground as small pellets of ice the size of the raindrops from which they formed.

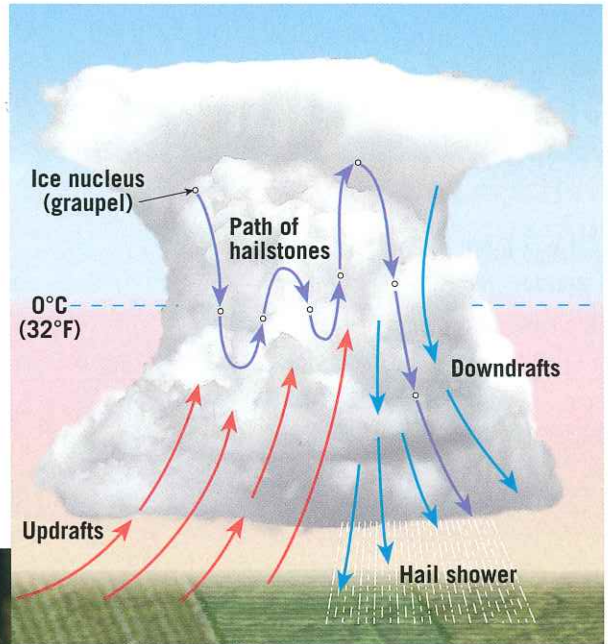
On some occasions, when the vertical distribution of temperatures is similar to that associated with the formation of sleet, **glaze** (**freezing rain**) results instead. In such situations, the subfreezing air near the ground is not thick enough to allow the raindrops to freeze. The raindrops, however, do become supercooled as they fall through the cold air and turn to ice upon colliding with solid objects. The result can be a thick coating of ice having sufficient weight to break tree limbs, down power lines, and make walking or driving extremely hazardous (**FIGURE 17.29**).

Hail

Hail is precipitation in the form of hard, rounded pellets or irregular lumps of ice. Moreover, large hailstones often consist of a series of nearly concentric shells of differing densities and degrees of opaqueness (**FIGURE 17.30**). Most hailstones have diameters between 1 centimeter (0.4 inch, pea size) and 5 centimeters (2 inches, golf ball size), although some can be as big as an orange or larger. Occasionally, hailstones weighing a pound or more have been reported. Many of these were probably composites of several stones frozen together.

Hail is produced only in large cumulonimbus clouds, where updrafts can sometimes reach speeds approaching 160 kilometers (100 miles) per hour and where there is an abundant supply of supercooled water. Hailstones begin as small embryonic ice pellets that grow by collecting supercooled water droplets as they fall through the cloud (see Figure 17.30A). If they encounter a strong updraft, they may be carried upward again and begin the downward journey anew. Each trip through the supercooled portion of the cloud results in an additional layer of ice. Hailstones can also form from a single descent through an updraft. Either way, the process continues until the hailstone encounters a downdraft or grows too heavy to remain suspended by the thunderstorm's updraft.

A. Hailstones begin as small ice pellets that grow by adding supercooled water droplets as they move through a cloud. Strong updrafts may carry stones upward in several cycles, increasing the size of the hail by adding a new layer with each cycle. Eventually, the hailstones encounter a downdraft or grow too large to be supported by the updraft.



B. This cut hailstone fell at Coffeyville, Kansas, in 1970 and weighed 0.75 kilogram (1.67 pounds). Notice its layered structure.

SmartFigure 17.30 Formation of Hailstones (Photo courtesy of University Corporation for Atmospheric Research / Science Source)

The record for the largest hailstone ever found in the United States was set on July 23, 2010, in Vivian, South Dakota. The stone was over 20 centimeters (8 inches) in diameter and weighed nearly 900 grams (2 pounds). The stone that held the previous record of 0.75 kilograms (1.67 pounds) fell in Coffeyville, Kansas, in 1970 (see Figure 17.30B). The diameter of the stone found in South Dakota also surpassed the previous record of a 17.8-centimeter (7-inch) stone that fell in Aurora, Nebraska, in 2003. Even larger hailstones have reportedly been recorded in Bangladesh, where a 1987 hailstorm killed more than 90 people. It is estimated that large hailstones hit the ground at speeds exceeding 160 kilometers (100 miles) per hour.

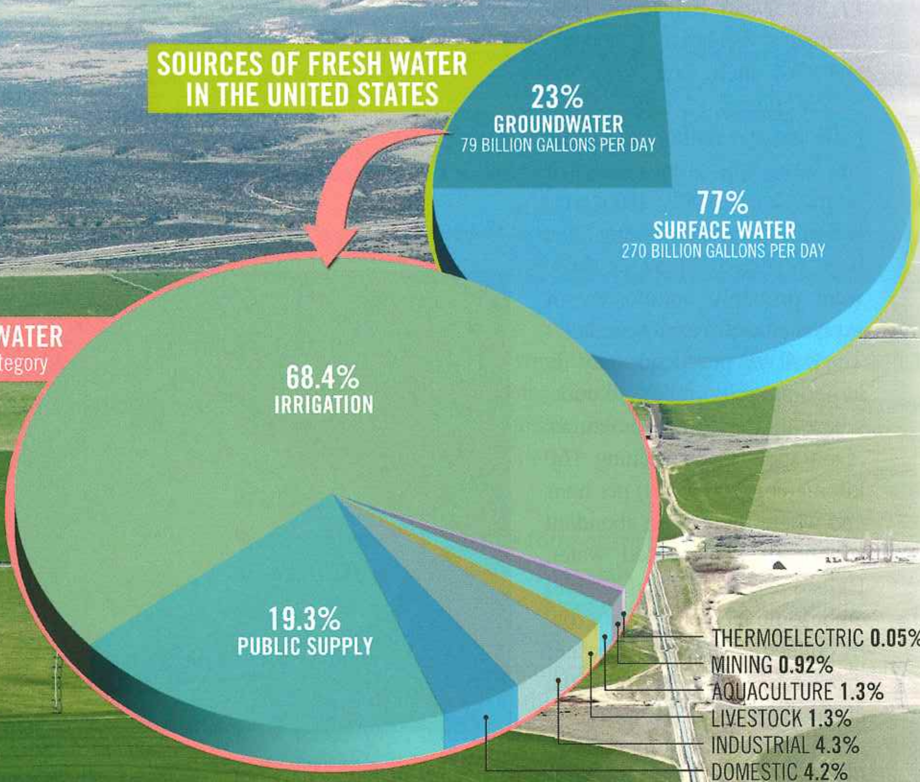
The destructive effects of large hailstones are well known, especially to farmers whose crops have been devastated in a few minutes and to people whose windows and roofs have been damaged (**FIGURE 17.31**). In the United States, hail damage each year costs hundreds of millions of dollars.

FIGURE 17.31 Hail Damage to Auto Hail damage that occured northeast of Denver, Colorado. (Photo by Hyoung Chang/Getty Images)

Our Water Supply

Water is basic to life. It has been called the "bloodstream" of both the biosphere and society. The needs of the world's rapidly growing population are putting Earth's water supply under unprecedented pressure.

FRESH WATER IN THE UNITED STATES

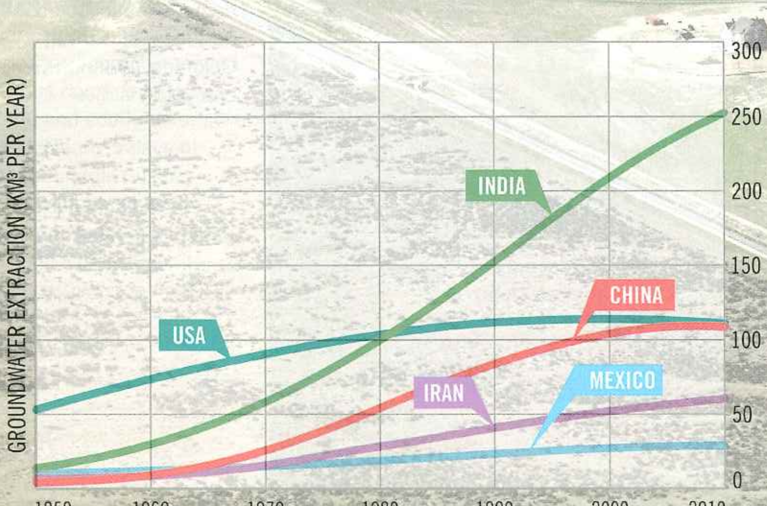


Irrigation is number one

There are nearly 60 million acres (nearly 243,000 square kilometers or about 93,700 square miles) of irrigated land in the United States. That is an area nearly the size of the state of Wyoming. About 42 percent of the water used for irrigation is groundwater.

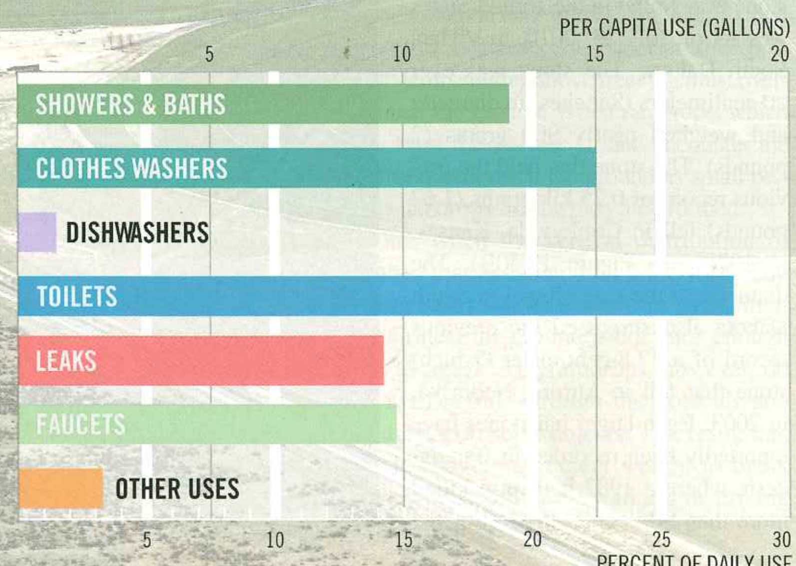
DRILLING DOWN

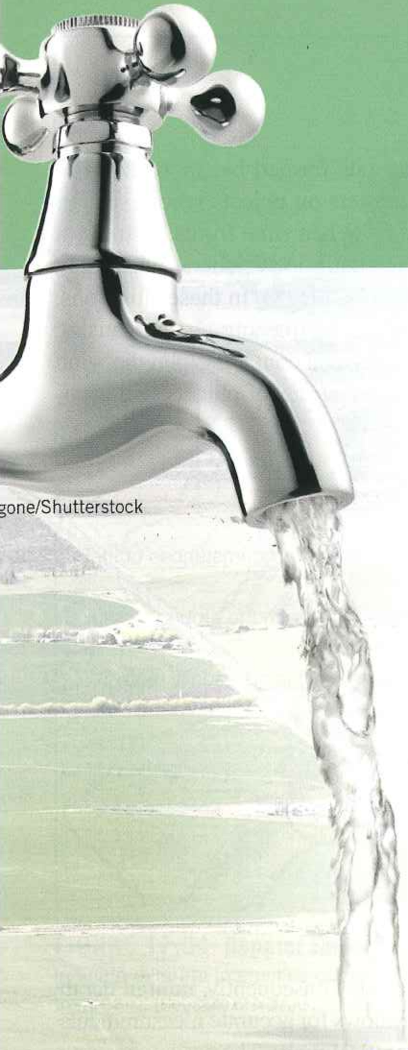
Countries are increasingly meeting demand by withdrawing groundwater from nonrenewable sources. Groundwater withdrawal worldwide tripled between 1950 and 2010 according to the United Nations. India has had the largest growth and accounts for about one-quarter of the total.



THE WATER WE USE EACH DAY

According to the American Water Works Association, daily indoor per capita use in an average single family home is nearly 70 gallons.

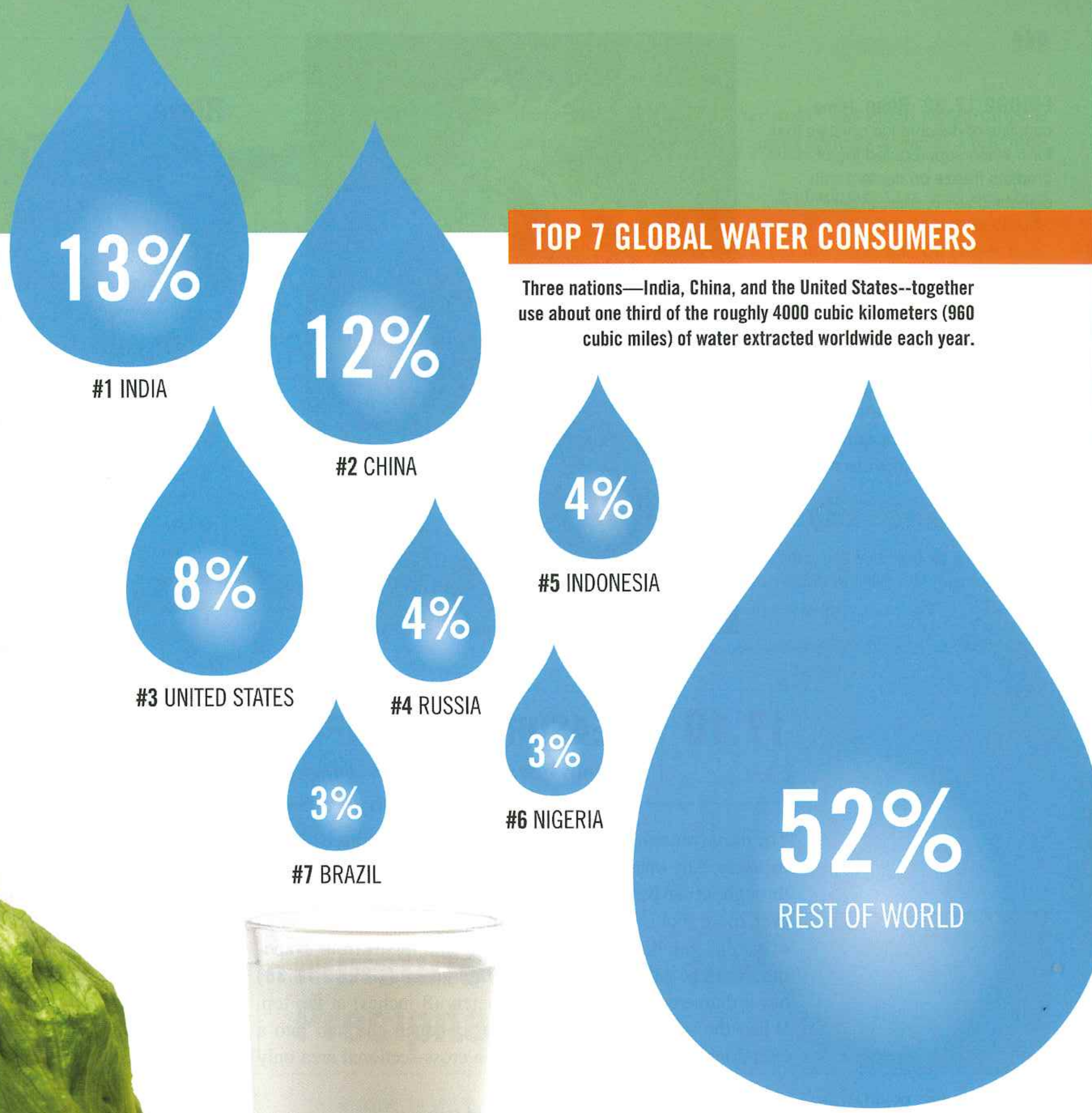




gone/Shutterstock

TOP 7 GLOBAL WATER CONSUMERS

Three nations—India, China, and the United States--together use about one third of the roughly 4000 cubic kilometers (960 cubic miles) of water extracted worldwide each year.



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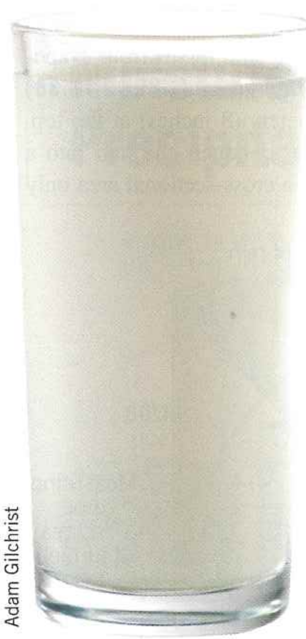


Adam Gilchrist

Dan Peretz/Shutterstock

6 gallons

It takes about 6 gallons of water to grow a single serving of lettuce.

49 gallons

It takes almost 49 gallons of water to produce just one eight ounce glass of milk. That includes the water consumed by the cow and to grow the food she eats, plus water to process the milk.

2,600 gallons

More than 2,600 gallons of water is required to produce a single serving of steak.

FIGURE 17.32 Rime Rime consists of delicate ice crystals that form when supercooled fog or cloud droplets freeze on contact with objects. (Photo by Siepman/Getty Images)

Rime

Rime is a deposit of ice crystals formed by the freezing of supercooled fog or cloud droplets on objects whose surface temperature is below freezing. When rime forms on trees, it adorns them with its characteristic ice feathers, which can be spectacular to behold (**FIGURE 17.32**). In these situations, objects such as pine needles act as freezing nuclei, causing the supercooled droplets to freeze on contact. When the wind is blowing, only the windward surfaces of objects will accumulate the layer of rime.

17.9 CONCEPT CHECKS

1. List the forms of precipitation and the circumstances of their formation.
2. Explain why snow can sometimes reach the ground as rain, but the reverse does not occur.
3. How is sleet different from glaze? Which is usually more hazardous?

17.10 MEASURING PRECIPITATION

Explain how precipitation is measured.

The most common form of precipitation—rain—is the easiest to measure. Any open container having a consistent cross section throughout can be used as a rain gauge. In general practice, however, more sophisticated devices are used so that small amounts of rainfall can be measured accurately and losses from evaporation can be reduced. A *standard rain gauge* (**FIGURE 17.33**) has a diameter of about 20 centimeters (8 inches) at the top. When the water is caught, a funnel conducts the rain into a cylindrical measuring tube that has a cross-sectional area only one-tenth as large as the receiver. Consequently, rainfall depth is magnified 10 times, which allows for accurate measurements to the nearest 0.025 centimeter (0.01 inch). The narrow opening also minimizes evaporation. When the amount of rain is less than 0.025 centimeter, it is reported as a *trace* of precipitation.

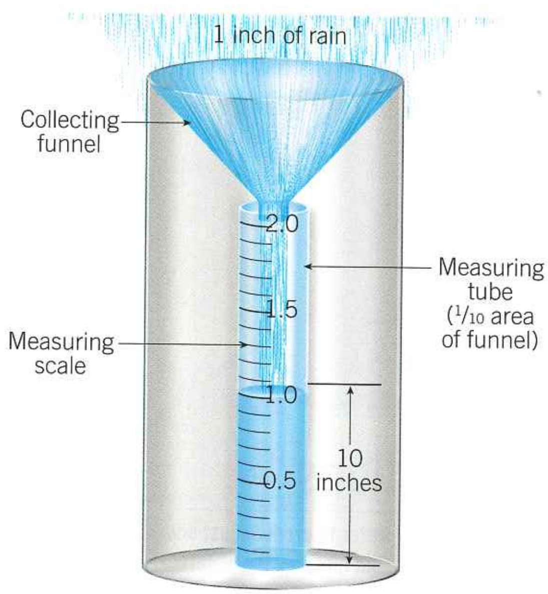


FIGURE 17.33 Precipitation Measurement Using a Standard Rain Gauge A standard rain gauge allows for accurate rainfall measurement to the nearest 0.025 centimeter (0.01 inch). Because the cross-sectional area of the measuring tube is only one-tenth as large as the collector, rainfall is magnified 10 times.

Measuring Snowfall

Snow records are typically kept with two measurements: depth and water equivalent. The depth of snow is usually measured with a calibrated stick. The actual measurement is simple, but choosing a *representative* spot often poses a dilemma. Even when winds are light or moderate, snow drifts freely, making measurement of snowfall difficult. As a rule, it is best to take several measurements in an open place away from trees and obstructions and then average them. To obtain the water equivalent, samples are melted and then weighed or measured as rain.

The quantity of water in a given volume of snow is not constant. A general ratio of 10 units of snow to 1 unit of water is often used when exact information is not available, but the actual water content of snow may deviate widely from this figure. It may take as much as 30 centimeters of light, fluffy dry snow or as little as 4 centimeters of wet snow to produce 1 centimeter of water.

Precipitation Measurement by Weather Radar

Weather forecasts use maps like the one in **FIGURE 17.34** to depict precipitation patterns. The instrument that produces

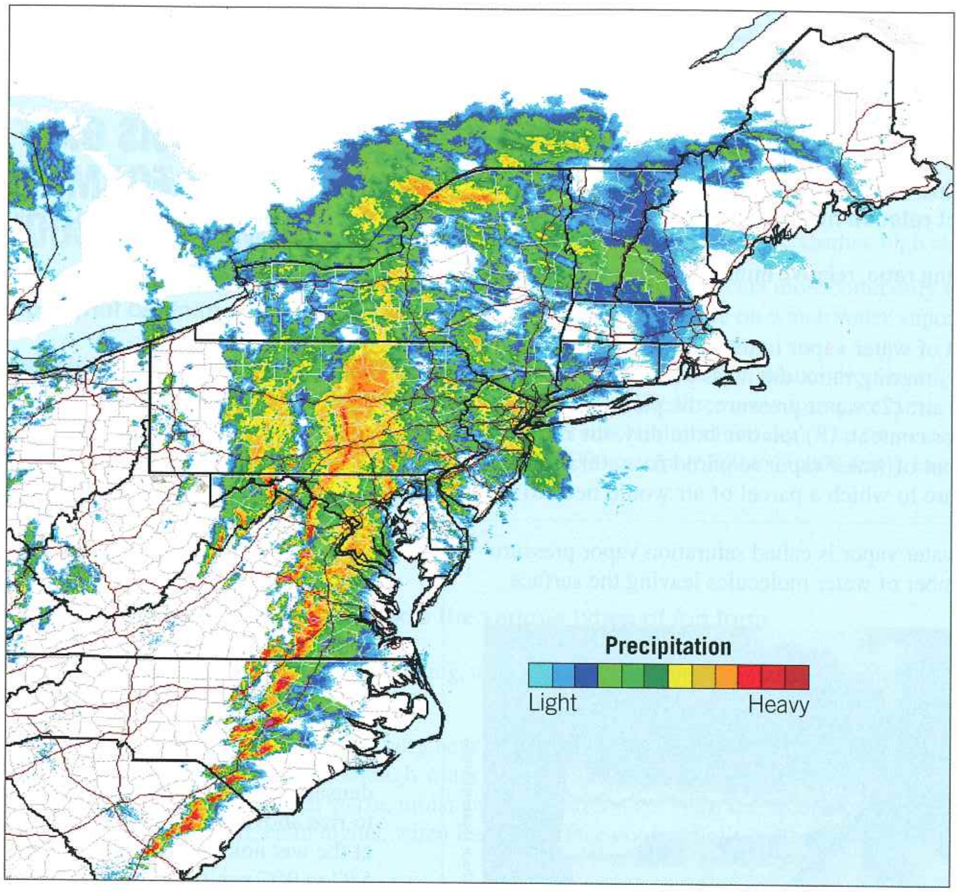


FIGURE 17.34 Doppler Radar Display Produced by the National Weather Service Colors indicate different intensities of precipitation. Note the band of heavy precipitation along the eastern seaboard. (Courtesy of NOAA)

these images, called *weather radar*, has given meteorologists an important tool to probe storm systems as far as a few hundred kilometers away.

Weather radar units have transmitters that send out short pulses of radio waves at wavelengths that can penetrate clouds consisting of small droplets but are reflected by larger raindrops, ice crystals, or hailstones. The reflected signal, called an *echo*, is received and displayed on a monitor. Because the echo is "brighter" when the precipitation is more intense, weather radar is able to depict not only the regional extent of the precipitation but also the rate of rainfall. Figure 17.34 is a typical radar display in which precipitation intensity is shown using colors. Weather radar is also an important tool for determining the rate and direction of storm movement.

17.10 CONCEPT CHECKS

1. Sometimes, when rainfall is light, it is reported as a *trace*. When this occurs, how much (or how little) rain has fallen?
2. Why is rainfall easier to measure than snowfall?

17 CONCEPTS IN REVIEW | Moisture, Clouds, and Precipitation

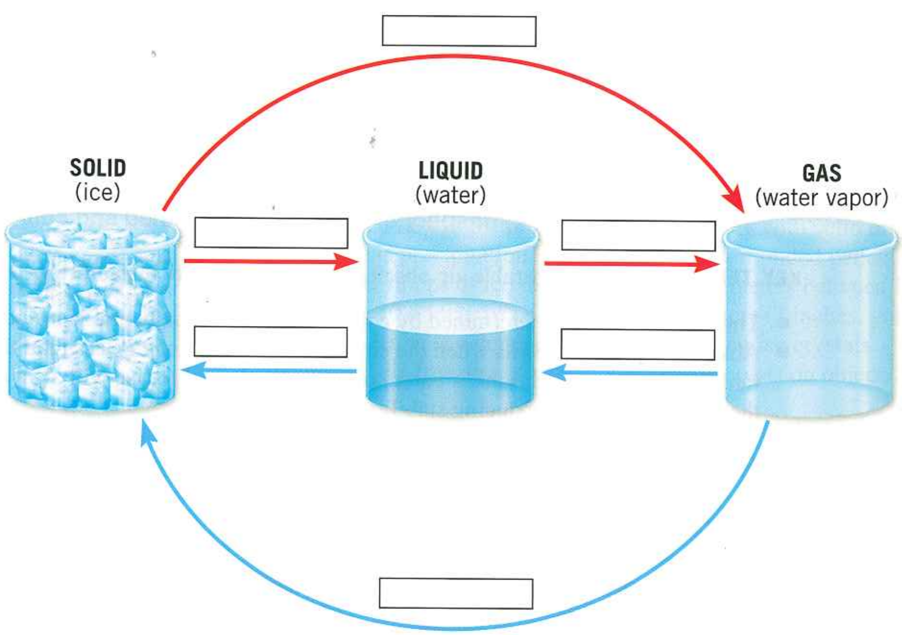
17.1 WATER'S CHANGES OF STATE

List and describe the processes that cause water to change from one state of matter to another. Define *latent heat* and explain why it is important.

KEY TERMS: calorie, latent heat, evaporation, condensation, sublimation, deposition

- Water vapor, an odorless, colorless gas, changes from one state of matter (solid, liquid, or gas) to another at the temperatures and pressures experienced near Earth's surface.
- The processes that result in a change of state are evaporation, condensation, melting, freezing, sublimation, and deposition. Evaporation, melting, and sublimation require heat, whereas condensation, freezing, and deposition result in latent (hidden) heat being released.

Q Label the accompanying diagram with the appropriate terms for the changes of state that are shown.



17.2 HUMIDITY: WATER VAPOR IN THE AIR

Distinguish between relative humidity and dew point. Write a generalization relating how temperature changes affect relative humidity.

KEY TERMS: humidity, saturation, vapor pressure, mixing ratio, relative humidity, dew-point temperature (dew point), hygrometer, psychrometer

- Humidity is a general term to describe the amount of water vapor in the air. The methods used to express humidity quantitatively include (1) mixing ratio, the mass of water vapor in a unit of air compared to the remaining mass of dry air; (2) vapor pressure, the part of the total atmospheric pressure attributable to its water-vapor content; (3) relative humidity, the ratio of the air's actual water-vapor content to the amount of water vapor required for saturation at that temperature; and (4) dew point, the temperature to which a parcel of air would need to be cooled to reach saturation.
- When air is saturated, the pressure exerted by the water vapor is called saturation vapor pressure. At saturation, a balance is reached between the number of water molecules leaving the surface of the water and the number returning. At higher temperatures, more water vapor is required to reach saturation because the saturation vapor pressure is temperature dependent.
- Relative humidity can be changed in two ways: by adding or subtracting water vapor or by changing the air's temperature.

Q Refer to the accompanying photo and explain how the relative humidity inside the house compares to the relative humidity outside the house on this particular day.

Photo by Clynt Garnham Housing/Alamy

17.3 THE BASIS OF CLOUD FORMATION: ADIABATIC COOLING

Explain how adiabatic cooling results in cloud formation.

KEY TERMS: adiabatic temperature change, parcel, dry adiabatic rate, wet adiabatic rate

- Cooling of air as it rises and expands, due to successively lower air pressure, is the basic cloud-forming process. Temperature changes that result when air is compressed or when air expands are called adiabatic temperature changes.
- Unsaturated air warms by compression and cools by expansion at the rather constant rate of 10°C per 1000 meters (5.5°F per 1000 feet) of altitude change, a quantity called the dry adiabatic rate. When air rises high enough, it will cool sufficiently to cause condensation and form clouds. Air that continues to rise above the condensation level will cool at the wet adiabatic rate, which varies from 5°C to 9°C per 1000 meters of ascent. The difference in the wet and dry adiabatic rates results because condensation releases latent heat, thereby reducing the rate at which air cools as it ascends.

17.4 PROCESSES THAT LIFT AIR

List and describe the four mechanisms that cause air to rise.

KEY TERMS: convective lifting, orographic lifting, rain shadow desert, front, frontal wedging, convergence, localized convective lifting

- Four mechanisms that can initiate the vertical movement of air are (1) orographic lifting, which occurs when elevated terrains, such as mountains, act as barriers to the flow of air; (2) frontal wedging, when cool air acts as a barrier over which warmer, less dense air rises; (3) convergence, which happens when air flows together, causing an upward movement of air; and (4) localized convective lifting, caused by unequal surface heating, which results in pockets of air rising because of their lower density (buoyancy).

17.5 THE WEATHERMAKER: ATMOSPHERIC STABILITY

Describe how atmospheric stability is determined and compare conditional instability with absolute instability.

KEY TERMS: stable air, unstable air, absolute stability, absolute instability, conditional instability

- The stability of air is determined by comparing the environmental lapse rate (change in temperature with altitude) to the wet and dry adiabatic rates.
- Absolute stability prevails when the environmental lapse rate is less than the wet adiabatic rate. Under these conditions, a parcel of air that is forced to rise will always be heavier than the surrounding air, producing stability.
- Absolute instability results when the environmental lapse rate is greater than the dry adiabatic rate. Specifically, a column of air exhibits absolute instability when the air near the ground is significantly warmer (less dense) than the air aloft and will rise like a hot-air balloon.
- Conditional instability occurs when moist air has an environmental lapse rate between the dry and wet adiabatic rates. Simply, the air is stable for an unsaturated parcel of air but becomes unstable if the parcel of air is forced high enough for it to become saturated.

Q Describe the atmospheric conditions that were likely associated with the development of the towering cloud shown in the accompanying photo.

Photo by Rolf Nussbaumer/Alamy

17.6 CONDENSATION AND CLOUD FORMATION

List the necessary conditions for condensation and briefly describe the two criteria used for cloud classification.

KEY TERMS: condensation nuclei, hygroscopic nuclei, cloud, cirrus, cumulus, stratus, high clouds, middle clouds, low clouds, clouds of vertical development

- For condensation to occur, air must reach saturation. Saturation occurs most commonly when air is cooled to its dew point, or, less often water, when vapor is added to the air. Condensation normally requires a surface on which water vapor can condense. In cloud and fog formation, tiny particles called condensation nuclei serve this purpose.
- Clouds are a form of condensation described as visible aggregates of minute droplets of water or tiny crystals of ice.
- Clouds are classified on the basis of their form and height. The three basic forms are cirrus (high, white, thin, wispy fibers), cumulus (globular, individual cloud masses), and stratus (sheets or layers that cover much or all of the sky). The four categories based on height are high clouds (bases normally above 6000 meters [20,000 feet]), middle clouds (from 2000 to 6000 meters [6500 to 20,000 feet]), low clouds (below 2000 meters [6500 feet]), and clouds of vertical development.

17.7 FOG

Define *fog* and explain how the various types of fog form.

KEY TERMS: fog, advection fog, radiation fog, upslope fog, steam fog, frontal fog (precipitation fog)

- Fog is a cloud with its base at or very near the ground. Fogs form when air is cooled below its dew point or when enough water vapor is added to the air to cause saturation.
- Advection fog forms when warm, moist air moves over a cool surface. Radiation fog forms on cool, clear, calm nights, when Earth's surface cools rapidly by the process of radiation cooling.
- When air becomes saturated through the addition of water vapor, the resulting fogs are called evaporation fogs. During a gentle rain when the air near Earth's surface is cool and near saturation, enough rain may evaporate to produce fog. A fog formed in this manner is called frontal fog, or precipitation fog.

Q Identify the type of fog shown in the accompanying photo.

(Photo by Pat and Chuck Blackley/Alamy)

17.8 HOW PRECIPITATION FORMS

Describe the two mechanisms that produce precipitation.

KEY TERMS: Bergeron process, supercooled, freezing nuclei, collision–coalescence process

- For precipitation to form, millions of cloud droplets must join together into drops that are large enough to reach the ground before evaporating. Two mechanisms have been proposed to explain this phenomenon: the Bergeron process and the collision–coalescence process.
- The Bergeron process operates in cold clouds where ice crystals and supercooled liquid droplets coexist. The ice crystals, which have a greater affinity for water vapor, grow larger at the expense of supercooled cloud droplets. When the ice crystals grow large enough, they reach the ground as snowflakes in winter, whereas in the summer they melt to form rain.
- The collision–coalescence process operates in warm clouds that contain large hygroscopic (water-seeking) nuclei, such as salt particles. The hydroscopic particles form large droplets, which collide and join with smaller water droplets as they descend. After many collisions, the droplets grow large enough so as not to evaporate before they reach the ground.

17.9 FORMS OF PRECIPITATION

List the different types of precipitation and explain how each type forms.

KEY TERMS: rain, snow, sleet, glaze (freezing rain), hail, rime

- The forms of precipitation include rain, snow, sleet, glaze, hail, and rime. The term rain is restricted to drops of water that fall from a cloud and have a diameter of at least 0.5 millimeter (0.02 inch). Snow is precipitation in the form of ice crystals (snowflakes) or, more often, aggregates of crystals. Sleet is a wintertime phenomenon and refers to the fall of small particles of ice that are clear to translucent, while glaze forms when supercooled raindrops turn to ice upon colliding with solid objects. Hail is precipitation in the form of hard, rounded pellets or irregular lumps of ice that usually have diameters between 1 centimeter (0.4 inch, pea size) and 5 centimeters (2 inches, golf ball size). Rime is a deposit of feathery-looking ice crystals formed by the freezing of supercooled fog droplets on objects.

17.10 MEASURING PRECIPITATION

Explain how precipitation is measured.

- Any open container having a consistent cross section throughout can be used as a rain gauge.
- Weather radar units have transmitters that emit short pulses of radio waves at wavelengths that can penetrate clouds consisting of small cloud droplets but are reflected by larger raindrops, ice crystals, or hailstones. Because the echo is "brighter" when the precipitation is more intense, weather radar is able to depict not only the regional extent of the precipitation but also the rate of rainfall.

GIVE IT SOME THOUGHT

1. Refer to Figure 17.2 to complete the following:
   a. In which state of matter is water densest?
   b. In which state of matter are water molecules most energetic?
   c. In which state of matter is water compressible?
2. The accompanying photo shows a cup of hot coffee. What state of matter is the "steam" rising from the liquid? Explain your answer.

Photo by Dmitry Kolmakov/Shutterstock

3. The primary mechanism by which the human body cools itself is perspiration.
   a. Explain how perspiring cools the skin.
   b. Refer to the data for Phoenix, Arizona, and Tampa, Florida, in Table A.
   c. In which city would it be easier to stay cool by perspiring? Explain your choice.

Table A

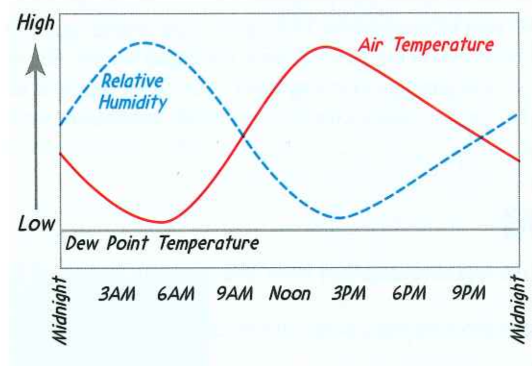
City	Temperature	Dew-Point Temperature
Phoenix, AZ	101°F	47°F
Tampa, FL	101°F	77°F

4. During hot summer weather, many people put "koozies" around their beverages to keep the drinks cold. In addition to preventing a warm hand from heating the container through conduction, what other mechanisms slow the process of warming beverages?
5. Refer to Table 17.1 to answer this question. How much more water is contained in saturated air at a tropical location with a temperature of 40°C compared to a polar location with a temperature of −10°C?
6. Refer to the data for Phoenix, Arizona, and Bismarck, North Dakota, in Table B, to complete the following:
   a. Which city has a higher relative humidity?
   b. Which city has the greatest quantity of water vapor in the air?
   c. In which city is the air closest to its saturation point with respect to water vapor?
   d. In which city does the air require the most water vapor in order to reach saturation?

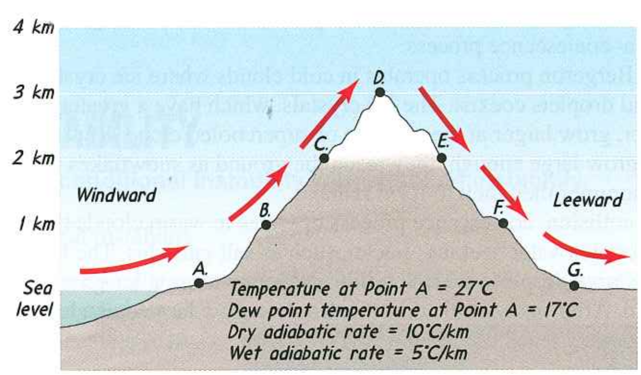
Table B

City	Temperature	Dew-Point Temperature
Phoenix, AZ	101°F	47°F
Bismarck, ND	39°F	38°F

7. The accompanying graph shows how air temperature and relative humidity change on a typical summer day in the Midwest. Assuming that the dew-point temperature remained constant, what would be the best time of day to water a lawn to minimize evaporation of the water spread on the grass?



8. The accompanying diagram shows air flowing from the ocean over a coastal mountain range. Assume that the dew-point temperature remains constant in dry air (that is, relative humidity less than 100 percent). If the air parcel becomes saturated, the dew-point temperature will cool at the wet adiabatic rate as it ascends, but it will not change as the air parcel descends. Use this information to complete the following:
   a. Determine the air temperature and dew-point temperature for the air parcel at each location (B–G) shown on the diagram.
   b. At what elevation will clouds begin to form (with relative humidity = 100 percent)?
   c. Compare the air temperatures at points A and G. Why are they different?
   d. How did the water vapor content of the air change as the parcel of air traversed the mountain? (*Hint:* Compare dew-point temperatures.)
   e. On which side of the mountain might you expect lush vegetation, and on which side would you expect desert-like conditions?
   f. Where in the United States might you find a situation like what is pictured here?



9. The cumulonimbus cloud pictured in Figure 17.21H is roughly 12 kilometers tall, 8 kilometers wide, and 8 kilometers long. Assume that the droplets in each cubic meter of the cloud total 0.5 cubic centimeter. How much liquid does the cloud contain? How many gallons is this? (*Note:* 3785 cm^3 = 1 gallon.)

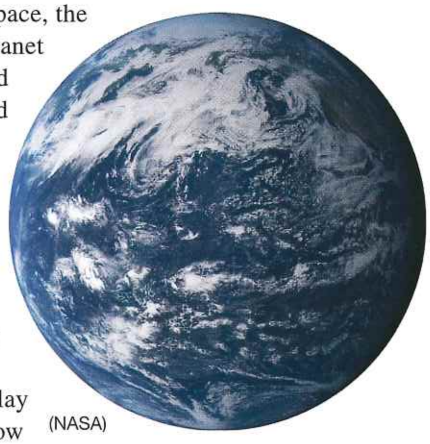
10. Cloud droplets form and grow as water vapor condenses onto hygroscopic condensation nuclei. Research has shown that the maximum radius for cloud droplets is about 0.05 millimeter. However, typical raindrops have volumes thousands of times greater. Explain how cloud droplets become raindrops.
11. Why does radiation fog form mainly on clear nights rather than on cloudy nights?
12. Which winter storm is likely to produce deeper snowfall: a low-pressure system that passes through the midwestern states of Nebraska, Iowa, and Illinois (26°F average temperature at the time of the storm) *or* exactly the same system passing through North Dakota, Minnesota, and Wisconsin (16°F average temperature at the time of the storm).
13. Weather radar provides information on the intensity of precipitation in addition to the total amount of precipitation that falls over a given time period. Table C shows the relationship between radar reflectivity values and rainfall rates. If radar measured a reflectivity value of 47 dBZ for 2½ hours over a location, how much rain will have fallen there?
14. What are the advantages and disadvantages of using rain gauges compared to weather radar in measuring rainfall?

Table C
Conversion of Radar Reflectivity to Rainfall Rate

Radar Reflectivity (dBZ)	Rainfall Rate (inches/hr)
65	16+
60	8.0
55	4.0
52	2.5
47	1.3
41	0.5
36	0.3
30	0.1
20	trace

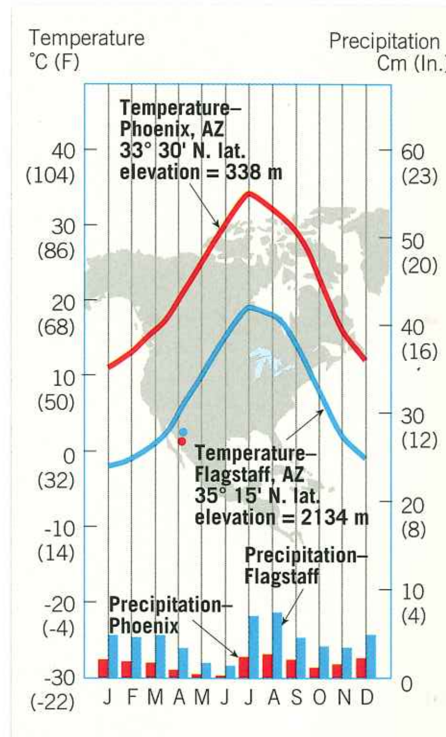
EXAMINING THE **EARTH SYSTEM**

1. The interactions among Earth's spheres have produced the Great Basin area of the western United States, which includes some of the driest areas in the world. Examine the map of the region in Figure 6.30. Although the area is only a few hundred miles from the Pacific Ocean, it is a desert. Explain why. Did any geologic factor(s) contribute to the formation of this desert environment? Do any major rivers have their source in the Great Basin? Explain. (For information about deserts in the United States, visit the U.S. Geological Survey's [USGS's] "Deserts: Geology and Resources" Website, at http://pubs.usgs.gov/gip/deserts/.)
2. When Earth is viewed from space, the most striking feature of the planet is *water*. It is found as a liquid in the global oceans, as a solid in the polar ice caps, and as clouds and water vapor in the atmosphere. Although only one-thousandth of 1 percent of the water on Earth exists as water vapor, it has a huge influence on our planet's weather and climate. What role does water vapor play in heating Earth's surface? How does water vapor act to transfer heat from Earth's land–sea surface to the atmosphere?



(NASA)

3. 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. How might each of the following alter the precipitation at a particular locale?
   a. An increase in the elevation of the land
   b. A decrease in the area covered by forests and other types of vegetation
   c. Lowering of average ocean-surface temperatures
   d. An increase in the percentage of time that the winds blow from an adjacent body of water
   e. A major episode of global volcanism lasting a decade
4. Phoenix and Flagstaff, Arizona, are both located in the southwestern United States, less than a 2-hour drive apart. Using the accompanying climate diagram (which gives the elevations of the two cities), describe the impact that elevation has on the precipitation and temperature of each city. Use the Internet to compare and explain the natural vegetation of these locations. Next, check the current weather conditions for Phoenix and Flagstaff, Arizona, by using The Weather Channel Website, at www.weather.com. Do the current conditions seem to fit climate data? Explain.



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